RECENT DEVELOPMENTS IN POLYCRYSTALLINE DIAMOND-DRILL-BIT DESIGN*

SAND79-1592C

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May 1980

Abstract

Development of design criteria for polycrystalline diamond compact (PDC) drill bits for use in severe environments (hard or fractured formations, hot and/or deep wells) is continuing at Sandia National Laboratories. This effort consists of both analytical and experimental analyses.

The experimental program includes single point tests of cutters, laboratory tests of full scale bits, and field tests of these designs. The results of laboratory tests at simulated downhole conditions utilizing new and worn bits are presented. Drilling at simulated downhole pressures was conducted in Mancos Shale and Carthage Marble. Comparisons are made between PDC bits and roller cone bits in drilling with borehole pressures up to 5000 psi (34.5 PMa) with oil and water based muds. The PDC bits drilled at rates up to 5 times as fast as roller bits in the shale. In the first field test, drilling rates approximately twice those achieved with conventional bits were achieved with a PDC bit. A second test demonstrated the value of these bits in correcting deviation and reaming.

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*Presented at the 1980 Energy-Sources Technology Conference, sponsored by the American Society of Mechanical Engineers, Petroleum Division, New Orleans, Louisiana, February 3-7, 1980.

RECENT DEVELOPMENTS IN POLYCRYSTALLINE DIAMOND DRILL BIT DESIGN

Introduction

The development of polycrystalline diamond compacts (PDC) (e.g., Stratapax*) has renewed interest in drag-type drill bits for oil, gas, and geothermal drilling. With the use of these new cutting elements has come the need for development of design criteria for these bits. This has led to a research program conducted by Sandia Laboratories for the DOE to determine design and performance criteria for PDC bits in severe environments. Initial activities focused on the development of a suitable technique for attaching PDC cutters to the bit [1-4]. The present program is based on an analytical and experimental approach which develops concepts from an elemental standpoint through the laboratory and field testing phases.

PDC cutters have the potential for increasing the drilling rate significantly in many formations. They are proving adaptable to both standard rotary and downhole motor drilling. The possibility of greatly improving performance in drilling shales seems reasonable, but considerable design effort lies ahead to optimize performance. An advantage over natural diamonds is the ability to maintain a good cutting edge while wearing. They can also sustain a large amount of wear before becoming unusable. The greatest problem impeding use of the PDC cutters currently is lack of sufficient information to design and utilize PDC bits to their full capacity.

This paper presents basic design concepts developed from single cutter and full scale laboratory and field tests. Extensive results from the full scale laboratory drilling simulations are presented.

Basic Design Concepts of PDC Bits

Mechanical rock drill bits can be classified as removing rock by grinding, machining, or crushing. Natural diamond bits grind rock and roller cone bits crush the rock. Drag-type bits generally provide a machining action, but are also capable of being used in the other modes of rock removal. The grinding mode occurs when the depth of cut is on the order of the radius of the cutting edge. The crushing mode exists when the fractures caused by the cutting edge initially propagate in a direction away from the free surface of the rock (Figure 1). When this begins to occur, the drilling rate for drag bits

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*GE trademark

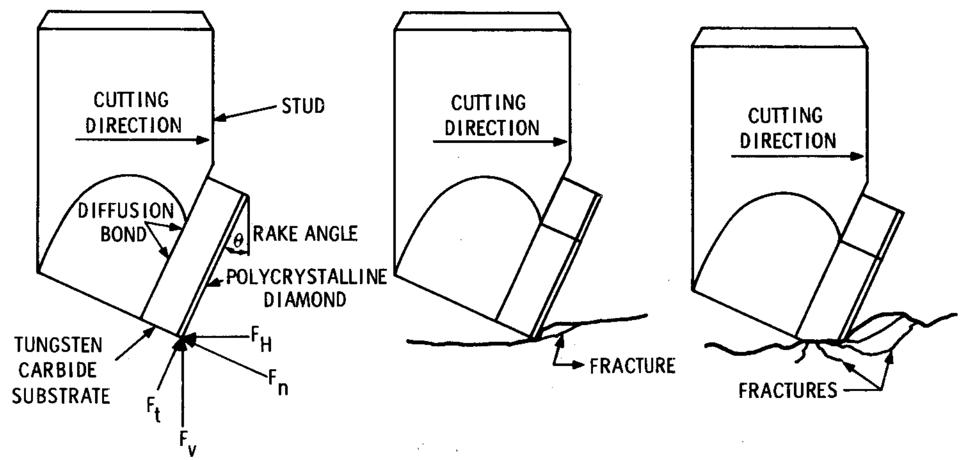

Figure 1. Rock failure mechanisms induced by polycrystalline diamond compact cutters

increases substantially with little additional torque or weight on bit. Prior to development of PDC cutters, crushing with drag bits was of little interest because of rapid degradation of cutting elements in this mode. This mode of operation has been observed in drilling Sierra White Granite in lab tests [4] as shown in Figure 2 and in several field tests in other types of rock. The data shown here is from a 4-3/4 inch bit tested at the Drilling Research Laboratory. In this particular rock, the torques required to drill in this mode of operation are very high. The torque as a function of weight on bit for a typical test in granite is shown in Figure 3. The peculiar shape of the curve can be explained in part by wear that occurs during each run. The numbers on the curve indicate the rate of penetration (ROP) at that load condition. It should be noted that the final portion of the curve where the bit reaches a quasi-steady state operation represents most of the distance drilled. Referring to Figure 2, it can be seen that as load is applied to the bit, the ROP increased slowly until a critical weight on bit is reached at which point the ROP increases rapidly to a high level. For a constant weight on bit below the critical load, the ROP slowly decreased with time as the bit wore. Above the critical load, the ROP increased with time in each test run.

There are two basic design concepts for mounting PDC cutters on bit bodies. In one concept, the cutter is exposed as much aspossible by mounting it on an extended stud or tool post, which is then either brazed or pressed into the bit body. The second type bit has the cutter mounted such that the depth of penetration is limited by either the supporting stud or bit body. This is accomplished by embedding the cutter and support in the bit body as in a matrix mounted bit. The difference in the concepts is that the exposed bit has the potential for drilling at higher rates, but the bits can be damaged more easily. The increased risk of damage requires considerable design effort to ensure that the dynamics of the bottomhole assembly minimize the severity of the bit loading.

Hydraulic considerations for PDC bits are somewhat different than for other types of bits. The cutting action tends to lift the fractured rock off the bottom of the hole where it may be swept away by a purely radial flow pattern. This is, of course, idealized and some of the rock either slides to the side or is fractured below the cutter and is not lifted at all. Roller cone bits on the other hand, lift only a small portion of the fractured rock. With diamond bits, most of the cuttings are pushed to the side because of the lack of clearance between cutter and bit body. This makes bit cleaning more difficult because the cleaning fluid needs to flow around three sides of the cutter to achieve direct chip removal.

In designing the hydraulics of a PDC bit, general turbulence created by throttling the mud flow through nozzles may be of

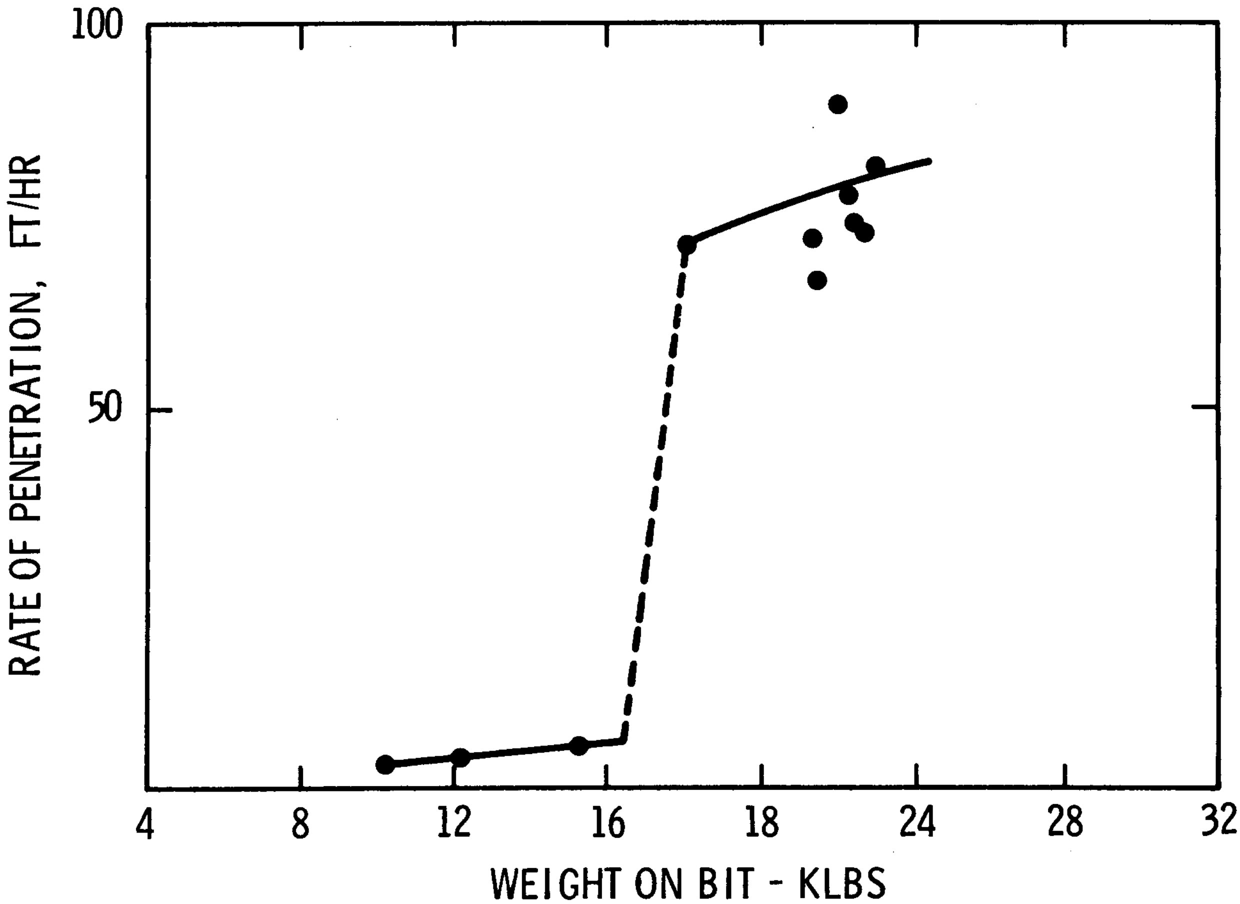

Figure 2. Rate of penetration vs weight on bit at end of each run in Sierra White Granite

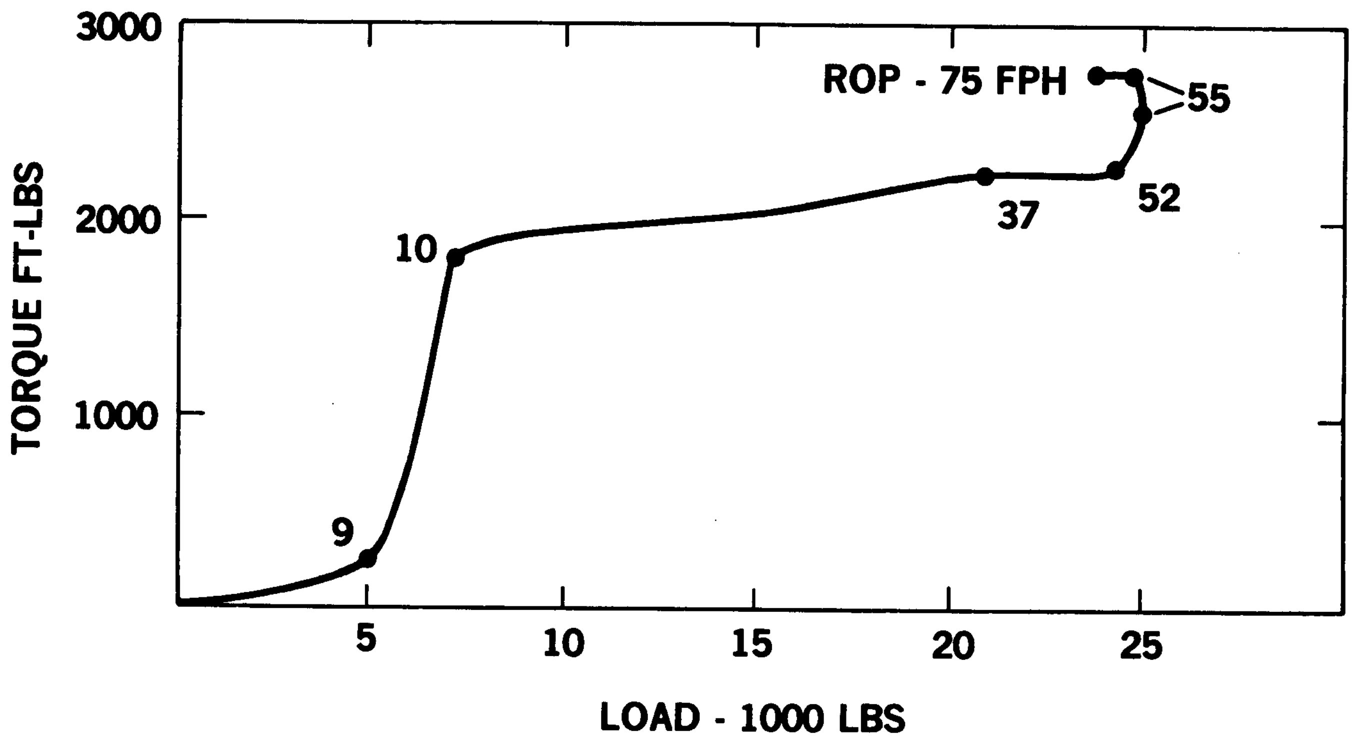

Figure 3. Typical torque curve vs weight on bit in Sierra White Granite

benefit in removing chips not sufficiently lifted by the cutters or from cutters not swept adequately by pure radial flow. An additional hydraulic consideration involves areas that can be plugged or blocked by material causing bit balling. Since there are normally several identical paths for fluid to flow through, a path that is blocked does not tend to be cleaned by the increase in pressure created by the flowing fluid unless the bridged area is sufficiently large so that the blockage has negligible structural strength. In order to avoid this problem, areas where material can pack into the bit should be avoided. Small flow channels and close packing of cutter supports are examples of problem areas. In designing bits, the consequences of blockage on bit performance must be considered since the possibility of "balling" exists on all bits.

Development of theories to predict the behavior of various aspects of bit design is needed before PDC bits can be efficiently utilized in extreme environments. It is the goal of this research program to develop basic design criteria and cutting theories, rather than to develop specific bit designs.

Development of Design Criteria

Experimental -- The development of design criteria through physical experiments is a feasible way of determining performance characteristics where there is a lack of adequate modeling of rock behavioral characteristics. Available to the researcher for experimental development are single cutter tests, full scale laboratory tests, and field tests. The ability to develop precise data is greatest with the single cutter tests but the conditions are somewhat unrealistic. Field tests give the ultimate indication of performance but usually fail to provide detailed design data. Full scale laboratory tests represent a compromise between the two and yield information adequate for design.

Single Cutter Tests -- These tests are conducted with cutters mounted on an instrumented tool holder and driven by a suitable machine tool. To date, the tests have been conducted on a large vertical milling machine. The information gained from the early experiments [5] was employed in designing the first generation bits for laboratory and field testing. Additional tests to determine optimum relative cutter positioning are planned.

The original tests showed that in hard formations rake angles greater than 20° (negative) prevented spalling of the diamond surface although the cutting forces were increased at the higher rake angles. At rake angles equal to or greater than

30° (negative), the cutting edge is unsupported and chipping can o-cur (a break in the cutter parallel to the rock surface) [5].

Full Scale Laboratory Tests -- These tests have yielded the most valuable design information because downhole conditions can be simulated while instrumentation and post test inspection capabilities are retained, and data is available after drilling short intervals. In the past two years, an extensive series of tests has been completed. Five PDC bits were tested with two roller cone bits used for comparison. Only the results of the 6-1/2 inch PDC bits are presented since these bits were tested the most extensively. Several of the tests were conducted at simulated downhole pressures in Carthage Marble and Mancos Shale. In order to gain the most information from the tests, bits that had varying degrees of wear were used.

Typically, drilling in the laboratory will be conducted in low abrasion rocks so that wear is not a consideration during the test. Wear in the tests reported here has been achieved by drilling in Sierra White Granite which causes rather rapid wear of the cutting edge. It is probable that the effect on the cutting edge due to wear will not be the same in all rocks. For instance, wear achieved by a grinding wheel leaves a much sharper cutting edge than wear caused by granite. Tests of bits worn in the field should give the most representative effects of wear on bit performance.

From this testing in granite, it was determined that wear is a stronger function of the distance the cutter travels than the volume of material removed. Figure 4 shows the wear of each cutter on two bits as a function of linear distance traveled. In these bits, each cutter (except center and gage cutters) was designed to remove the same volume of rock per revolution. Both bits drilled the same distance (10 feet) so that each cutter removed the same volume of rock. In addition to radial position, the differences in distance traveled by each cutter results from different penetration rates for each bit in removing the same volume of rock. Cutter velocity above certain levels may also have an effect on wear but no data was generated to determine this effect.

In designing PDC bits for full-scale tests, there are several characteristics that should be kept in mind. Bit hydraulics are recognized as a key to success of any bit design. Because of the possibility of varying penetration from 0.004 inch (0.1 mm) to over 0.400 inch (10 mm) per revolution with PDC bits, the hydraulic performance of a bit can vary significantly with different drilling rates. This is illustrated in Figure 5 which shows the ROP (rate of penetration) for two flow rates with apparent weight on bit. Because the back pressure on the bit varies with depth of cutter engagement (and hence ROP) for a given flow rate, the portion of the apparent weight on bit

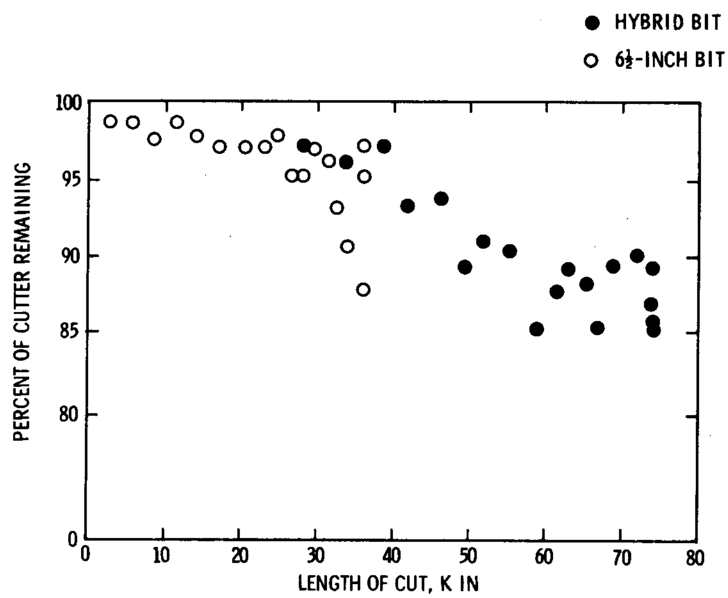

Figure 4. Wear of cutters

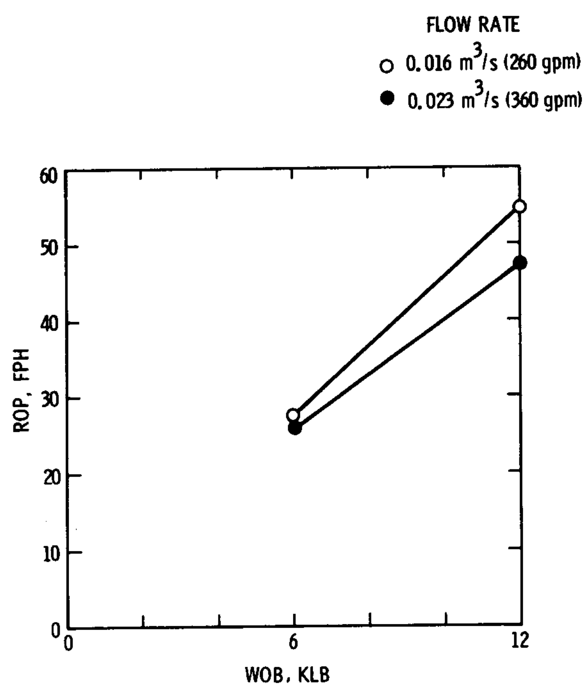

Figure 5. Rate of penetration for two flow rates

that is caused by fluid pressure cannot be determined. Figure 5 shows the effect of increasing the flow rate and consequently increasing back pressure for a bit run in a laboratory test. The weight-on-bit (WOB) is the apparent value and still contains a force from the back pressure. As seen in the figure, as the apparent WOB increases, the penetration for the higher flow rate is the lower of the two and does not increase as much with increased WOB as for the lower flow rate because the back pressure becomes larger with the increased penetration of the cutters. Because the back pressure causes considerable variations in true weight on bit, comparisons between bits probably should use torque as the independent variable.

The tests of the bits under simulated downhole pressures were conducted in the wellbore simulator at the Drilling Research Laboratory in Salt Lake City in July and September of 1979. Carthage Marble and Mancos Shale were used in these tests. The borehole pressure (P_B) was varied from 100 psi to 5000 psi in the tests. The overburden stress was set at 2 P_B and the confining stress at 1.34 P_B for all tests except where P_B was below 500 psi. Here, in order to keep the sample from rotating, the minimum overburden pressure is 1000 psi. A 9.5 lb/gal water base mud and a 12.4 lb/gal high loss filtrate oil base mud were used. As a comparison, a 7-7/8 inch Smith F3 roller cone bit was tested in the marble while the comparison in shale was with a 6-1/4 inch Smith F2 roller cone bit.

The effects of the pressure on drilling rates can be seen in Figure 6 for both rocks when water based mud is used. The ability to drill Carthage Marble is reduced significantly at very low borehole pressures, while the Mancos Shale gradually becomes more difficult to drill with pressure. Interestingly, the cuttings from the marble were extremely fine while cuttings from the shale tests were fairly large particles (1 mm thick by 5 mm in diameter). The opposite was true for the roller cone bits where chips were produced in drilling marble but the shale was fully comminuted. A worn 6-1/2 inch PDC bit was used in both rocks [6].

The torques required to drill with the PDC bits at various pressures in shale and marble are shown in Figure 7. The differences in drillability of the two rocks is apparent when considering either WOB or torque. In drilling rocks at depth where the toughness is increased by borehole and overburden stresses, the torque required is a strong function of depth of cutter penetration. When rocks fracture brittlely, it has been observed in these tests that torque is predominantly a function of weight on bit and less dependent on penetration. Frictional forces also become much more significant if a bit is worn or designed so that the supporting elements can drag on the rock. The torques for a 6-1/2 inch bit in several different rocks at atmospheric conditions are shown in Figure 8. Although the ROP for any particular WOB varied considerably,

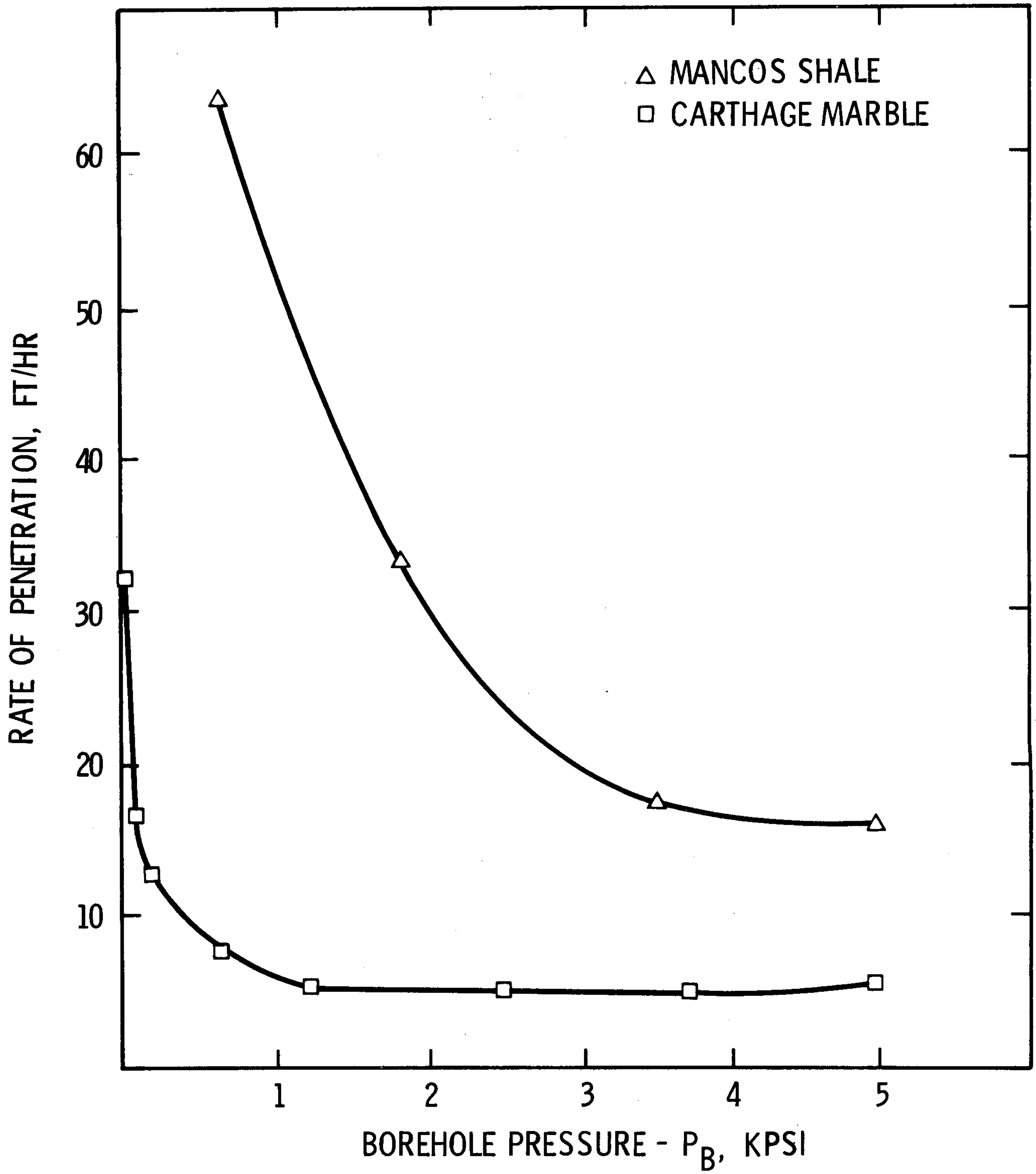

Figure 6. Effect of borehole pressure on ROP for Sandia PDC bit with water base mud (WOB = 10 KLB, N = 50 RPM)

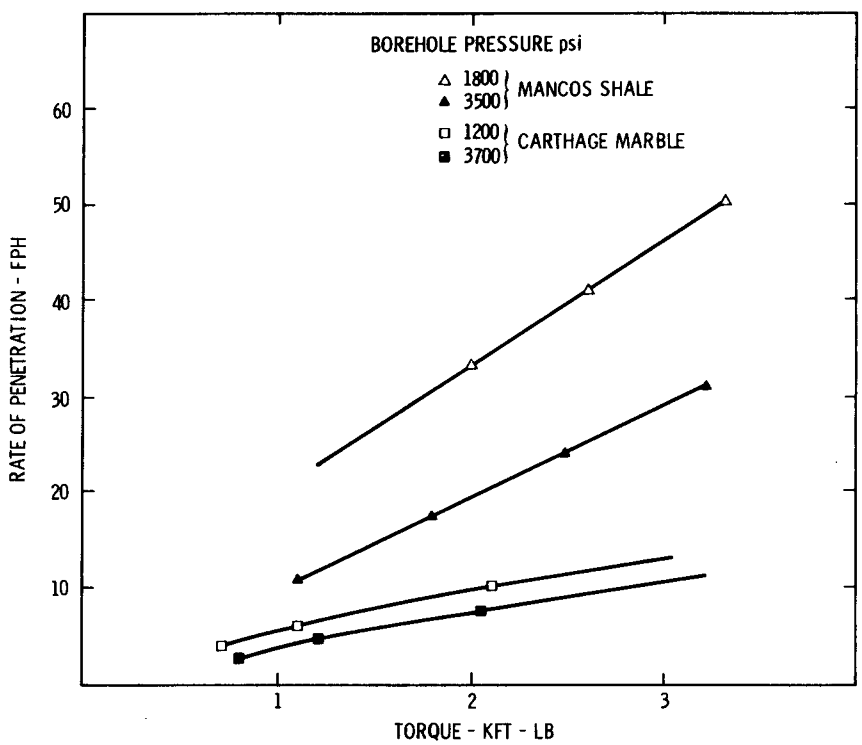

Figure 7. Rate of penetration vs torque for worn Stratapax bit in Mancos Shale and Carthage Marble with water base mud (N = 50 RPM)

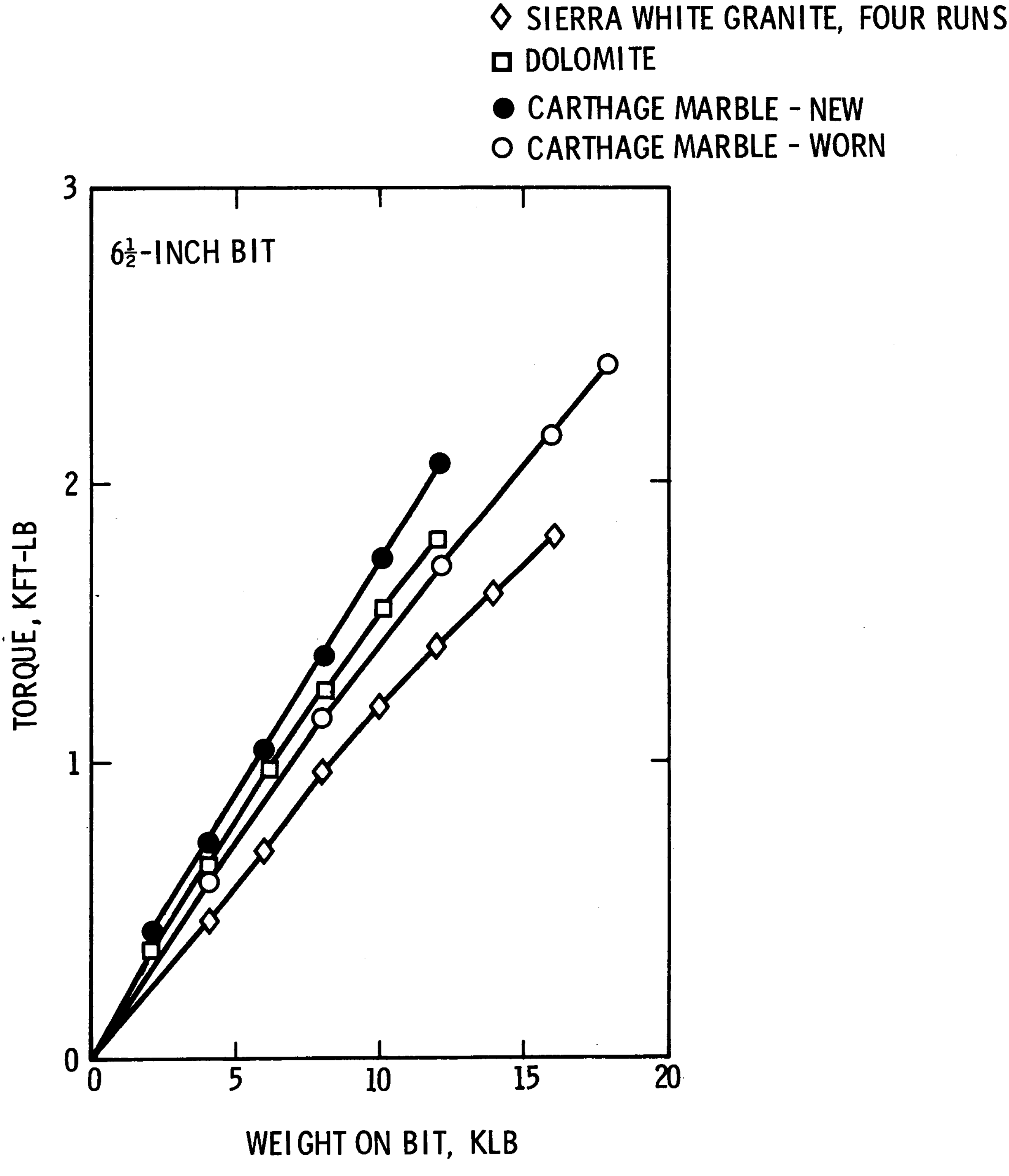

Figure 8. Torque required by 6-1/2" bit

the torques required for drilling several rock types at various wear states were similar. Since the penetration varied for each wear condition in the same rock the energy expended in drilling was not a strong function of volume of rock removed per revolution or of chip size. Therefore, the frictional forces consumed a large portion of the energy required for drilling these basically brittle rocks. In Figure 9, the ROP in marble is shown varying significantly with wear, but the torques required vary little (Figure 8) for any given WOB. The performance in granite, an extremely brittle rock, shows almost no variation in torque while wearing, but a large increase in required WOB to achieve a given ROP (not shown).

Mancos Shale was chosen for additional tests because its drilling characteristics are of great interest. Shales of this type are frequently encountered and are often difficult to drill, especially because of bit cleaning problems.

The rates of penetration for a PDC bit and a roller cone bit in Mancos Shale are shown in Figure 10. This data was collected in the wellbore simulator using a water base mud. As seen from the data, the performance of the PDC bit increases significantly at higher rpm. Figure 11 illustrates this even more dramatically since torque is of primary concern on PDC bits. This 6-1/2 inch PDC bit was designed to carry up to a 40,000 lb load, but the torques would be excessive. The 6-1/4 inch roller cone bit is load, not torque, limited and is designed to operate with 18,000 lb. The performance of the PDC bit was superior to the roller cone bit except in cases where low torque (500 ft-lbs) and low rotation rate (50 rpm) are required.

The difference in performance of PDC bits and roller cone bits was even more pronounced when an oil base mud was employed (Figures 12-13). In this case, with the roller cone bit tending to ball, the PDC bits performed better at all conditions. The data for the roller cone bit is not shown for 100 rpm because bit balling made the data meaningless. The difference in the performance of the two PDC bits is accounted for in their design and wear condition. The NL-Hycalog bit was a matrix-type bit designed for long life in a hard formation. The bit was new and was not worn in testing. The testing occurred almost universally at penetration rates greater than that for which it was designed, but even in the overloaded condition it drilled well. The Sandia bit which was worn prior to the test was a stud-type bit and was designed to penetrate up to 0.250 inch (6.4 mm) per revolution.

In Figure 14, a comparison of the torque vs. WOB required in the oil and water base muds for the Sandia bit shows almost no difference at 50 rpm, although the ROP in the water base muds is slightly higher for equal weight on bit. (See Figures 10 and 12). At 300 rpm, the ROP with oil base muds is much

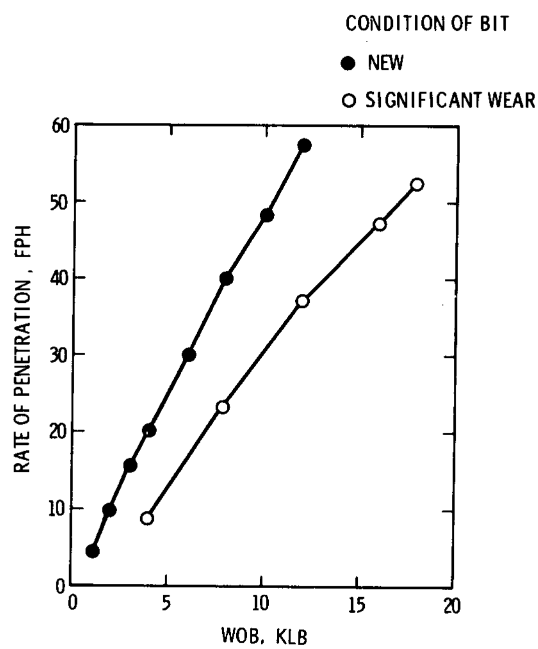

Figure 9. Wear effects on ROP for 6-1/2" bit

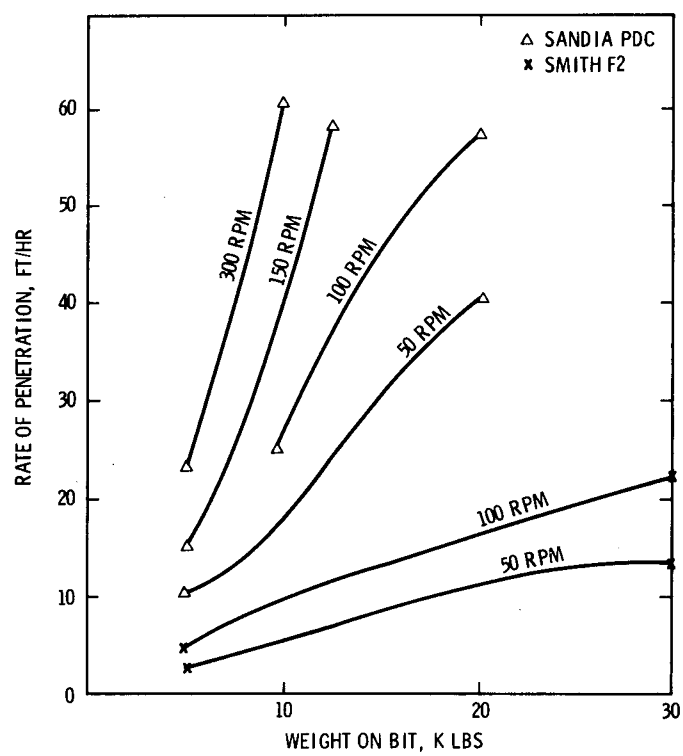

Figure 10. Performance of a 6-1/2" PDC and a 6-1/4" roller cone bit in Mancos Shale with water base mud (borehole pressure 4000 psi)

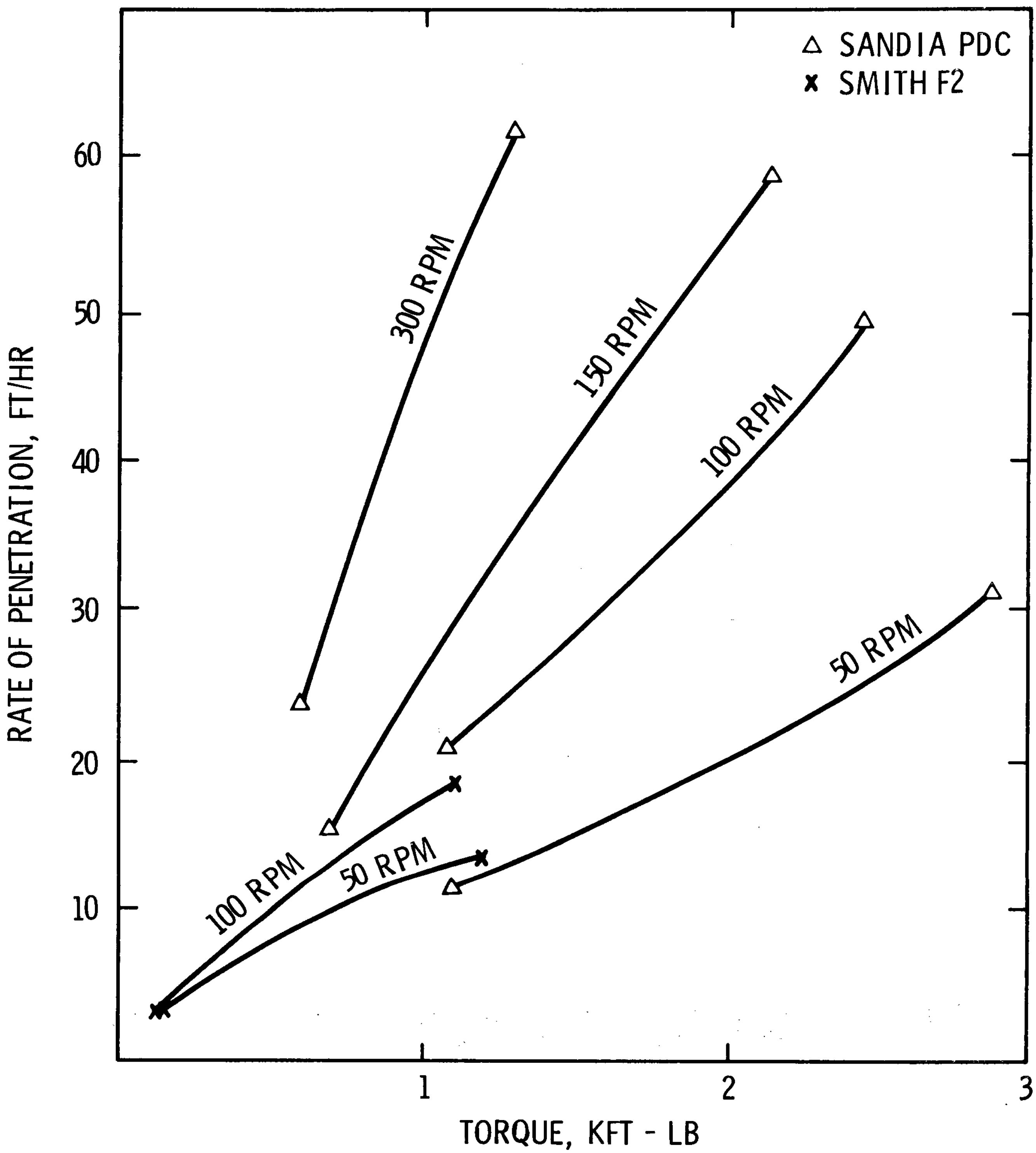

Figure 11. ROP as a function of applied torque for PDC and roller cone bits in water base mud (P_B - 4000 psi)

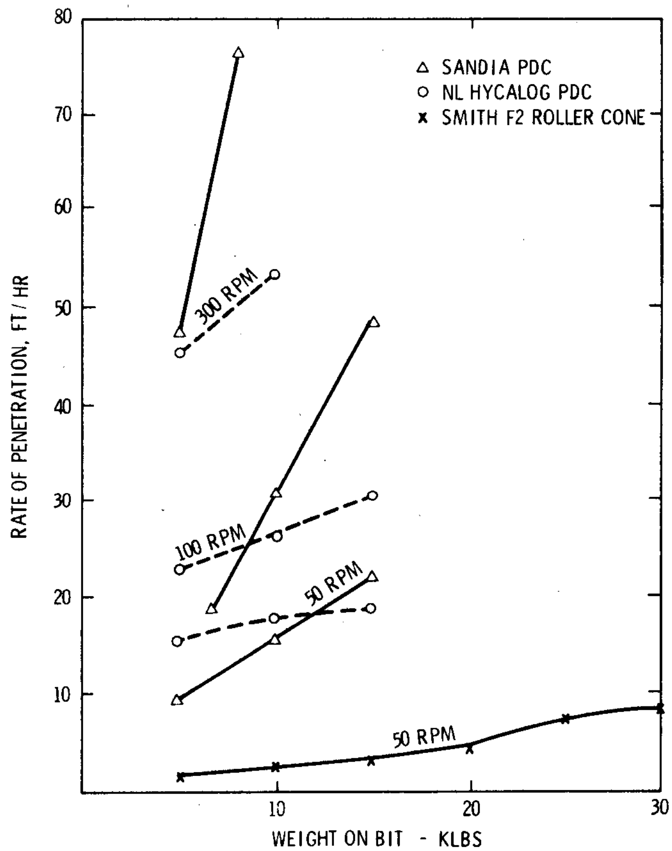

Figure 12. Performance of PDC and roller cone bits in Mancos Shale with oil base mud (P_B - 4000 psi)

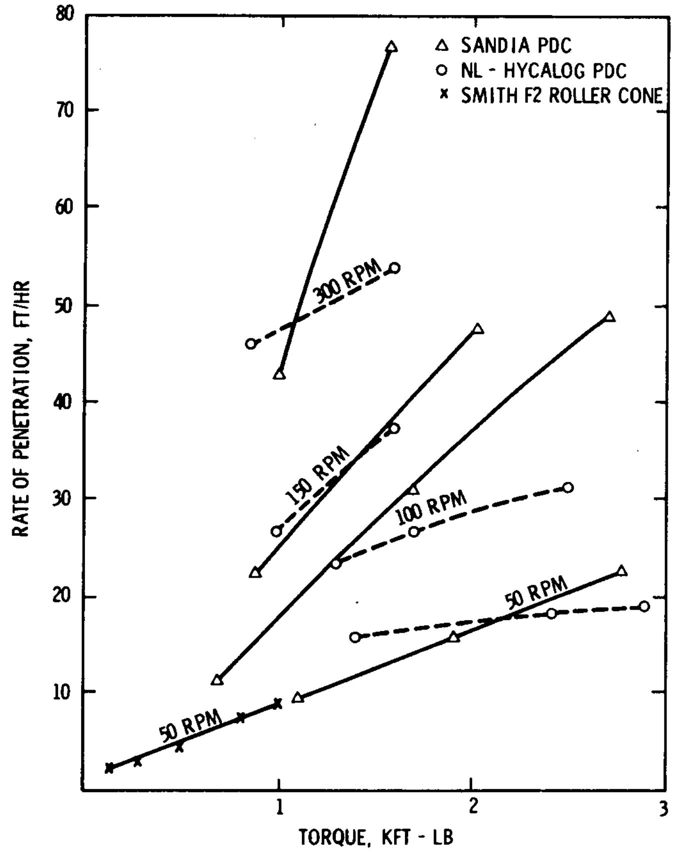

Figure 13. ROP as a function of applied torque for PDC and roller cone bits in oil base mud (P_B - 4000 psi)

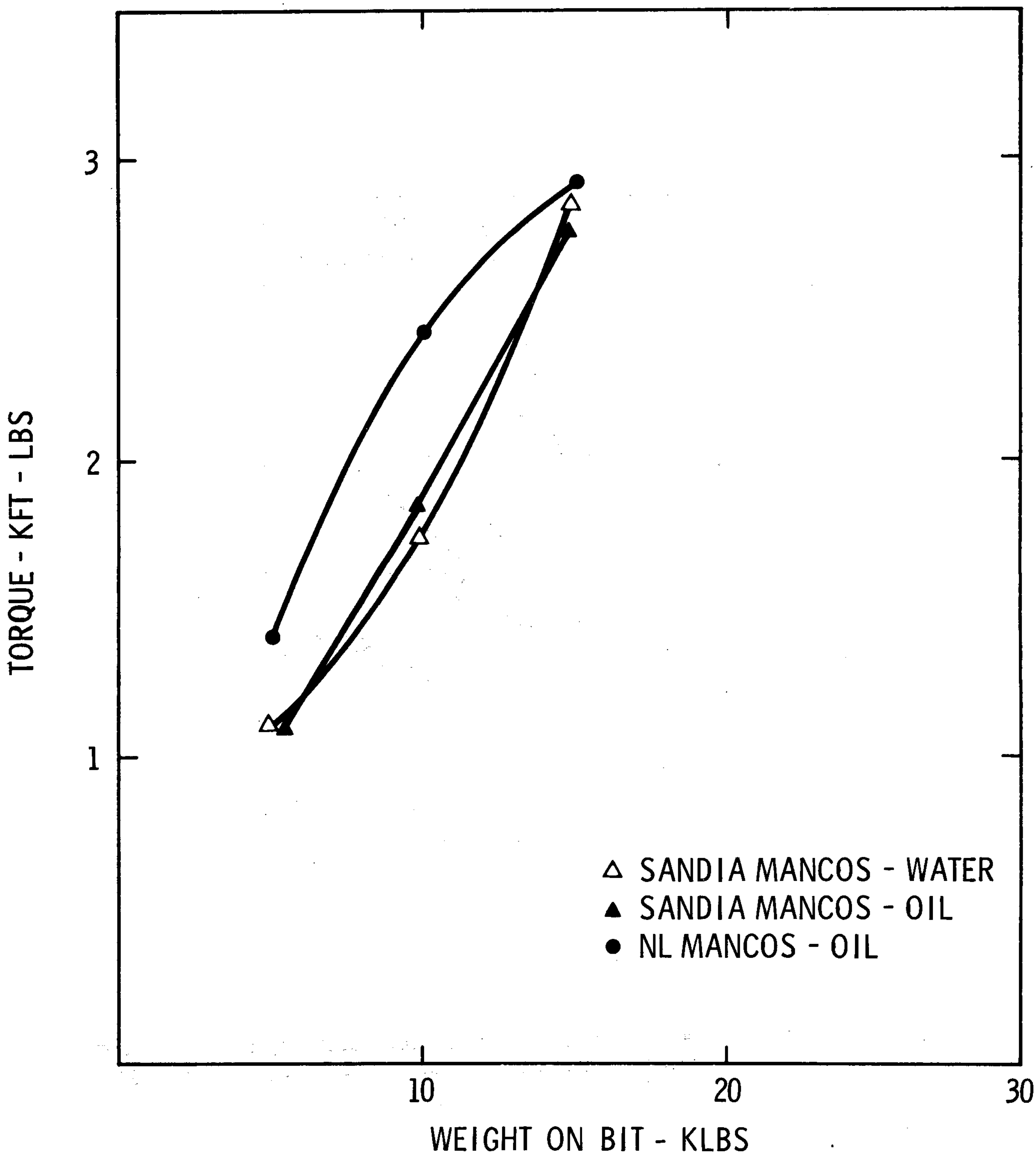

Figure 14. Torque as a function of weight on bit for oil and water base muds (P_B - 4000 psi, N - 50 RPM)

higher for a given WOB but the torque required for the same ROP is identical (Figures 10-13).

The torque characteristics when drilling Carthage Marble under pressure are shown in Figure 15.

A 7-7/8 inch roller cone bit was run under the same test conditions. A direct comparison is not made because of the different diameters, but the performance in marble for the PDC bit was not as good as for the roller cone bit until a higher rotation rate was used. The higher rotation rate would be used with PDC bits to keep the required torque low for high rates of penetration.

In comparing PDC bits with roller cone bits, operating conditions such as rotation rate, weight on bit, drilling fluid, formation characteristics as well as bit life have a definite bearing on the relative performance rating. Although the energy required to fracture the rock is not always thought of as critical, it is important and should be considered. Figure 16 gives the specific energy for fracturing shale as a function of rpm. The 20,000 lb WOB was chosen as the optimum for the roller cone bit. An upper limit of 1000 ft0lb of torque was chosen for the PDC bit although the load was less than 10,000 lbs. The specific energy of removal of marble was similar to that for shale for the roller cone bit but the PDC bit required 50% more energy for the marble. While the efficiency of the PDC bit changes little with rpm, the roller cone bit drastically loses efficiency as indicated by the increase in specific energy of removal shown in Figure 16. If this data is typical for formations encountered in drilling, design improvements wihl be required for PDC bits to be economical at low rpm in certain formations and improved cutter design will be required for high speed roller cone bits in addition to improved bearing capability.

In general, increasing the rotation rates will improve ROP for PDC bits. There are, however, conditions which will preclude this improvement. In Figure 17, the ROP as a function of rpm is plotted for drilling at atmospheric conditions in marble and granite. As can be seen, the rate of penetration actually decreases in going from 75 rpm to 100 rpm in the granite. In this test the granite was extremely load-rate sensitive. In drilling other rock, the actual penetration of the cutters frequently drops with increasing rpm, but this was the only repeatable case where the resulting ROP dropped.

<u>Field Tests</u> -- A field test series has been initiated to test the technology developed in this program. Presently all field tests are run under conditions where testing is of minor importance in the operation. Because of this, they represent proof tests and yield little design information. Hopefully, some

future tests can be conducted on dedicated test rigs with adequate instrumentation. Two field tests have been conducted in this program. The first was a field test of a 7-7/8 inch Hybrid bit conducted in Wheeler County, Texas, in May, 1979 [6]. This bit had been tested in the laboratory and the performance was found to be similar to other PDC bits tested. The formation drilled is called the Panhandle Lime.

In this operation the instrumentation was limited to a weight on bit indicator, a flow line pressure gage, and a device to indicate each time one foot is drilled on a time base recording chart. Rotation rate was determined with the aid of a stop watch so that only average rates could be obtained.

Various loads and rotation rates were attempted before 20,000 lbs at 50 rpm was determined to yield the most satisfactory results. At other weights and speeds, performance was not as acceptable because the operation was unsteady as a result of varying torque and vibrations.

Because of lost circulation problems, the flow rate was held to less than 200 gpm limiting the ROP to 50 fph. Increasing the flow rate to 350 gpm uielded a ROP of greater than 65 fph, but the flow rate could not be maintained because of lost circulation. Typical drilling rates in this formation with roller cone bits are 15-20 fph. The test continued for a total of 230 ft when the drilling fluid supply was depleted.

Upon recovery of the bit, inspection revealed severe chipping of half the cutters even though the bit had continued to drill well until pulled. The unfortunate part, as in most field tests, is that the damage mechanism is indeterminant. Indications from laboratory full-scale testing are that certain operating conditions, not the most extreme, cause damage. In testing the 6-1/2 inch bit at DRL, it was found that operating at 5000 lbs WOB at 3000 rpm causes severe vibration with resulting damage, while increasing the WOB to 10,000 lbs totally eliminates the problem. This condition, of course, is caused by the dynamic interaction of the test rig and bit and probably would not occur at the same conditions in the field. The possibility exists that in the field certain operating conditions should be avoided even for short periods of time. Unfortunately, without adequate instrumentation, these conditions can only be determined by trial and error, a very inefficient process.

Results from this test and from the full-scale laboratory tests indicate that a dynamic analysis of the bit and drill string should be included when designing bits. To properly accomplish this task, shock, vibration, and loading data from field tests are needed.

The second field test was conducted on a deep well in Winkler

County, Texas. The well was being directionally drilled to a target area and deviation from the planned trajectory was a problem. A 6-1/2 inch all-PDC bit was run into the hole at 17,000 ft to correct the deviation. It was run with very little weight on bit (drilling rate held to 4 fph) and the deviation angle reduced about 4 degrees in 100 ft. Because of the contour of the hole, torque became a problem and the bit was pulled. All cutters remained on the bit indicating the attachment technique was acceptable. Two cutters were cracked and were replaced before the bit was run back into the hole on a stiff bottomhole assembly. The bit reamed 500 ft of hole before drilling resumed resulting in a considerable reduction in torque. The bit drilled another 30 ft when a high concentration of chert was encountered and drilling ceased. The bit successfully corrected the unwanted deviation and increased the radius of the curves to reduce parasitic torque.

Conclusion

A combination of single cutter, full-scale laboratory, and field tests are required to efficiently design high performance drill bits. The techniques and equipment to conduct the laboratory tests are readily available. Improved instrumentation is required before field testing can be adequately used as a design tool. The present design information is adequate to design first generation bits. Additional techniques must be developed to optimize designs of high performance bits.

This program utilized the three types of tests and analytical analysis to develop design criteria for polycrystalline diamond compact bits. Important concepts derived from these tests include:

1) Rake angle should be in excess of 20° (negative) in hard formations.

2) Torque as important as an independent variable in design analysis.

3) The linear distance traveled is the overriding consideration in wear of cutters.

4) Performance varies as a function of cutter wear condition.

5) The energy required to remove rock is relatively independent of rotation rate.

The design concepts developed in this program were used to build several bits that were successfully field tested. One bit was used to achieve high penetration rates and the other was used to ream and correct deviation from a planned trajectory.

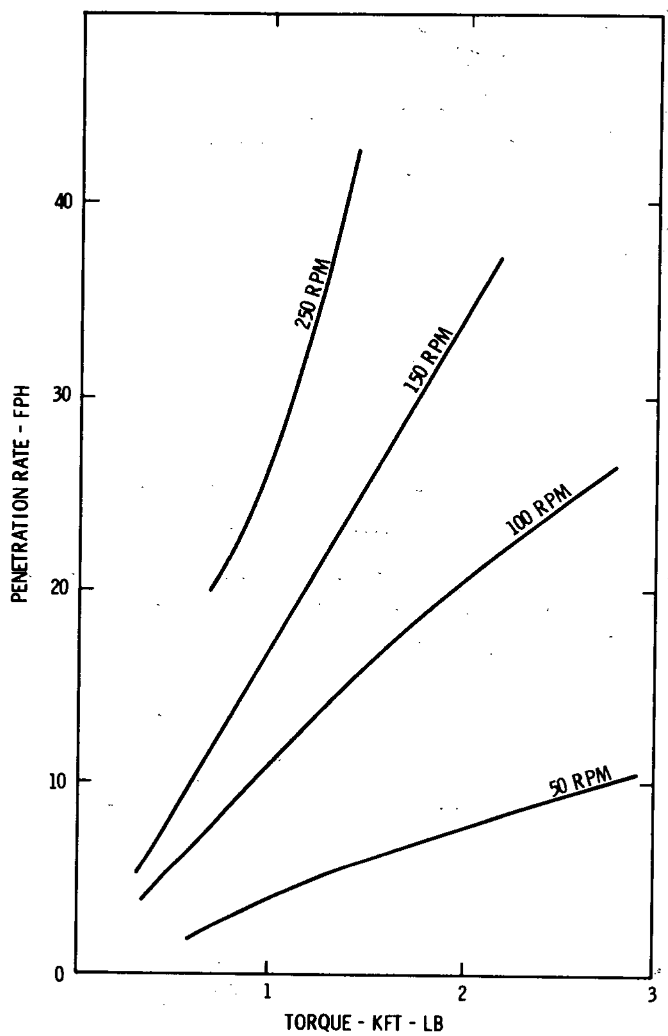

Figure 15. Rate of penetration of a PDC bit as a function of torque when drilling Carthage Marble under pressure (P_B = 1200 psi)

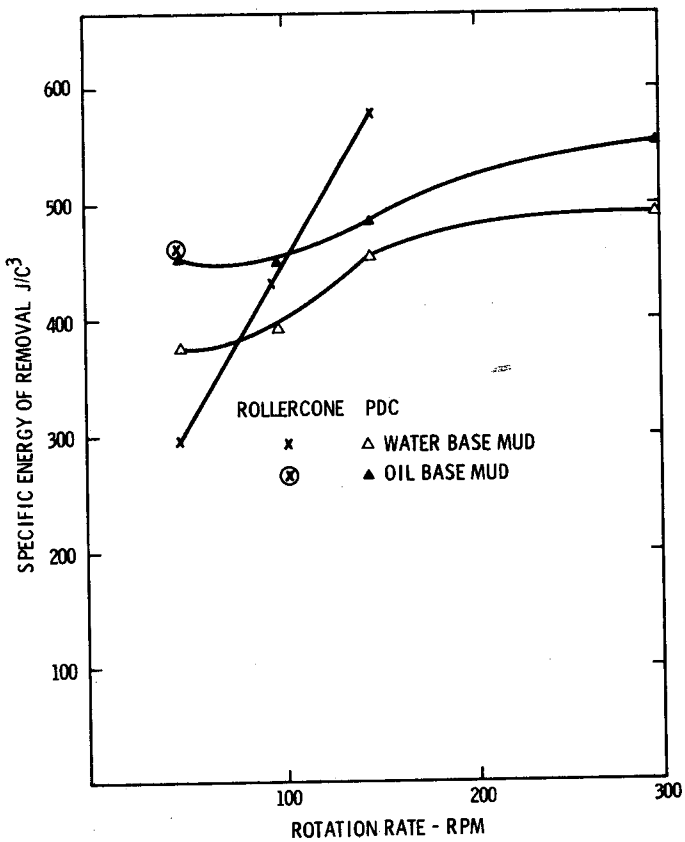

Figure 16. Specific energy of rock removal of Mancos Shale for roller cone bit at 20 K lbs WOB and PDC bit at 1000 ft/lb torque

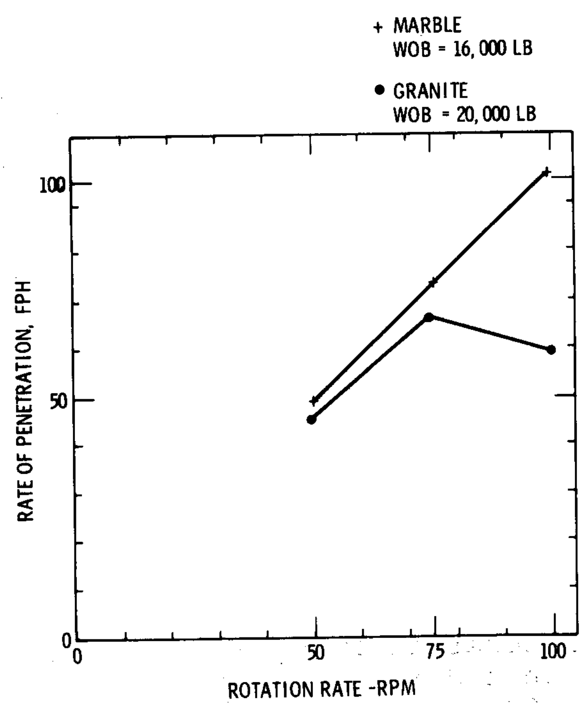

Figure 17. Effect of Rotation Rate on Performance of 6-1/2 inch PDC bit in Marble and Granite

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