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The Positive Effects of Side Rake in Oilfield Bits Using Polycrystalline Diamond Compact Cutters

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ABSTRACT

What used to be considered a novel drilling technique, the use of synthetic diamond cutters in a drag bit configuration, has now emerged in the drilling industry as a time and cost efficient drilling tool. These bits, utilizing polycrystalline diamond compact cutters for drilling soft or plastic formations have been proven successful through a systematic development. First, the main problem associated with drilling soft or plastic formations was identified as bit cleaning. Second, laboratory tests of a single compact cutting plastic shale under confining pressure with a load dynamometer and high speed photography were studied. The results demonstrated that a compact incorporating side rake angle and ample chip clearance space can provide efficient mechanical cleaning action. Finally, new style drill and core bits, built with side rake orientation along with previous style drill and core bits without side rake features, were field tested and observed in the same drill hole or in the same formation. The drill or core bits with side rake features always drilled or cored faster in the soft or plastic formations than those bits without side rake under the same operating parameters (hydraulic, bit weight and rpm). It was concluded that bits with side rake features can enhance the bit cleaning by mechanical cleaning action and, therefore, improve the bit performance in soft or plastic formations.

INTRODUCTION

Since 1973, Christensen Diamond Products has experimented with polycrystalline diamond compact (PDC) cutters for oil field applications¹. These synthetic diamond cutters are called Stratapax^R or Syndite^R, developed by General Electric or DeBeers, respectively. These PDC cutters consist of a layer of polycrystalline synthetic diamond and cemented tungsten carbide

produced as an integral blank by a high-temperature, high-pressure technique². They combine the features of the larger, sharper cutting edges of a tricone rock bit with the efficiency and endurance of diamonds. Additionally, unlike conventional bits that drill by fracturing or crushing, PDC bits drill with a shearing action. Since rock requires significantly less energy to fail in shear, more efficient drilling with less weight on the bit is possible. All these advantages enable the PDC bits to outperform or compete with the conventional bits in certain application areas. Considerable progress had been made by bit fabricators in the design evolution of PDC bits for specific drilling applications. However, until recently PDC bits had generally not performed competitively when drilling soft or plastic formations, particularly shale.

The main problem of PDC bits drilling soft or plastic formation was identified as bit balling. Extensive field testing of PDC bits in soft or plastic shale showed shale cuttings clogged in front of the PDC cutters even when the bit hydraulic horsepower per square inch exceeded 3 HSI (enough HSI for a conventional bit to maintain good bit cleaning). Since shale comprises the bulk of the footage drilled for oil and gas wells, the bit balling problem in shale demanded intensive investigation.

PROBLEM DIAGNOSIS

Formation chip analysis is a valuable tool for the bit manufacturer. Field observation of the cuttings of soft or plastic shale drilled by the PDC bit revealed a unique feature of the cuttings. Unlike the round or polygonal shape of brittle rock cuttings, the shale cuttings recovered from the shale shaker contained many curved strips or segments (Figures 1 & 2). The curved segment had a smooth convex side and a

References and illustrations at end of paper

peeled concave side, a feature closely resembling that of metal cuttings. At the same time single point cutting tests were conducted at the University of Tulsa. These early studies were done on the PDC cutters without any side rake and results have been published³. In cutting Mancos shale under confining pressures of 2,000 psi and higher with a single PDC cutter, the chip generation was similar to that of cutting metal (Figure 3). The chip was formed in front of the cutter and moved up the front of the cutter face in a curved shape. The chip generated in this laboratory was the same as that collected in the field operation; a curved segment with a smooth convex side and a peeled concave side.

A shale chip has the tendency to stick to the cutter face with an adherence which is strong even after the cutting tools were removed from the testing chamber.

These observations of shale cutting and chip generation studied in the laboratory gave the clue to the bit balling problem in soft or plastic formation drilling. From the hydraulic point of view the cutter exposure is preferred to be small to induce high fluid velocity for sweeping away the cuttings and cooling the diamond. But from the chip generation point of view, the chip clearance should be ample enough to allow smooth and uninterrupted chip generation.

Figures 4 and 5 help to explain the conflict between bit hydraulics and chip clearance. Figure 4 shows that chip generation and removal was impeded due to small clearance. In consequence, the chip will be pressed between the bit body and rock formation. If the rock formation is soft or plastic, the chip will be packed tight in front of the cutter. This packing of plastic chips will then demand extremely high jet velocity to move it clear of the cutter. Unfortunately, in practical field operation, high hydraulic horsepowers are not always available and our field experience indicated that even hydraulic horsepower of 4 or 5 horsepower per square inch may not be enough to get complete cleaning. Another negative effect of chip interference is that the chip will push the bit body upwards and thus reduce the actual bit weight applied to the formation.

To insure an uninterrupted chip generation large clearance is necessary as shown in Figure 5. However, the large clearance for the chip means large fluid areas which in-turn induces low fluid velocity. The low fluid velocity may not have enough momentum to sweep away the plastic chip. Sooner or later, these chips will be trapped or clogged in the large fluid area and the bit will be balled up. An actual field example of a bit balled-up is shown on Figure 6. Here the chips plugged up the big fluid course where the fluid velocity is the lowest. Another detrimental effect of large fluid courses is the low fluid velocity in the fluid course area of the waterway drastically reduces the cooling effect on the PDC cutter. This poor cooling of the diamond will always lead to premature wear of the bit (Figure 7).

Unable to find a satisfactory solution to the bit cleaning problem after numerous attempts with different combinations of bit hydraulics and chip clearance, the effects of side rake on bit cleaning were examined. Side rake is the angle between the cutter face and the radial plane of the bit (Figure 8). As mentioned before, the chip generation of soft or plastic formation cut by a PDC cutter was very similar to that of cutting metal. In the machine tool the side rake is a regular feature incorporated into the tool to facilitate chip removal. If the side rake works in the machine tool, it may also be beneficial in the cutting of soft or plastic formation by PDC cutters.

To investigate the problem, in early 1979 Melaugh did laboratory testing, under confining pressure, of a single PDC cutting shale with side rake.

LABORATORY TESTING

Since experiments on single PDC without side rake were published earlier, only a brief description of the test apparatus will be presented in this paper³. A pressure chamber (Figure 9) was used to simulate well bore pressures up to 10,000 psi. The chamber contains four Lucite windows: two are used for illuminating the specimen, one for photographing the cutting process under pressure, and one for the measuring equipment. The cutter is mounted on a three-dimensional dynamometer which is capable of measuring vertical, horizontal, and side load simultaneously. The chamber also incorporated a DC drive mechanism with a variable reduction ratio gear box to rotate the cylindrical shale specimen in the range of 1 to 150 rpm. The rock specimen used is Mancos shale whose properties are available in Reference 3.

The data set consists of observations from cutting tests with the PDC cutter set with various back rake angles and side rake angles. The engagement area of the cutter for each depth of cut, which is a function of back and side rake angles, was held to be constant at 0.001 in². The new data from the shale tests with the cutter set at various side rake angles was combined with data from earlier single point tests without side rake to study the effect on observed cutter loads of the major measured variables, i.e., back rake angle (α), side rake angle (β), pressure (P), rotational speed (N), and size of ledge (L). The definition of rake angles and ledge are shown on Figure 8. The ledge is a relative measure of the chip clearance using datum at the center plane of the PDC. For the entire data set (151 observations), the following relationships were found for vertical load, horizontal load, and side load:

$$F_v = .9\alpha + 1.4\beta + 31.9 \log_{10} (P+1) + 5.0N^{1/2} - 28.4L \quad (1)$$

$$F_H = 6.0 \log_{10} (\alpha + 1.0) + 17.5 \log_{10} (P + 1 + 0.1N) + 19.3 \quad (2)$$

$$F_s = 0.44\alpha + 0.42\beta - 6.4L + 7.6 \quad (3)$$

Our major interest was still the effect of side rake and chip clearance on other factors, especially the vertical load. Figure 10 shows vertical load as a function of side rake angle for three values of pressure (0, 5,000, 10,000 psi) and a fixed value of 100 rpm, 5° back rake angle, and a 1.0 ledge. The vertical load required for a constant engagement area of cut increases with increasing side rake angle. Rigid-plastic behavior was noted in the shale under bore hole pressures; the forces required for a constant depth of cut rose very rapidly from 0 to 5,000 psi borehole pressure. At higher borehole pressures the load increased slowly with pressure. The vertical loads also depend on the rotational velocity as revealed by Figure 11. It indicated that higher vertical loads are required for higher rotational speeds.

Figure 12 shows side loads as a function of side rake angle. The variable is the ledge condition or the amount of chip clearance. This figures shows that side load decreases as the chip clearance becomes larger. The vertical load also decreases as the chip clearance increases as revealed in equation (1). These facts clearly confirm the previous speculation that bigger chip clearance reduces the interference of chip generation which corresponds to decreasing the reaction force of the chip on the bit body. Thus both vertical load and side load decrease with less chip interference. The independence of horizontal load on chip clearance revealed in equation (2) is not surprising since the generated chip only moves upwardly or sidewardly (with side rake) on the bit body and not horizontally as shown in Figure 4.

The question is then how useful is side rake. The equations and figures show that vertical load increases with increasing side rake angle. A close look at the figures indicate that the amount of increase is not that great. At 100 rpm, 5,000 psi bore hole pressure, 5° back rake and a 1.0 ledge an increase of side rake from 0° to 30° only increases the vertical load from 150 lbs to 190 lbs which amounts to an increase of 26 %. This increase of vertical load will not adversely affect the field operation of PDC bits as they require much less bit weight than do surface-set diamond bits, usually about one half the weight. For instance, a 6 1/2 inch PDC bit requires only 8-12,000 lbs. of bit weight on bit compared to 18-24,000 lbs. needed for a diamond bit. An increase of 26% on 10,000 lb. bit weight only raises the bit weight to 12,600 lbs which will pose no problem to the driller. The increase in side load with increasing side rake on a single cutter also has no adverse effect on the bit. Since the side load is in a radial direction, the side load induced by a certain cutter will be cancelled by the equal and opposite side load of another cutter set at 180°. Overall, the side loads of every PDC cutter with side rake are likely to be balanced by other cutters and the resultant side load on the total bit will be nil if the bit is carefully designed.

The real benefit of side rake on PDC cutters is the mechanical cleaning action. Visual observation of the cutting action inside the pressure chamber showed that a PDC cutter with side rake can direct the chip flow to the outside. With side rake the chip was pushed forward both tangentially and radially compared to the sole tangential direction of PDC cutter without side rake (Figure 13). The cutter also showed less incidence of the chip sticking to it as shown previously on Figure 3. The greater the degree of side rake the less chance of the chip sticking to the cutter.

Earlier this year, Salzer et al, published a paper⁴ based on similar work at the University of Tulsa. Their results show the same trends of the PDC with side rake; the vertical load and side load increase with increasing side rake. The horizontal load ("drag force" in their paper) also is independent of side rake. One difference is that the chance of the chip sticking to the cutter is minimal at 15° side rake, while our tests indicate decreasing chance of sticking with increasing side rake. This discrepancy may be due to the different speed of cut and engagement area used in the tests.

FIELD APPLICATION

Based on preliminary findings in the early period of the side rake laboratory test, field tests of the new style PDC bits with side rake were begun in the middle of 1979. A new drill bit (Style A, Figure 14) was modified from a then dominant drill bit (Style B) that has no side rake. These two styles have the same bit profile, cutter style, cutter exposure, chip clearance and back rake with only the side rake being the main variable. So far, 150 drill bits of both style have been built and tested, with one third being Style B (without side rake) and two thirds being Style A (with side rake). The majority of these bits were run in soft or plastic formations. The overall field observation confirmed that bits with side rake have less tendency to ball up and the drilling performances are better than those bits without side rake (Table 1).

Table 2 presents some typical performances of these two style bits. The two bits were run in the same well and same formation, and the Style A bit was run immediately after the Style B bit. Style A bit not only drilled faster, but also drilled longer than style B bit, with an increased penetration rate of 38%. There was an interesting phenomenon in this field test. Because the Style B bit was partially balled during the run, this bit actually required more bit weight, higher rotary speed, and a greater flow rate to achieve a decent rate of penetration. This observation supports the earlier argument about side rake - the benefit of mechanical cleaning action can overcome the disadvantage of the slightly increased vertical load required.

Core bits (Style C) with side rake were run against core bits (Style D) without side rake. Figures 15 and 16 show these two styles of core

bits. They have the exact same bit profile, cutter style, cutter exposure, number of cutters, and chip clearance. However, the core bit with side rake outperformed the core bit without side rake. Table 3 exhibits the typical performance of both styles of core bits, which were run in the same area, formation, and approximately at the same depth and operating conditions. The Style C core bit cored 2 1/2 times the footage of the style D core bit and at a faster penetration rate. This indicated that by preventing the formation cuttings from inhibiting the diamond cutter, better cooling of the cutting edge is achieved and thus longer bit footage is insured.

CONCLUSIONS

When the combination of bit hydraulics and chip clearance cannot prevent bit balling problems in soft or plastic formations, side rake can be a dependable alternative. The mechanical cleaning action of the PDC with side rake can reduce the tendency of formation chips sticking to the cutting surface. Laboratory and field testing has proven the positive effect of side rake in soft or plastic formation. An ideal drill or core bit should take into consideration the advantage of side rake and combine it with good bit hydraulics and chip clearance to obtain an optimum design.

ACKNOWLEDGMENTS

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NOMENCLATURE

$F_H =$	cutter horizontal load (lbs)
$F_S =$	cutter side load (lbs)
$F_V =$	cutter vertical load (lbs)
$L =$	ledge, relative measure of chip clearance
$N =$	rotational speed (rpm)
$P =$	simulated well bore pressure (psi)
$\alpha =$	back rake angle (deg.)
$\beta =$	side rake angle (deg.)

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Table 1
Average Performance of Style A and Style B Bits in Shale Formation

Drill Bit Style	Side Rake	Average Footage Per Bit (ft)	Average Life Per Bit (hr)	Average ROP (ft/hr)
A	Yes	941	53.8	17.5
B	No	596	71.3	8.36

Table 2
Typical Performance of a Style A Drill Bit and a Style B Drill Bit
Formation: Shale, Sand
Size: 6-1/2"
Mud: 15 ppg Oil Base

Drill Bit Style	Side Rake	Bit Weight (lbs)	Rotary Speed (rpm)	Flow Rate (gpm)	Depth Out (ft)	Footage (ft)	Life (hrs)	ROP (ft/hr)
A	Yes	8/12,000	90	180	11,854	864	99.0	8.7
B	No	12/14,000	110	200	10,990	623	97.5	6.3

Table 3
Typical Performance of a Style C Core Bit and a Style D Core Bit
Formation: Soft Sand, Clay
Size: 9-7/8" x 5-1/4" with 8 x 5-1/4 Core Barrel
Mud: 9 ppg Water Base

Core Bit Style	Side Rake	Bit Weight (lbs)	Rotary Speed (rpm)	Flow Rate (gpm)	Total Core (ft)	Core Recovery	Average ROP (ft/hr)
C	Yes	8/14,000	50	108	763	100	20
D	No	8/14,000	50	108	292	100	15

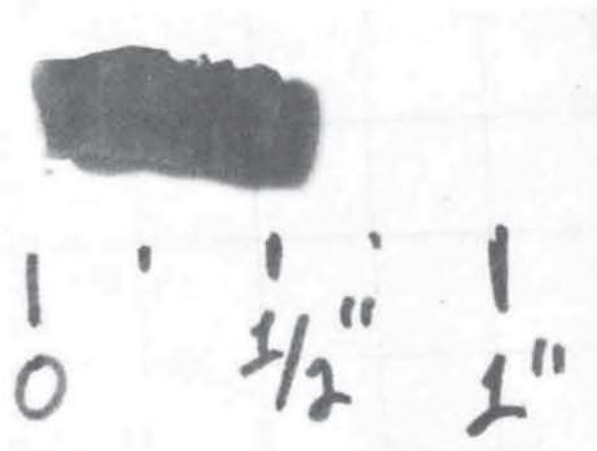


Fig. 1 – Smooth convex side of a shale cutting.

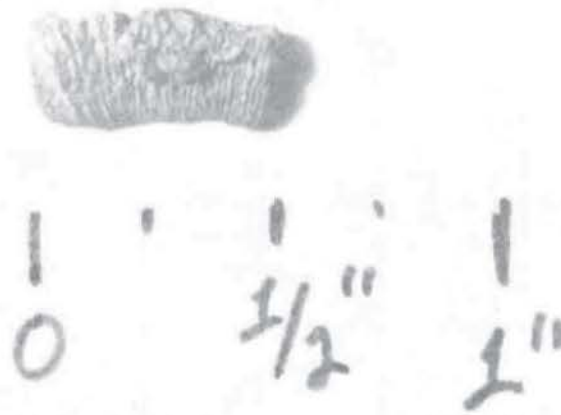


Fig. 2 – Rough concave side of a shale cutting.

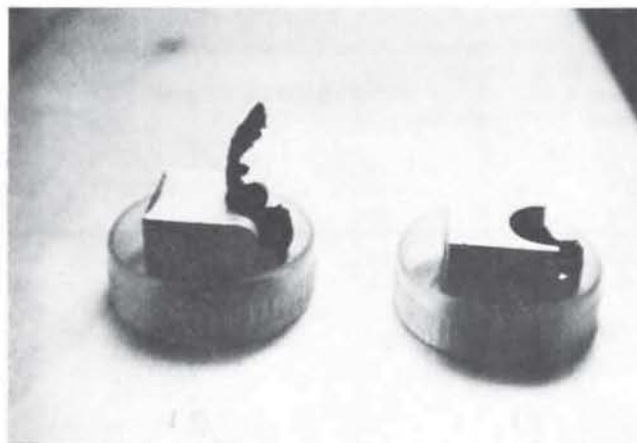


Fig. 3 – Chip generated by a single cutter in pressure chamber.

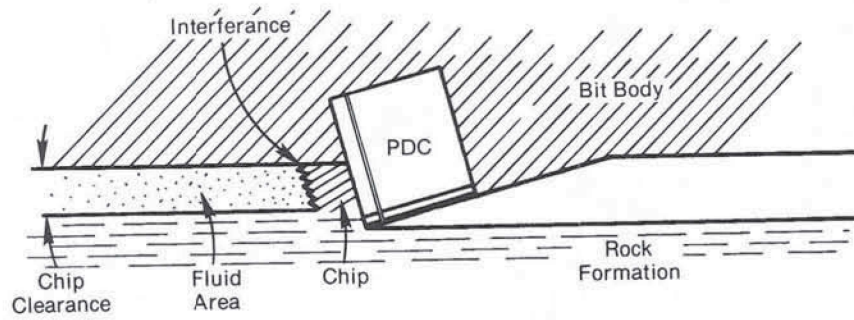


Figure 4 Interference of Chip Generation Due to Small Clearance

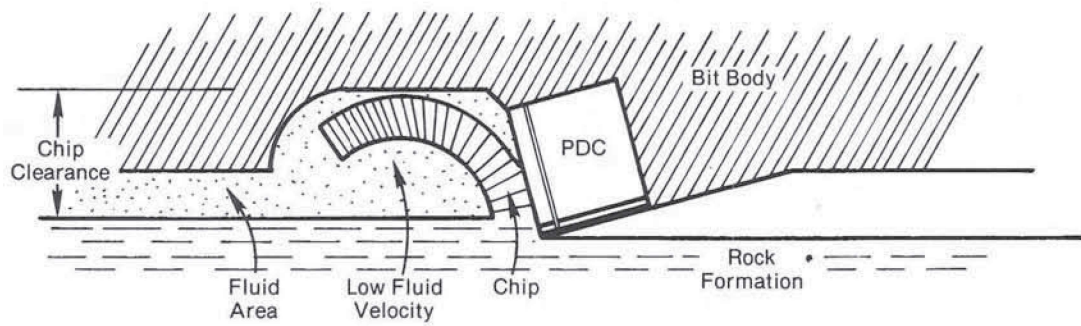


Figure 5 Low Fluid Velocity Due to Big Clearance

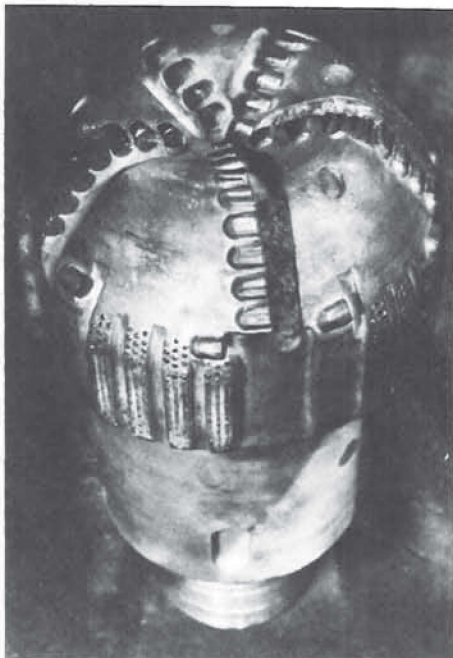


Fig. 6 – A balled bit run in a plastic shale formation.

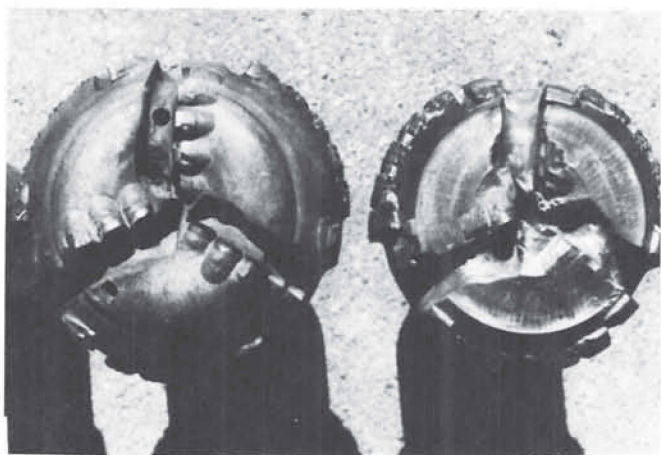


Fig. 7 – Premature wear of bits due to large fluid area.

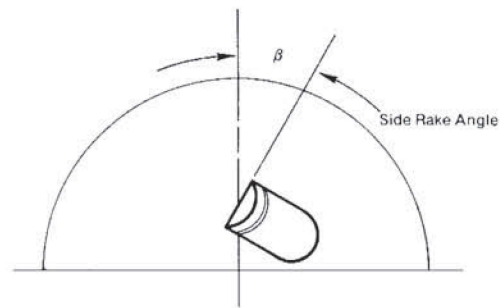
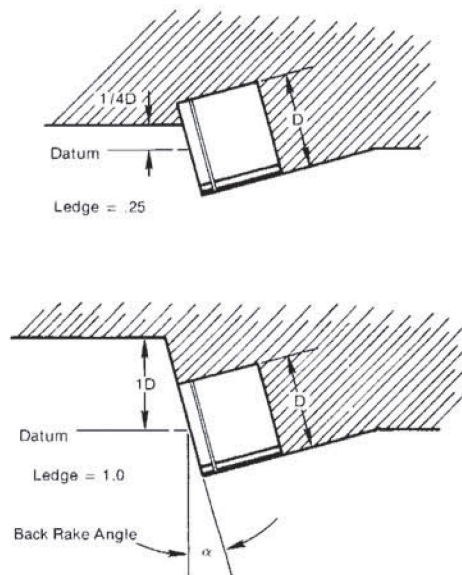


Figure 8 Rake angle and Ledge

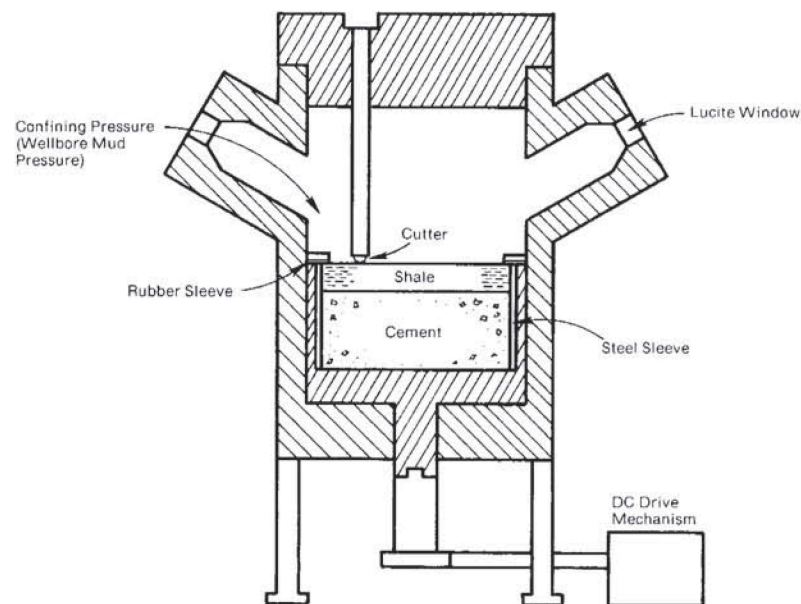


Figure 9 Pressure Vessel for Laboratory Tests

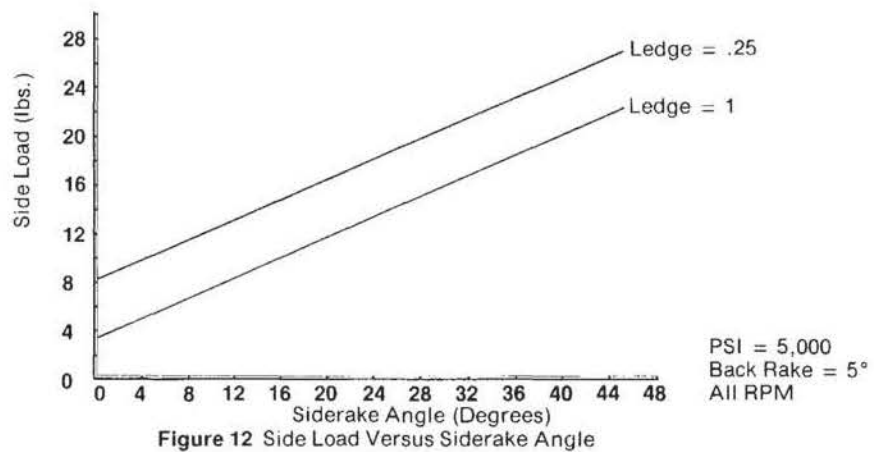
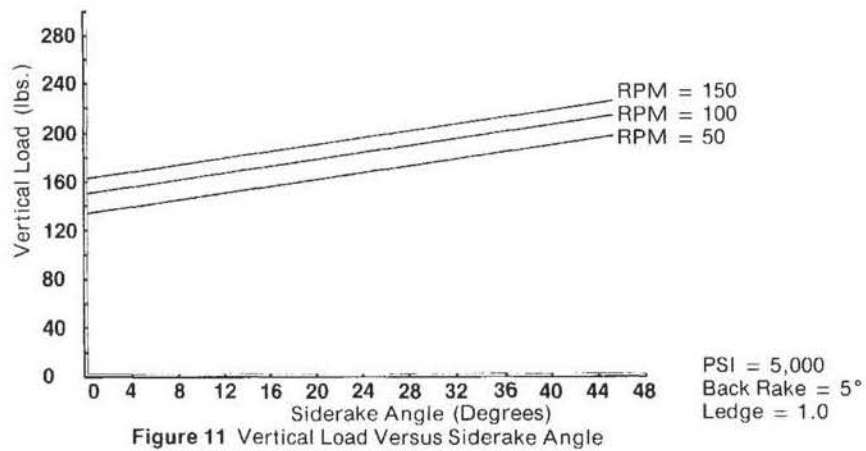
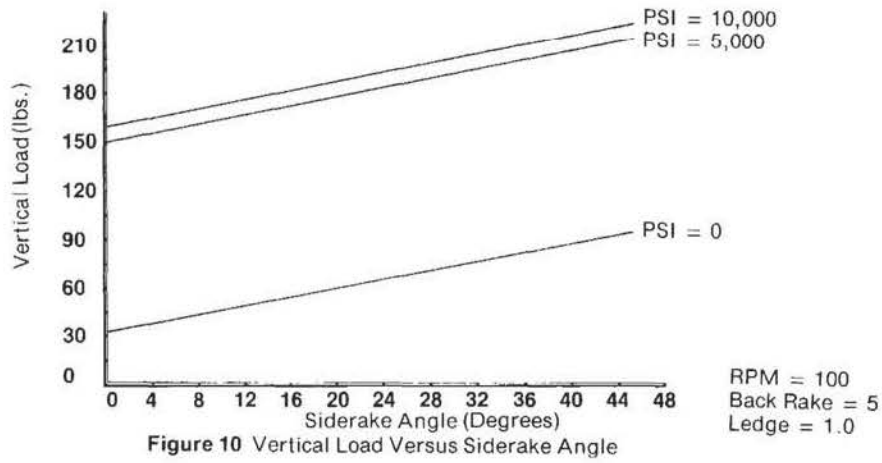




Fig. 13 – Chip generated by a PDC cutter with side rake.



Fig. 14 – Style A drill bit (with side rake).

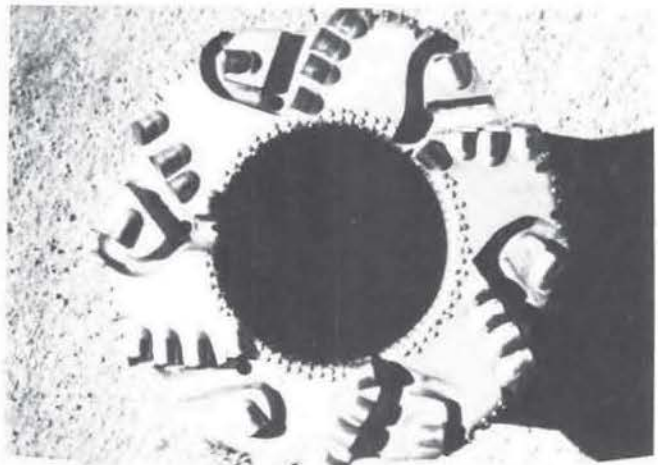


Fig. 15 – Style C core bit (with side rake).



Fig. 16 – Style D core bit (no side rake).