Drag-Bit Performance Modeling

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Summary. Models for the forces required to remove a fixed volume of rock with a single cutter have been applied to different polycrystalline-diamond-compact (PDC) bit designs. The integration of the forces for each cutter over the bit face gives the torque and weight on bit (WOB) required for a particular rate of penetration (ROP). This paper presents the results of comparing such a model to laboratory drilling tests for four radically different bit designs in four different rocks. The geometry of each cutter on the bit was determined by detailed measurements of the bit with a three-axis coordinate measuring machine. Drilling tests were conducted by "reaming" rock with an 8½-in. [21.6-cm] bit that was previously drilled with a 6¼-in. [15.9-cm] bit. Only the peripheral cutters engaged the rock during reaming. Additional tests were conducted in which the WOB and torque were recorded during drilling of a pilot hole into the top of a flat rock and during drilling through two different bed boundaries with constant ROP. The model predictions compared well to the measured data for both the reaming and pilot-hole tests.

Introduction

Analysis of the drilling mechanics of large-cutter (> ¼ in. [>0.64 cm] in diameter) PDC bits is much easier than that of roller-cone bits because of their simpler geometry. At the same time, variations in PDC bit designs result in a wider range of performance than observed with roller-cone bits. PDC bit performance is extremely sensitive to formation properties and operating conditions. There is a fine balance between bit durability and designs that ball up in shales. This paper concentrates on the mechanical design parameters for PDC bits. Bit-cleaning considerations are discussed in a companion paper.[1]

The PDC bit model described in this paper was developed to aid bit selection and evaluation. The model also serves as a baseline to identify and to quantify additional factors that affect bit performance by comparing model predictions with actual data, either from the laboratory or from field drilling.

PDC Bit Model

The simple kinematics of a large-cutter drag bit allows the position of each cutter in space to be easily tracked for a given rotational speed and ROP. The volume of rock removed by each cutter can be calculated for a given steady-state ROP because each cutter on the bit remains at a constant position relative to a coordinate system that moves with the bit body.

The PDC bit model is a combination of rigorous geometrical relationships used to describe the kinematics of a particular bit geometry and single-cutter force and wear models. The single-cutter models predict such items as cutter forces, temperatures, and wear. These predictions are for a single cutter and are independent of the cutter's position on the bit. Detailed cutter placement information is used to integrate these single-cutter models for a specific bit. The assumptions used in the overall model development, in the individual force and wear models, in the method used to generate the cutter location coordinates, and in other model information can be found in Ref. 2.

Input to the model comprises detailed cutter geometries, formation properties, ROP, and rotational speed. The model calculates the volume of rock removed by each cutter, total WOB, bit torque, bit imbalance force, and total wear-flat area.

Example Model Results

A generic bit design is used to demonstrate the results obtained with the model. The 8½-in. [21.6-cm] bit is composed of seven 1½-in. [3.8-cm] cutters arranged on three blades located 120° apart. Fig. 1 shows the bit profile and the angular location of the cutters on the bit.

Table 1 shows the predicted results for drilling with this bit in Berea sandstone at 50 ft/hr [15 m/h] with a rotary speed of 120 rev/min and the cross-sectional area of each cutter engaged in the rock, volumes of rock removed, resultant force angles, effective side- and backrakes, and cutter velocities. These quantities result directly from geometrical considerations and are not influenced by the empirical force models. The circumferential, axial, and normal forces are calculated for each cutter on the basis of the empirical force models.

Summary data are printed below the individual cutter data. The WOB is the sum of the axial cutter forces, and the bit torque is the sum of the circumferential forces times the cutter-moment arm. The magnitude and the direction (relative to the position of Cutter 1) of the imbalance force are also calculated and will be discussed later.

Laboratory Drilling Tests

Laboratory drilling tests were conducted with four 8½-in. [21.6-cm] -diameter bits (Fig. 2) to provide model validation data and to develop the force functions used in the model. Tests were conducted in Catoosa shale, Indiana limestone, Berea sandstone, and Carthage marble. The conditions of these tests are discussed in more detail by Warren and Armagost.[1]

Figs. 3 and 4 show the laboratory data and model predictions for three different rocks drilled with Bits B and C. Rock strengths of 2.6, 1.2, and 0.7 were used for the Carthage marble, Berea sandstone, and Catoosa shale, respectively, for the model results presented in these and following figures. Unless otherwise noted, a bit factor (BF) of 1.0 was used. The model for the large-cutter-bladed bit, Bit C, fit the data for all three rocks well. Examination of the bit after each test showed no balling on the cutters for any of the rocks when a flow rate of 450 gal/min [1.7 m^3/min] was used.

Good predictions for the flat-faced bit were obtained in the sandstone and marble, but not in the shale. The bit was balled up after the test in shale (see Ref. 1). The balling caused the observed ROP to be considerably less than the model predicted. These data for Bits B and C indicate that the basic model performance is good as long as the cutters are cleaned.

Fig. 5 shows test data and the model predictions (BF=0.73) for drilling in shale at a range of rotary speeds from 60 to 180 rev/min with Bit D. The model fits these data very well, but in cases where poor cutter cleaning was suspected, it did not work as well for rotary speed response.

The bottomhole pattern was examined for most of the laboratory bit runs. The observed pattern was compared with the model predictions to help identify the amount of fracturing that occurs between the cuts made by individual cutters. Fig. 6 is a comparison between a bottomhole pattern predicted by the model and the pattern measured with a coordinate measuring machine. In general, the patterns show little evidence of fracturing but often show evidence of off-center rotation.

To provide a more rigorous test of the model, the 8½-in. [21.6-cm] bit, Bit A, was used to ream a previously drilled 6¼-in. [15.9-cm] hole. In this way, the forces on the inner cutters were eliminated, while the outer cutters were loaded under the same conditions as if they were drilling. The ROP, torque, and model predictions (BF=1.22) for both drilling and reaming are shown in Fig. 7. The bit removed only 41% as much rock volume while reaming as while drilling. The model predictions of both torque and WOB were slightly low for the reaming case. This probably results from a higher relative imbalance force during reaming than during drilling.

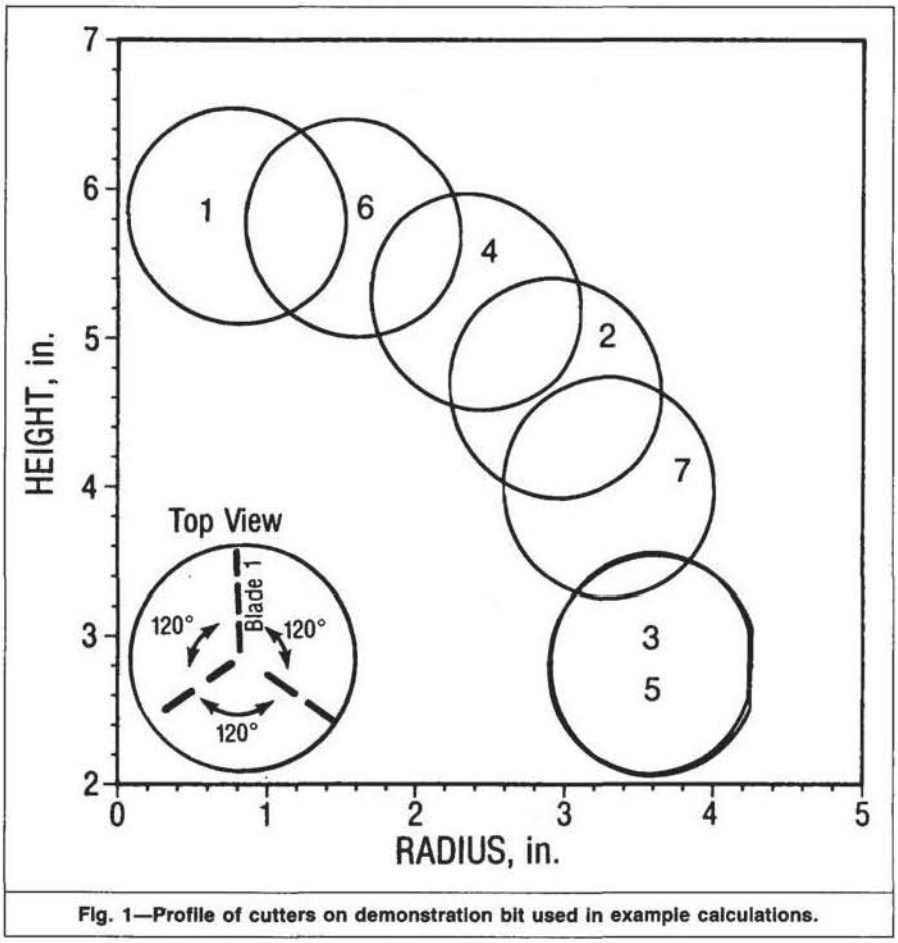

Fig. 1—Profile of cutters on demonstration bit used in example calculations.

The reaming tests were also conducted in Berea sandstone and with a different bit than in Carthage marble with similar results.

During several tests, the WOB and torque were recorded while a pilot hole was drilled into the top of a flat rock at a constant ROP. Fig. 8 shows two sets of data for drilling with Bit D into the top of a Berea core and into a shale core. These data tested the model as an increasing number of cutters engaged the rock. The predicted torque and weight agree reasonably well with the observed values.

Cutter-Removal Tests. Cutters were removed from a sharp bit similar to Bit B to examine the effect of cutter interaction on bit performance. As cutters are removed from a bit, adjacent cutters must remove more rock to maintain the ROP. The objective of the cutter removal tests was to increase the rock removed by the remaining bit cutters systematically and to observe the change in bit loading required to drill at various rates. The cutters were removed in groups of four. Fig. 9 shows the cutter profile at the beginning, end, and two intermediate stages of the test. At the end of the test, only the minimum number of cutters required to cut the hole bottom remained. Fig. 10 shows schematically the objective of these tests. Ref. 1 contains a description of the tests.

The cutter-removal tests show that there is a negligible effect of cutter interaction on the cutter forces required to drill Carthage limestone (Fig. 11). At the higher WOB, there was a very slight increase in ROP for a given WOB. Similar results were obtained for the bit torque in Carthage limestone and for both ROP and torque in Indiana limestone.

TABLE 1—EXAMPLE OUTPUT FROM PDC MODEL

Cutter	Cut Area	Cut Volume	Force Angle (degrees)	Circular Force (lbf)	Vertical Force (lbf)	Normal Force (lbf)	Velocity (m/s)	Effective Siderake	Effective Backrake
1	0.0947	0.3804	−13.8	1,359	1,398	1,440	0.21	−14.2	−9.1
2	0.0470	0.9957	41.6	946	648	867	1.08	−10.0	−16.3
3	0.0174	0.4543	55.1	448	268	469	1.32	−12.7	−14.1
4	0.0699	0.1728	27.8	1,558	1,135	1,284	0.85	−12.3	−19.2
5	0.0039	0.1006	48.2	85	67	101	1.31	−17.9	−16.6
6	0.0868	0.9426	16.3	1,436	1,280	1,333	0.55	−11.9	−14.5
7	0.0293	0.7046	51.1	601	356	567	1.23	−10.0	−16.5

Rotary speed, rev/min	120
ROP, ft/hr	50
Rotating time, hours	0
Imbalance force, lbf	2,180
Imbalance force angle, degrees	189
WOB, lbf	5,153
Bit torque, ft-lbf	1,271

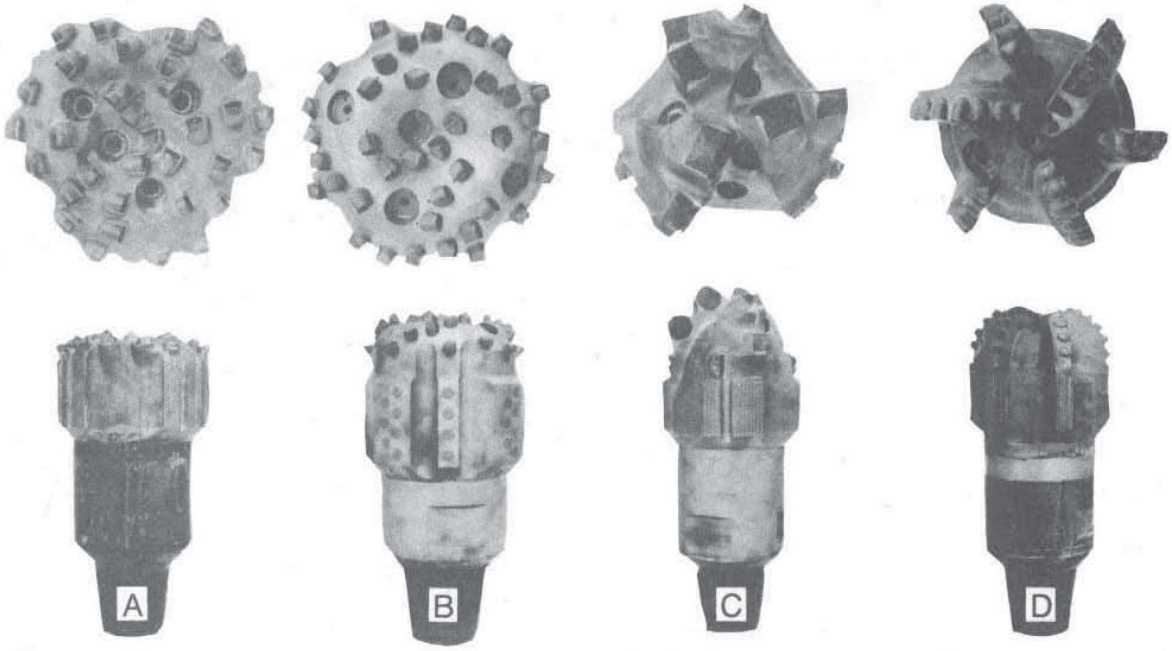

Fig. 2—Photographs of 8.5-in. bits used in test program.

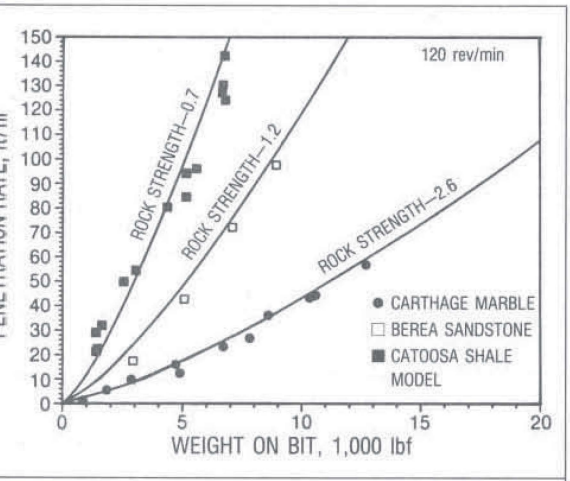

Fig. 3—Comparison of model predictions and laboratory data for Bit C.

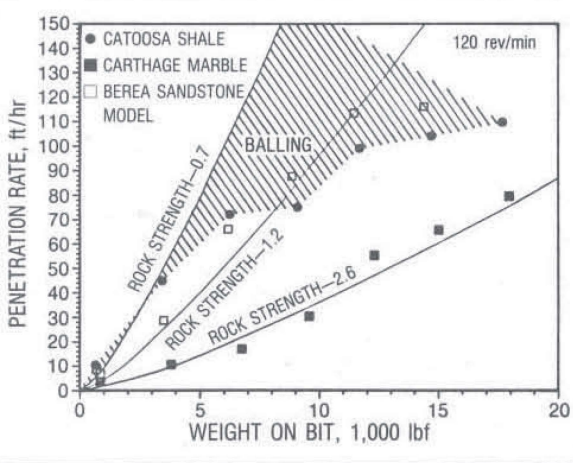

Fig. 4—Comparison of model predictions and laboratory data for Bit B.

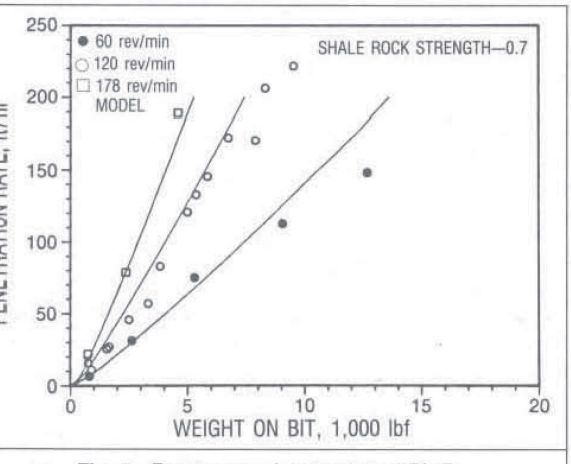

Fig. 5—Rotary speed response of Bit D.

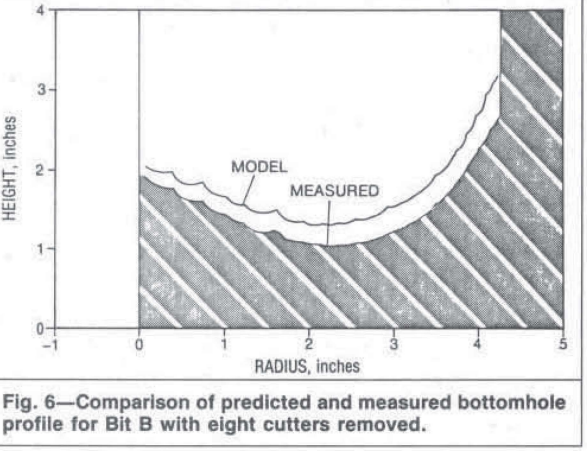

Fig. 6—Comparison of predicted and measured bottomhole profile for Bit B with eight cutters removed.

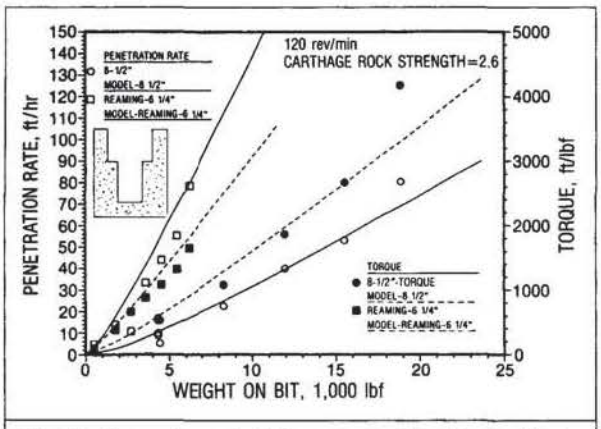

Fig. 7—Comparison of drilling vs. reaming data for Bit A.

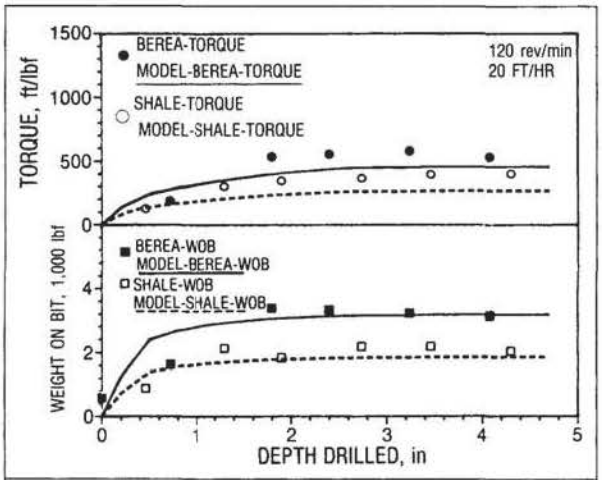

Fig. 8—Data measured and predicted during drilling of pilot hole in Berea and shale core with Bit D.

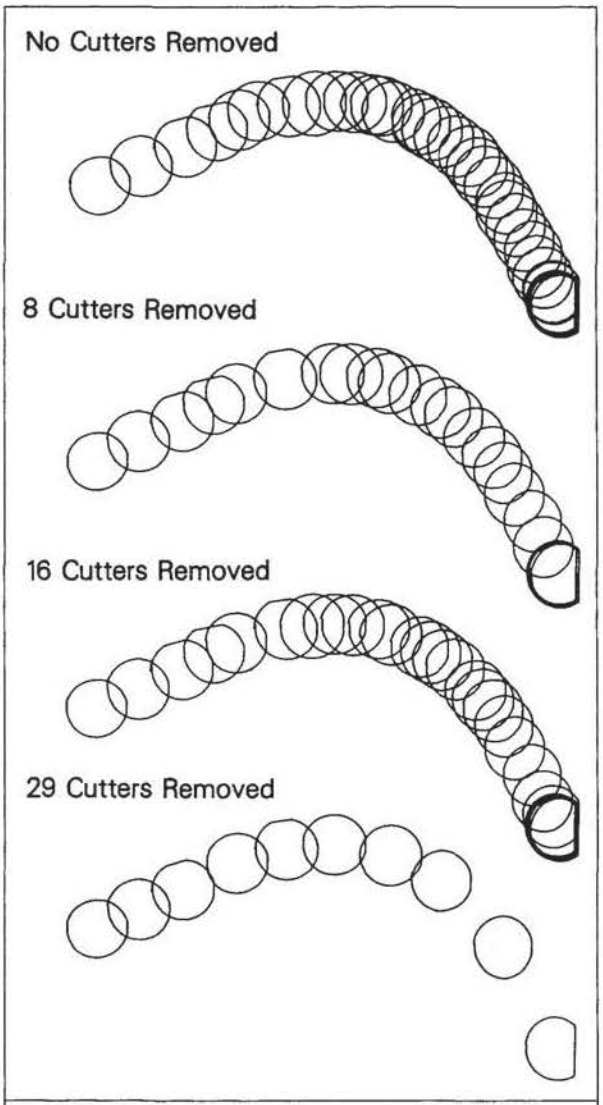

Fig. 9—Cutter profile at various stages of cutter-removal tests.

Fig. 12 shows the calculated vertical load on the same 10 cutters on the bit before any cutters were removed and after 29 cutters were removed. The cutter force is much greater for the peripheral cutters after 29 cutters were removed, even though the ROP is not immediately affected. The change in load is caused by a change in the volume of rock removed and by a change in the effective backrake. For example, the ninth cutter originally had a cutting area of 0.0122 in.^{2} [0.0787 cm^2] and an effective backrake of $-19°$. After 29 cutters were removed, this cutter had a cutting area of 0.0475 in.^{2} [0.3065 cm^2] and an effective backrake of $-6.7°$. The increase in cutting area tends to increase the cutter load, but the decrease in effective backrake tends to reduce the cutter load by 40%. The combination of high cutter load and high linear velocity of the peripheral cutters will severely accelerate cutter wear.

Tests With Worn Bits. Tests were conducted with a moderately worn bit similar to Bit B to compare the ROP for sharp and worn cutters in several rocks. The worn bit had a total wear-flat area of 2.48 in.^{2} [16 cm^2] after 1,020 ft [311 m] was drilled in 170 hours (6 ft/hr [1.8 m/h]). The diamond layer was worn even with the carbide wear-flats. This is typical of bits worn in hard rocks.

Fig. 13 shows a comparison between the model predictions and experimental data for both the sharp and worn bits during drilling of Berea sandstone and Carthage marble. The bit-wear effect is accounted for in the model by adding the normal force resulting from cutting to a load supported on the wear-flat. The entire wear-flat area is assumed to be in contact with the rock in this example.

Many field-dulled bits show the carbide backing to be worn below the diamond layer.[3] For these cases, the entire wear-flat area is not in contact with the formation and does not impede the drilling rate as severely as the example shown in Fig. 13.

Cutter-removal tests were conducted with the moderately worn bit used in the tests described above. These tests were conducted in the same manner as those that used the sharp bit. Fig. 14 shows that the ROP increased steadily as the cutters were removed. The model predicts an increase in ROP, but not the steep rate of increase that was observed during the experiment.

Cutter-Force Balance

It is generally recognized in the drag-bit industry that the forces acting on a drag bit should be balanced. It is not clear that this is totally accomplished in many commercial bit designs, nor is it clear that a uniform definition of "force balance" is used.

The cutter-force components in a plane normal to the bit axis can be resolved into a moment about the bit centerline and a radial force. The moment is simply the bit torque, and the radial force is the imbalance. This imbalance force is oriented in a fixed direction relative to the bit face. It tends to push the bit into the wall of the hole as the bit rotates. The results of force imbalance in some cases

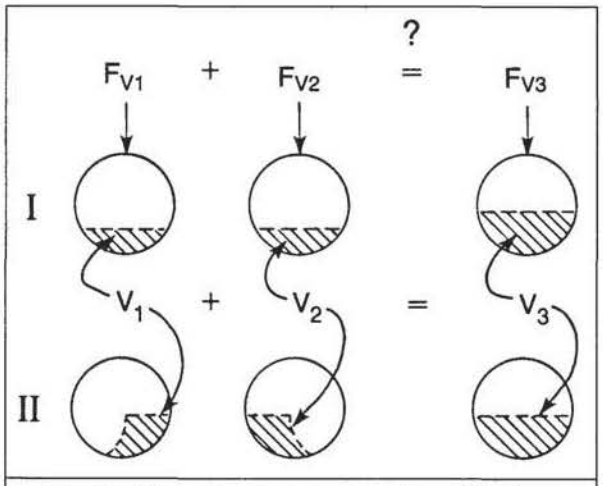

Fig. 10—Schematic of cutter-removal test objective.

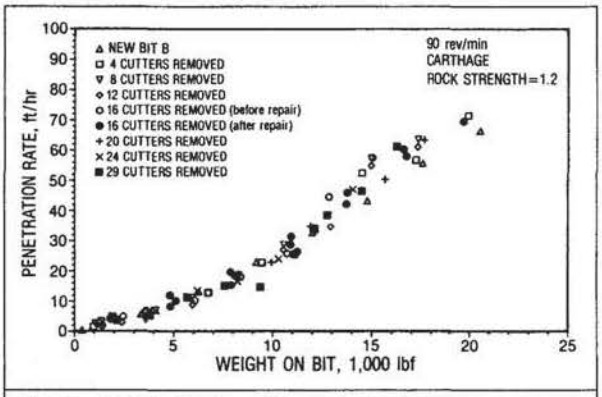

Fig. 11—ROP in Carthage limestone for cutter-removal test.

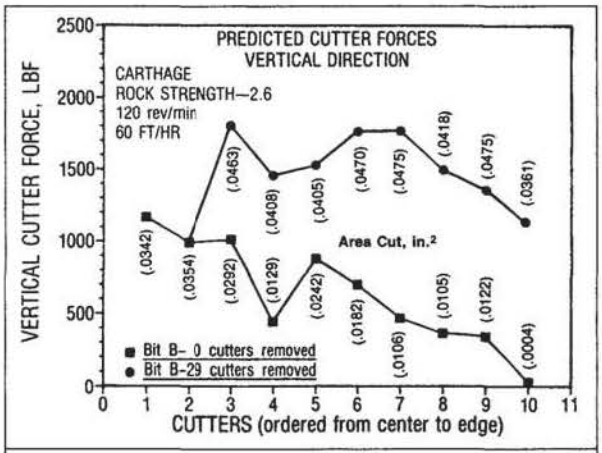

Fig. 12—Normal force on cutters before and after 29 cutters were removed.

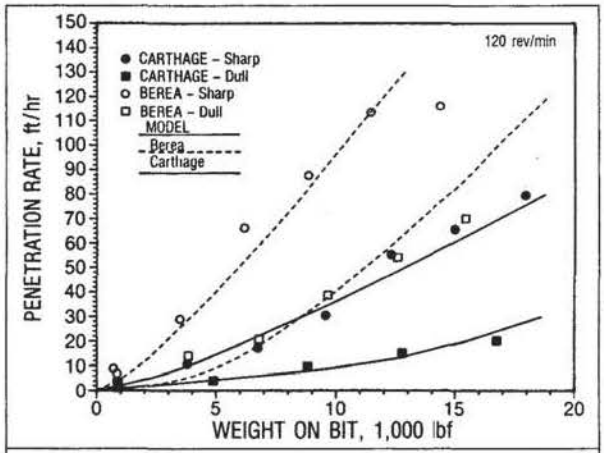

Fig. 13—Comparison of drilling rate with sharp and moderately worn bits.

can be seen in laboratory drilling by the existence of an overgauge hole.

If the forces are not balanced, the bit tends to rotate off-center, resulting in accelerated wear and reduced ROP. The large full-gauge stabilizer sections on bits tend to counteract the imbalanced cutting forces and cause the bit to rotate around its centerline.

Bit imbalancing forces have several sources. For bits with a tapered profile, the normal force on the cutters can be resolved into a vertical force (WOB component) and a radial component (Fig. 15). The vectorial sum of the radial components for all cutters generates one potential for a force imbalance. A second source of imbalance is a nonzero vectorial sum of the circumferential cutting forces acting on all the cutters.

The two imbalance sources discussed above can be computed with the PDC model because they rely on basic physics, geometry, and the cutting-force models. A third source of imbalance is cutter siderake. Prediction of single-cutter sideforces caused by siderake are limited because of scarce experimental measurements.[4,5] Unlike the penetrating and cutting forces, the effect of sideforce cannot be evaluated indirectly from drilling tests unless a method is available to measure the bit sideforce generated at the cutters. This force is resisted by the stabilizer contact force; thus, any measurements must be made at the stabilizer/rock interface and, therefore, are impractical. In this paper, the effect of siderake is neglected, but it is recognized as a potential source of error. It is doubtful that an imbalance force caused by this effect would coun-

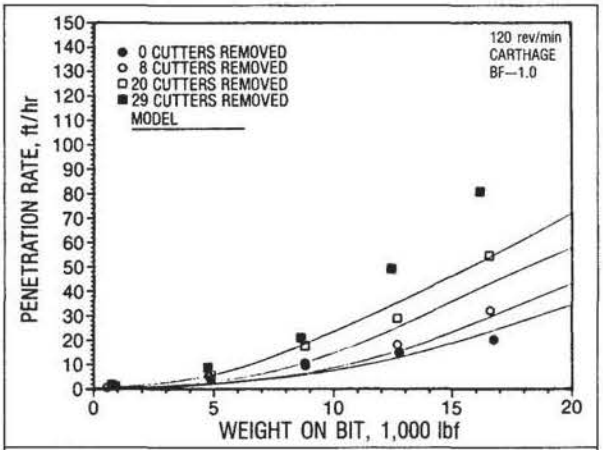

Fig. 14—Comparison of predicted and observed ROP for cutter-removal tests with worn bit.

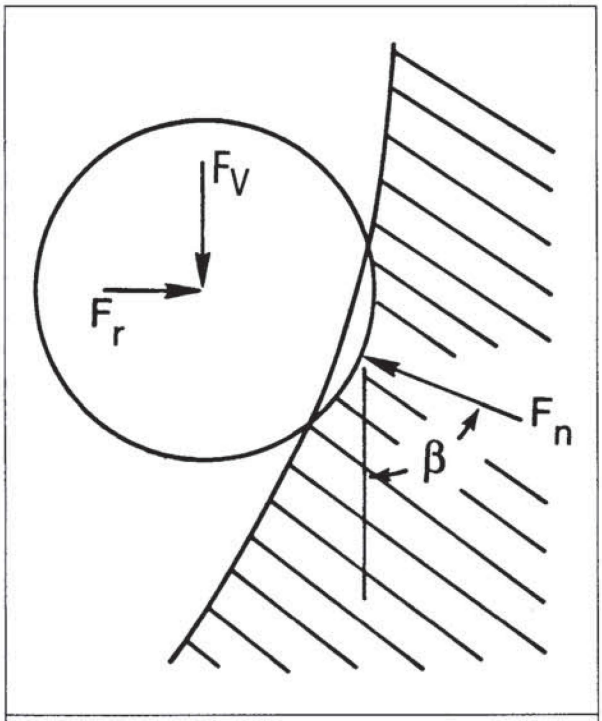

Fig. 15—Cutter on inclined surface.

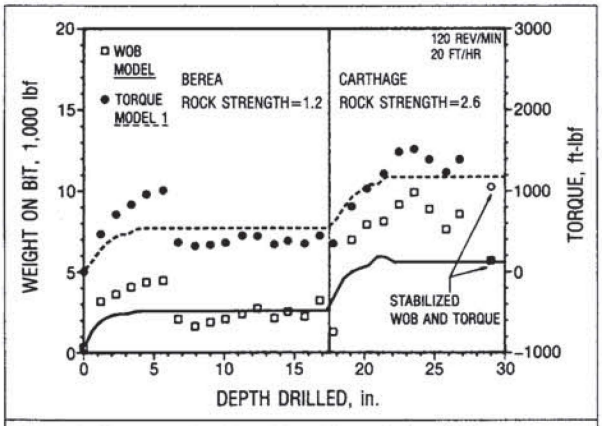

Fig. 16—Measured and predicted data during drilling through bed boundary with Bit C.

teract the imbalance caused by the other two sources; thus, the imbalance force calculations are conservative.

A bit may also be imbalanced because of its mass distribution, but this is insignificant at normal rotary drilling speeds. In cases where the bit is run on a turbine, the mass balance may be significant.

The generic bit used in the previous example to demonstrate the PDC model operation has an imbalance force of 2,180 lbf [9697 N] (at the specified operating conditions), which is 42% of the applied WOB. Without stabilization, the bit would rotate off-center and would drill a 9.3-in. [23.6-cm] -diameter hole. This assumes that the bit rotates so that the resultant side loading is reduced to zero.

The cutters on the bit can be relocated to reduce the imbalance force. Repositioning Blade 3 from its position at 240° from Blade 1 to 210° reduces the imbalance force to 30 lbf [133 N].

Bit C was used to drill a core that was prepared to test bit response at bed boundaries. The top half of the core was Berea sandstone; the bottom half was the stronger Carthage marble. Fig. 16 shows that the initial WOB and torque are higher than expected for this

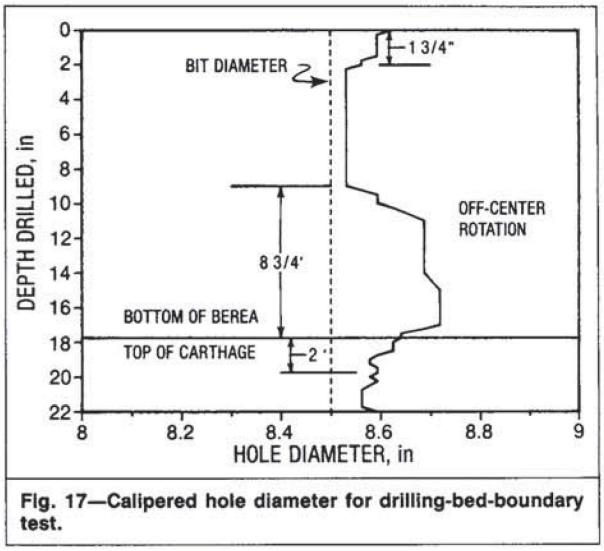

Fig. 17—Calipered hole diameter for drilling-bed-boundary test.

bit. This occurs because the small number of cutters on the bit provide poor bit stabilization as the bit drills into the top of the core. The calculated imbalance force is only 218 lbf [970 N] for the conditions used, but this is sufficient to cause the hole to be drilled slightly overgauge before the stabilizer pads engage the rock. Fig. 17 shows the calipered hole diameter for this test, and Fig. 18 shows the bit dimensions. Notice that the length of overgauge hole coincides with the distance from the first gauge cutter to the diamond stabilizer section on the bit. After the stabilizer pads engage the rock, the differences between the predicted and observed WOB and torque are much smaller.

The hole was nearly gauge during drilling of the Berea core, until the nose cutter of the bit hit the harder Carthage rock. The bit was considerably unbalanced as it drilled through the Berea/Carthage boundary. The calculated imbalance force increased from 200 lbf [890 N] while Berea rock was drilled to a maximum of 730 lbf [3247 N] when the nose cutter was ½ in. [1.3 cm] into the Carthage rock. The imbalance force gradually decreased to a value of 437 lbf [1944 N] while only Carthage rock was drilled. This imbalance was sufficient to cause the stabilizer pads on the bit to cut the Berea hole 0.2 in. [0.5 cm] overgauge. The hole diameter in the Carthage rock gradually decreased as the stabilizer pads entered the top of the Carthage.

The model predictions shown in Fig. 16 qualitatively track the increases in WOB and torque as the bit drills across the bed boundary, but the actual measured values are about 50% higher than the model predictions. The values are also higher than the stabilized values from the performance tests with the bit while other Berea and Carthage rocks were drilled (these values are included in Fig. 16). It is apparent that the test was stopped (because maximum allowable drilling depth was reached) before the WOB and torque returned to their stabilized values for drilling in Carthage rock at 20 ft/hr [6 m/h].

The predicted WOB and torque for Bit D during drilling of a pilot hole was more correct (Fig. 8) than the predictions for drilling with Bit C (Fig. 16). The WOB and torque for Bit D did not overshoot the stabilized values as they did for Bit C. Bit D provided a more balanced cutting action, with six blades and small cutters when only a fraction of the bit face was buried, than Bit C.

The tests indicate that the WOB and torque required to drill at a fixed ROP when the bit is unbalanced, as indicated by the overgauge hole, are much higher than those required when the bit is operating in a stabilized condition. This phenomenon has been observed several times in the laboratory. It implies that the model-predicted ROP is too high if the bit drills in an unstable mode.

The above discussion describes a mechanism that causes a balanced bit design to drill unstably as it drills across bed boundaries. Even when homogeneous rock is drilled, the bit imbalance force will change as the ROP changes. An unstable drilling condition can also be caused by poor bit design or by manufacturing imperfections.

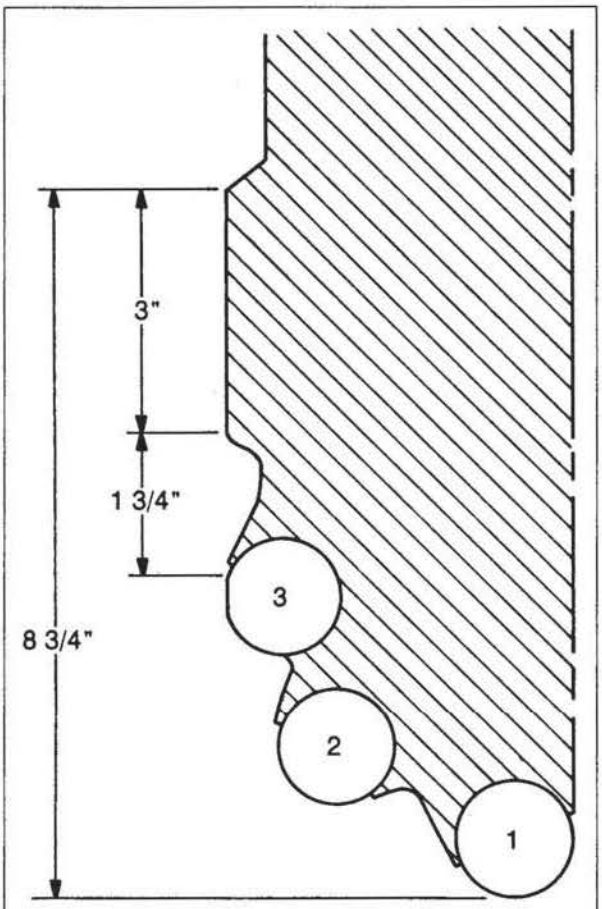

Fig. 18—Schematic of blade on Bit C used in bed-boundary drilling test.

From a bit-design standpoint, the cutters must be placed not only to minimize imbalance, but also to equalize wear on the cutters (see Ref. 6 for equal-wear criteria). Additionally, the cutters must be located so that the bit can (1) be manufactured with ease and reliability, (2) maintain structural integrity, and (3) be cleaned by the drilling fluid. Thus, any practical bit design is a compromise among the solutions for several different problems.

Manufacturing Defects

Fig. 19 shows the initial tests with Bit D when it was first run as a new bit. Even though the bit drilled a nearly gauge hole, the bottom hole pattern showed a distinct seven-lobe pattern rather than a smooth, circular pattern. The bit ROP increased by a factor of 2 to 3 after Carthage rock was drilled with the bit, as indicated by the later tests in Fig. 19. This change occurred after only a few feet were drilled under laboratory conditions. Several additional tests were run to confirm the ROP improvement and to identify the cause of the performance improvement. After these tests were completed, it was apparent that the backup material behind several of the cutters was rubbing on the formation. Wear-flats had begun to develop even though the diamond layer was not worn at all (Fig. 20).

The low initial ROP observed with the new bit was caused by the carbide cutter backing rubbing against the formation. This caused the bit to chatter until the protrusion was worn away.

Fig. 21 shows the measured profile of the bit in the area of the defective cutters. The bit apparently was manufactured with several cutters set at incorrect angles. This allowed the carbide behind the cutter to engage the rock. After the bit was run for a short time, the carbide wore away and the bit performance significantly improved.

The defect may have resulted in only a short-duration, superficial reduction in bit performance, or it may have had more serious

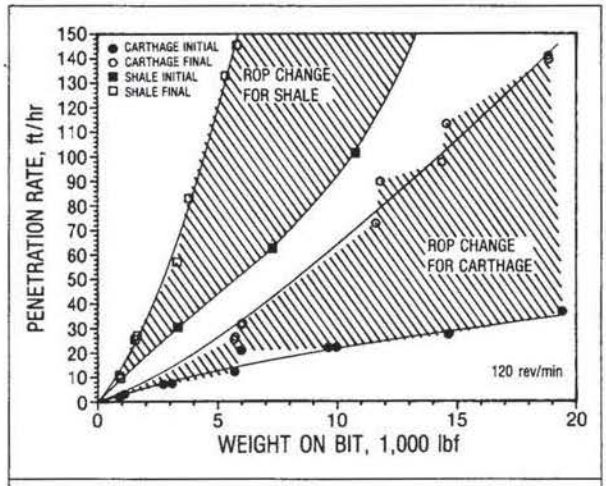

Fig. 19—Bit D ROP before and after initial wear.

Fig. 20—Localized wear on Bit D.

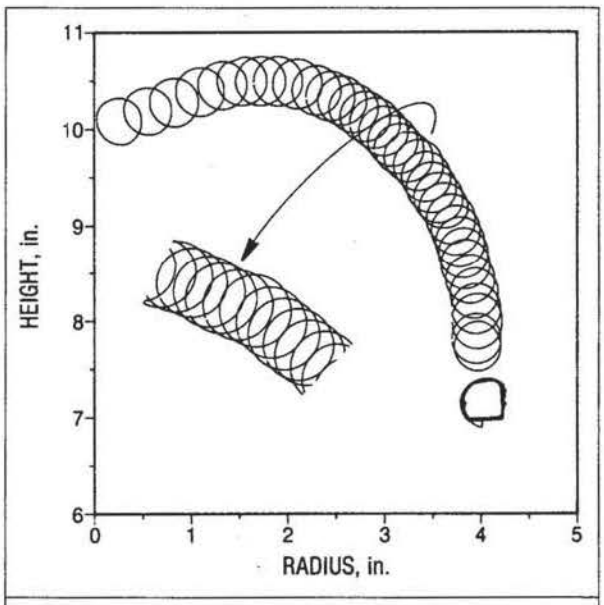

Fig. 21—Bit D measured cutter profile.

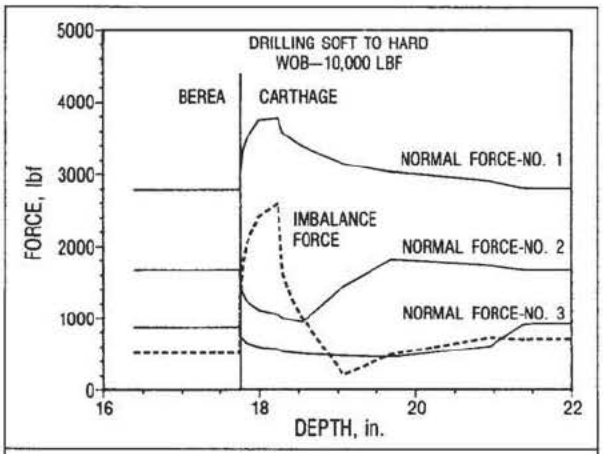

Fig. 22—Predicted cutter and imbalance forces during drilling across a bed boundary.

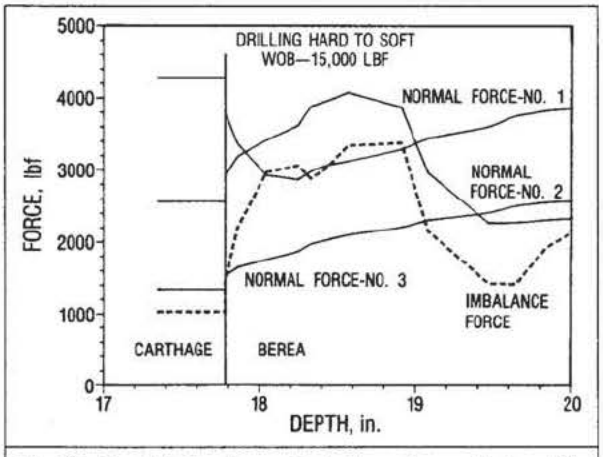

Fig. 23—Predicted cutter and imbalance forces during drilling across a bed boundary.

repercussions if the bit had been run in the field. Heat checking in the carbide material supporting the low cutters was obvious, even in the short time the bit was run in the laboratory. This could easily cause a transverse fracture in the backup carbide and result in the loss of the cutter. The loss of a single cutter in the location of the defect probably would cause the bit to ring out and to fail prematurely.

Simulations for Drilling Layered Rock

The PDC-bit model was used to simulate drilling through a bed boundary with an 8½-in. [21.6-cm] tapered-bit profile like that shown by Bit C in Fig. 2. Cases were run for drilling from a rock similar in strength to Berea sandstone into a rock similar to Carthage limestone. Fig. 22 shows the change in normal load on three cutters (the same as in Fig. 18) on the bit as it passes through the bed boundary. The distance shown on the plot is referenced to the position of the bit nose.

For the case of drilling from soft to hard rock, it is assumed that the bit is being run at 120 rev/min and drilling at 120 ft/hr [37 m/h]. The WOB is maintained at 10,000 lbf [45 kN] during drilling across the bed boundary. The predicted ROP rapidly decreases from 120 to 45 ft/hr [37 to 14 m/h]. The cutter forces shown in Fig. 22 are steady-state calculations and are probably very conservative. As shown in laboratory drilling tests, the actual WOB and torque may be 30 to 50% higher than the steady-state predictions. Additionally, there could be significant cutter impact loading. These loads can be sufficient to chip the cutters severely and, in some cases, break the whole cutter away from the bit body.

For the case of drilling from hard to soft rock, it is assumed that the initial WOB is increased to 15,000 lbf [67 kN] after the hard layer is encountered to increase the ROP. This significantly increases the loading on the cutters. Fig. 23 shows the calculated forces as the bit drills through the boundary from hard rock to softer material. The ROP increases from 75 to 185 ft/hr [23 to 56 m/h] as the bit passes the boundary.

Comparison of the two cases indicates that drilling from hard to soft rock may be more detrimental to the bit than drilling from soft to hard rock. The imbalance condition is higher and is maintained for a longer time period. The laboratory tests show that the total bit loading predicted by the model is very conservative. Individual cutter loading in excess of that shown in Fig. 23 is expected. These cases indicate that for the particular bit used in the calculations, the middle cutter on the blade is more likely to be damaged than either the nose or gauge cutter.

Laboratory drilling tests with a bit similar to the one used in these simulations show that the bit has excellent performance in soft rock and does not ball up in shale, but they also point out that the bit may be susceptible to damage when drilling nonhomogeneous rock. They also indicate that if an unexpected hard streak is encountered during drilling with a bit of this type, the best procedure is to refrain from increasing the WOB to protect the bit as it comes out the bottom of the hard streak.

Cutter Balling

The ROP performance of the flat-faced bits in Indiana limestone indicated that the bits were balled up, but there was little visual

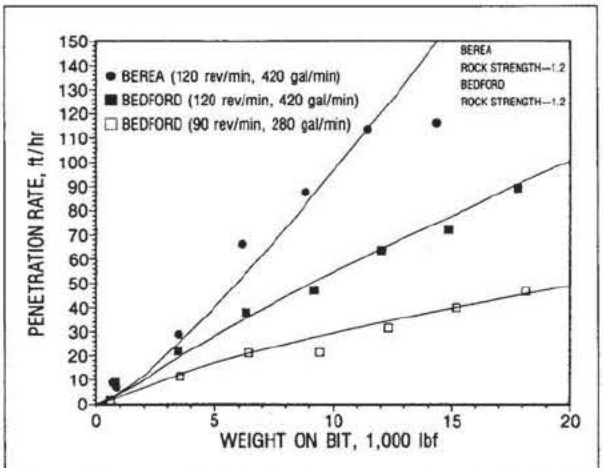

Fig. 24—Bit B ROP in Indiana limestone.

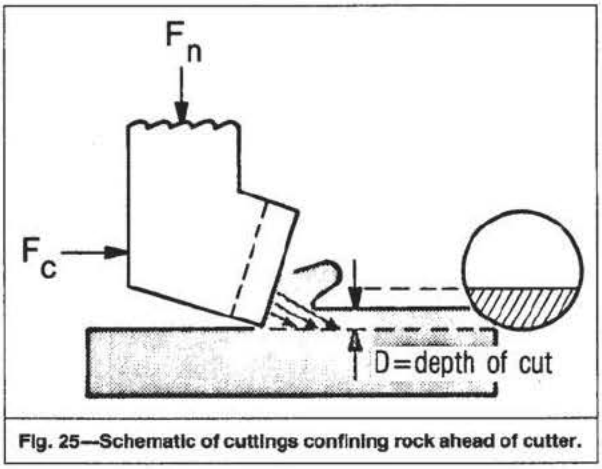

Fig. 25—Schematic of cuttings confining rock ahead of cutter.

evidence of bit balling at the end of the tests. Fig. 24 shows a typical ROP response curve obtained with Bit B. It appears that the limestone material packs in front of the cutters and decreases the ROP by the combined effect of supporting the cutter load and of confining the rock (Fig. 25). This is surmised from the reduced rate of increase in ROP as the WOB is increased.

The force model can be made to predict the correct ROP (Fig. 24) by assuming that the rock debris confines the rock in front of the cutter, increasing its effective strength. This increase in strength is assumed to be a function of the cut depth. The effective rock-strength function for each condition is included in Fig. 24. At low WOB, the rock strength is unaffected; at high WOB, however, the effective rock strength is a function of both cut depth and hydraulic energy. For example, the effective rock strength at 10,000-lbf [45-kN] WOB is 1.7 at 420 gal/min [1.6 m^3/min] and is 2.3 at 280 gal/min [1.1 m^3/min] rather than the original value of 1.2. Unfortunately, there is no mechanism in the model to decide when to apply this phenomenon. Consequently, this portion of the model can be used to match observed data but has little predictive capability until a mechanism is included to predict imperfect cutter cleaning.

Review

A model for PDC bits that is useful for evaluating the mechanical design of a particular bit was developed and confirmed by laboratory tests. The model is based on static cutter-force calculations. In many cases, the actual cutter loads are higher than those calculated by the model or, conversely, the ROP is lower than expected at a particular applied load.

Laboratory tests demonstrated the adverse effect of imbalanced bit loading on the ROP and bit torque. These tests pointed out the detrimental effect of seemingly minor manufacturing defects in cutter placement.

The rapidly changing cutter loading and the increased imbalance loads during drilling through dissimilar materials were demonstrated. The practice of increasing WOB to maintain ROP in a hard streak may be counterproductive if the bit is damaged when it exits the hard layer.

Nomenclature

D = cut depth, in. [cm]
F = cutter force, lbf [N]
F_c = circumferential cutter force, lbf [N]
F_n = normal cutter force, lbf [N]
F_r = radial cutter force, lbf [N]
F_V = vertical cutter force, lbf [N]
V = rock volume, $in.^3$ [cm^3]
β = inclination of normal cutter force, degrees

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SI Metric Conversion Factors

ft	× 3.048*	E−01	= m
ft-lbf	× 1.355 818	E−03	= kJ
in.	× 2.54*	E+00	= cm
$in.^2$	× 6.451 6*	E+00	= cm^2
lbf	× 4.448 222	E+00	= N
lbm	× 4.535 924	E−01	= kg

*Conversion factor is exact.

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