

# Evolution of Polycrystalline Diamond Compact Bit Designs for Rocky Mountain Drilling



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## Summary

The Rocky Mountain region of the U.S. has proved to be a good area for polycrystalline diamond compact (PDC) bits in selected formations. Lower costs per foot as a result of higher penetration rates and longer bit lives have been realized in many applications. PDC bits are used routinely in Wyoming in the Green River and Powder River basins.

Simply using a PDC bit in these areas does not necessarily ensure an economical run. Care must be taken in choosing the correct bit design for each application to obtain the lowest cost per foot. Since the first PDC bit run, there has been an evolution of designs to enhance penetration rates, and thus to lower drilling cost per foot. This evolution has included changes in bit profile, cutter density, cutter exposure, cutter side rake, and cutter shape. When optimally combined, these features have increased penetration rates by well over 100% in many formations.

## Introduction

PDC drill bits have proved to be economical tools in certain drilling applications in the Rocky Mountain region. Two areas in the Rockies found to be particularly suited to the application of PDC bits are the Green River and the Powder River basins.

To compete in these areas, a PDC bit must be capable of high penetration rates as well as longer bit life to justify the added cost of the PDC bit compared to conventional roller-cone bits. These are the two bit performance factors that determine drilling cost per foot—the most accurate measurement of drilling efficiency.<sup>1</sup> Given an adequate bit life, any parameter that can be altered to improve the penetration rate of a drill bit will further improve the drilling efficiency and result in lower drilling costs.

This paper discusses design features that can be incorporated into PDC bits to improve penetration rates. Bits with these design features were tested in the Powder River and Green River basins, and field results are reported in this paper.

## Bit Design Features

The design features incorporated into the PDC bits that were tested in the Rocky Mountains include variations in bit profile, cutter density, cutter exposure, cutter side

rake, and cutter shape. Although these are not all the possible design criteria for PDC bits, they are among the most important. All bits used in this test were steel-bodied, stud-cutter bits, with 20° back rake on the cutters—with back rake defined as the angle of the cutter in relation to the axis of the stud to which the cutter is attached.

**Bit Profiles.** The first bit profile evaluated is shown in Fig. 1. This is a short-tapered profile with a concave, shallow-cone center, referred to as Style A. This profile was originally chosen to attempt PDC drilling in the area because of its durability. Among the earliest PDC bit profiles, it has stood the test of time in attempting new PDC bit applications. With this profile, the cutting action of the bit relieves the confining formation pressures over a broad area, beginning near the bit's outside diameter. Also, the short-tapered profile allows for variations in cutter density, cutter profile, and cutter orientation without losing bottomhole coverage.

Fig. 2 (Style B) shows a more aggressive bit profile because of its longer taper. The concave, shallow-cone center is still present on this style, but the cutter placement and cutting mechanism are different from Style A. The longer taper on this bit provides fewer cutters on the leading edge. Thus, the unit load per cutter is higher and there are fewer cutters acting to relieve the confining formation pressures. These factors lead to a bit that will drill faster than Style A; however, more care should be taken in application selection because higher unit cutter loads can cause rapid failures in hard or abrasive formations.

Fig. 3 (Style C) shows an even more aggressive profile because of the absence of the center cone. This bit has a convex center with the same taper as Style B. There are even fewer cutters on the leading edge of this profile; thus, it is the most aggressive of three profiles discussed. For this reason, care should be taken in selecting a suitable application for this profile because the bit dulls quickly when a hard formation is encountered.

**Cutter Density.** Cutter density refers to the number of PDC cutters that are used on a bit of a given size. This almost always will vary with profile because of the necessity of obtaining sufficient bottomhole coverage. However, within the same profile, the cutter density can be altered if care is taken to ensure bottomhole coverage. Reducing the number of cutters on a bit has the effect of raising the unit load per cutter [given the same weight



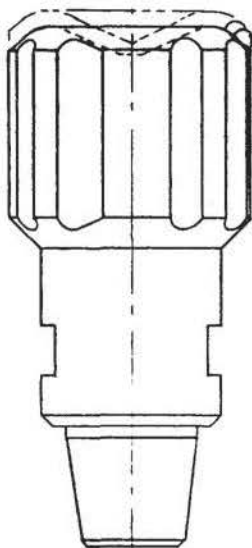


Fig. 1—Style A bit.

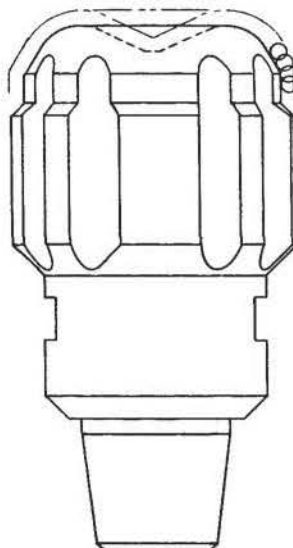


Fig. 2—Style B bit.

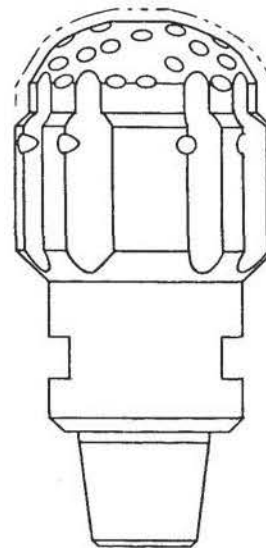


Fig. 3—Style C bit.

on bit (WOB)] and thus achieving more penetration per revolution and a higher penetration rate. It also has the advantage of being easier to clean—fewer cutters provide greater fluid and cuttings escape area. However, care again should be taken in choosing a bit with lower cutter density because it is not as durable as one with more cutters, particularly when hard stringers are present.

**Cutter Exposure.** For some formations, increased cutter exposure is necessary to remove the cuttings from the bit face adequately. Fig. 4 shows full exposure as opposed to standard exposure. The advantages and disadvantages of increased cutter exposure were discussed by Huang and Iversen.<sup>2</sup> Here, we shall just mention that a PDC bit can drill only as fast as cleaning allows. Thus, for fast drilling applications, more clearance is necessary between the bit face and the formation to allow all the cuttings to escape. This can be accomplished by exposing the cutters farther away from the body of the bit.

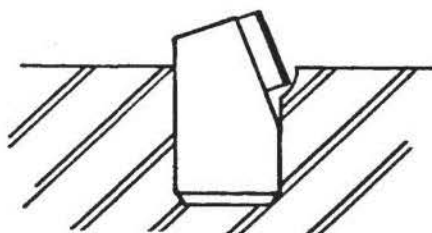
**Cutter Side Rake.** Side rake also has been discussed in detail,<sup>2,3</sup> so we shall simply summarize the highlights. Side rake is depicted in Fig. 5 and can be defined as the angle between the face of the cutter and a line drawn perpendicular to the centerline of the bit. The advantage

of this feature is that it allows the cuttings to slide off the cutter more easily than if the cutter is oriented so that it attacks the formation straight on.

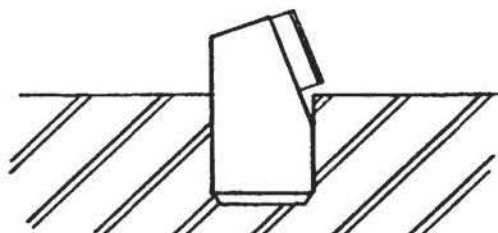
**Cutter Shape.** Cutter shape refers to the shape of the PDC compact itself, which is normally round. However, recent developments in the PDC industry have made it possible to obtain alternative shapes. One alternative shape that has been particularly successful is the chisel-shaped cutter. Fig. 6 compares round and chisel-shaped cutters and shows how the chisel-shaped cutter is able to increase penetration rates.

The chisel shape allows the cutter to penetrate farther into the formation for the same force applied. It has the same net effect in terms of unit loading as the reduced cutter pattern, but without the overall reduction in strength that occurs. Also, because the amount of carbide entering the formation is reduced, the operating temperature of the diamond decreases and its abrasion resistance is higher, resulting in longer cutter life.<sup>4,5</sup>

**Materials and Manufacturing Considerations.** The performance benefits of design modifications such as greater exposure, side rake, chisel-shaped cutters, and fewer cutters have been well known for years. These concepts only



Standard Exposure



Full Exposure

Fig. 4—Standard vs. full exposure.

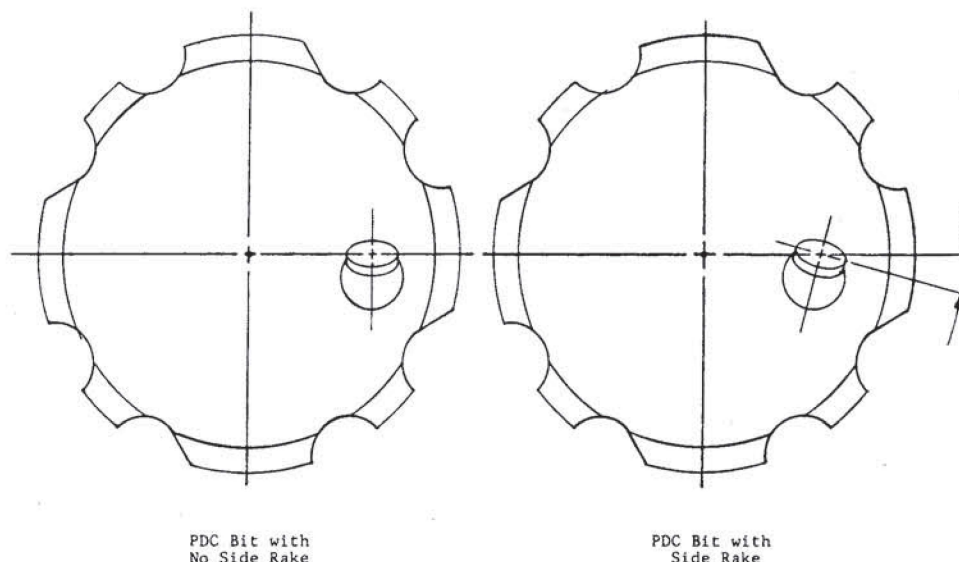


Fig. 5—Side rake.

recently have been applied successfully because of inherent limitations in manufacturing and materials, which caused early failures. The major breakthroughs have been metallurgical and manufacturing advancements that allow the design engineer freedom of concept. The bits in this study are based on the same steel and tungsten carbide technology that have carried the roller-cone bits for decades. The problem of poor erosion resistance has been circumvented by putting a matrix facing over the steel. Other advancements include (1) longer studs of improved carbide grade to improve retention and strength at high exposure, (2) higher bond strength at high temperatures to allow lower cutter density, (3) high tolerance precision of five-axis numerically controlled machining to ensure uniform stress on each cutting element, (4) threaded nozzles capable of withstanding extremely high hydraulic conditions in abrasive muds, and (5) development of nondestructive testing methods for highly improved quality control techniques.

### Field Results

The remainder of this paper will describe how the various design features actually affected PDC bit performance in the field. These results are current to Jan. 1984. New features and different combinations of features are being tested and evaluated on a continuing basis. This section will trace the evolution of bit designs, beginning with conventional roller-cone bits and ending with the best PDC design tested to that date.

**Green River Basin.** Until 1982, the wells in the Green River basin were drilled almost exclusively with roller-cone bits. Although drilling becomes somewhat more difficult in this field going from south to north, the same basic formations are encountered. For continuity, this paper reports the results in Township 25N and Ranges 110W and 111W. The formations of interest (where PDC bits have proved to be economical) in the Green River basin begin with the Hilliard shale and continue through the Aspen. The specific formations encountered from top

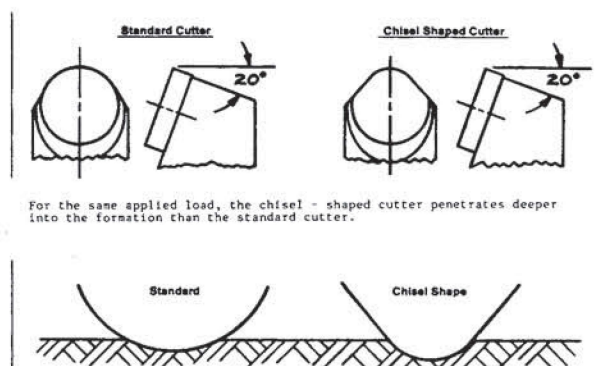


Fig. 6—Chisel-shaped PDC cutter vs. standard, round PDC cutter.

to bottom are the Hilliard, First Frontier, Second Frontier, and Aspen. These are predominantly shale sections, with some sand stringers and sandstones, that range from approximately 5,000 to 9,500 ft [1524 to 2896 m]. Table 1 lists the approximate depths of these formation tops along with basic lithology descriptions in Township 25N, Ranges 110W and 111W.

Before the use of PDC bits in the Green River basin, these sections normally were drilled with soft-formation, journal-bearing insert bits (IADC Code 517). A typical well would use three or four of these bits to drill the 4,500-ft [1372-m] interval at an overall penetration rate of about 22 ft/hr [6.7 m/h].

The first reported PDC bit run in this area was in early 1982 and was used for directional purposes. Because of deviation problems on this particular well, the operators were unable to apply enough WOB to obtain a satisfactory penetration rate with roller-cone bits. When the PDC bit (Style A) was run, it was found that the penetration rate was doubled with even less WOB and no additional deviation problems. Bit life also was more than doubled when compared to the previous Type 517 bit. After this



**TABLE 1—BASIC LITHOLOGY DESCRIPTION FOR PDC APPLICATIONS IN THE GREEN RIVER BASIN (T25N, R110W, and 111W)**

Formation	Approximate Depth of Formation Top		Description
	(ft)	(m)	
Hilliard	5,100	1554	Dark gray shale, silty, with bentonite and sand stringers
First Frontier	7,900	2408	Sand lenses on top, followed by silty shales
Second Frontier	8,900	2713	Sand lenses on top, followed by silty shales
Aspen	9,400	2865	Very firm, calcareous shales

run, it was obvious that PDC bits did have an application in Rocky Mountain drilling and could be used to save money on nonproblem wells as well as in controlled drilling applications.

During the introductory stage of PDC bits in the Green River basin, the predominant formation drilled was the Hilliard shale. Style A, without any modifications in cutter density, exposure, or side rake, was the first bit investigated in the Hilliard shale, competing against roller-cone bits drilling 24 ft/hr [7.3 m/h].

The average for this bit in the Hilliard was 28.4 ft/hr [8.7 m/h]—an 18% increase over conventional bits. In addition, the PDC bit was able to drill more than one well. When the dull bits were examined, it was obvious that the design could be modified to improve penetration rates without sacrificing bit life.

Next, tests were run with various PDC bit designs. All bits investigated were 7 $\frac{7}{8}$ -in. [20-cm] OD. The PDC bits were run with rotary speeds ranging from 80 to 100 rev/min. WOB for the PDC bits ranged from 12,000 to 20,000 lbf [53 379 to 89 964 N]. Flow rates varied somewhat, but were generally between 300 and 330 gal/min [19 and 21 dm<sup>3</sup>/s]. Thus, the drilling parameters were fairly consistent, and the assumption here is that each bit was run to achieve its optimum penetration rate.

Fig. 7 shows the evolution of bit design features that were used in the testing. The penetration rates given in this figure are averages of all runs of each bit style in the Hilliard shale—a total of 20 runs were investigated. Also shown is the average roller-cone bit performance; all runs have been adjusted to show a 2,800-ft [853-m] run. (All bits investigated drilled to the bottom of the Hilliard, but actual footages varied from 2,000 to 3,000 ft [610 to 914 m].)

The first modification tried was rather conservative—simply reducing the number of face cutters (nongauge cutters) in Style A by 11%. This reduction in cutter density improved the penetration rate from 28.4 to 39.1 ft/hr [8.7 to 11.9 m/h]—a 38% increase. Next, full cutter exposure and side rake were added to the reduced-cutter-density bit. Side rake was added together with full cutter exposure because full cutter exposure reduces the fluid velocities

across the bit face and a mechanism is necessary to remove the cuttings from the face of the PDC blanks.<sup>3</sup> When these features were added, the penetration rate was increased by another 9% to 42.6 ft/hr [13.0 m/h].

From this point, it seemed that increasing the load per cutter (reducing cutter density) had a greater effect on penetration rates than did additional cleaning capabilities, although both features enhanced penetration rates. Consequently, the next step was to reduce further the number of face cutters, retaining the full cutter exposure and side rake. Cutter density was reduced by another 12%, and the bits were tested. The penetration rates were increased by an additional 17% to 50 ft/hr [15.2 m/h]. At this point, it was not possible to reduce the cutter density on the Style A bit any further for fear of losing adequate bottomhole coverage. Thus, a more aggressive profile was needed. The final style tested in the Hilliard (as of Jan. 1984) was Style B. This bit proved to be the best so far, increasing the penetration rate another 16% to 58.2 ft/hr [17.7 m/h].

Overall, in the Hilliard shale, use of PDC bits increased penetration rates by 143% over roller-cone bits. Also, from the originally tested PDC bit design (Style A, unmodified) to the PDC bit design currently used (Style B), penetration rates have been increased by 105%.

While tests were being run in the Hilliard, it became evident that PDC bits were capable of drilling through the Frontier formations and into the Aspen formation. In drilling from the Hilliard to the Second Frontier, roller-cone bits drilled the interval at an average penetration rate of 21.5 ft/hr [6.6 m/h] and used two trips. Two styles of PDC bits were tested in this study: (1) Style A, unmodified, and (2) Style A, with a 21% reduction in cutter density, full cutter exposure, and side rake. The PDC bits were able to drill the entire interval with one bit. In addition, penetration rates were increased by 99% over roller-cone bits (from 21.5 to 42.9 ft/hr [6.6 to 13.1 m/h]) with the modified version of Style A.

Beginning with the Second Frontier, drilling begins to slow down. Roller-cone bits generally drill this section with one or two bits at an overall penetration rate of 15 ft/hr [4.6 m/h]. However, drilling slows down drastically toward the bottom of the Second Frontier and into the Aspen (6 to 10 ft/hr [1.8 to 3.0 m/h] for roller-cone bits) because of harder shales and increased mud weights. Style A bits have been able to increase the penetration rate over conventional bits by 20% to 18 ft/hr [5.5 m/h] overall. These bits also have the advantage of continuing through to the Aspen from the Hilliard, thus saving trips. The above increase in penetration rate over roller-cone bits is not insignificant, but cannot prove economical without being able to drill more than just the Second Frontier and Aspen on one well. PDC bits, as well as roller-cone bits, show the tendency to slow down toward the bottom of the Second Frontier; however, this change is not as drastic with PDC bits, and penetration rates generally remain above 15 ft/hr [4.6 m/h].

The best design feature tested thus far for this harder section is the chisel-shaped cutter. This cutter in a Style A bit profile increased penetration rates up to 103% over the standard Style A bit in the Second Frontier and through the Aspen. The initial test bit drilled 1,426 ft [435 m] in 40 hours for an overall penetration rate of 36.6 ft/hr [11.2 m/h]. The average penetration rate of all test bits with chisel-shaped cutters and Style A bit bodies was 29.4 ft/hr



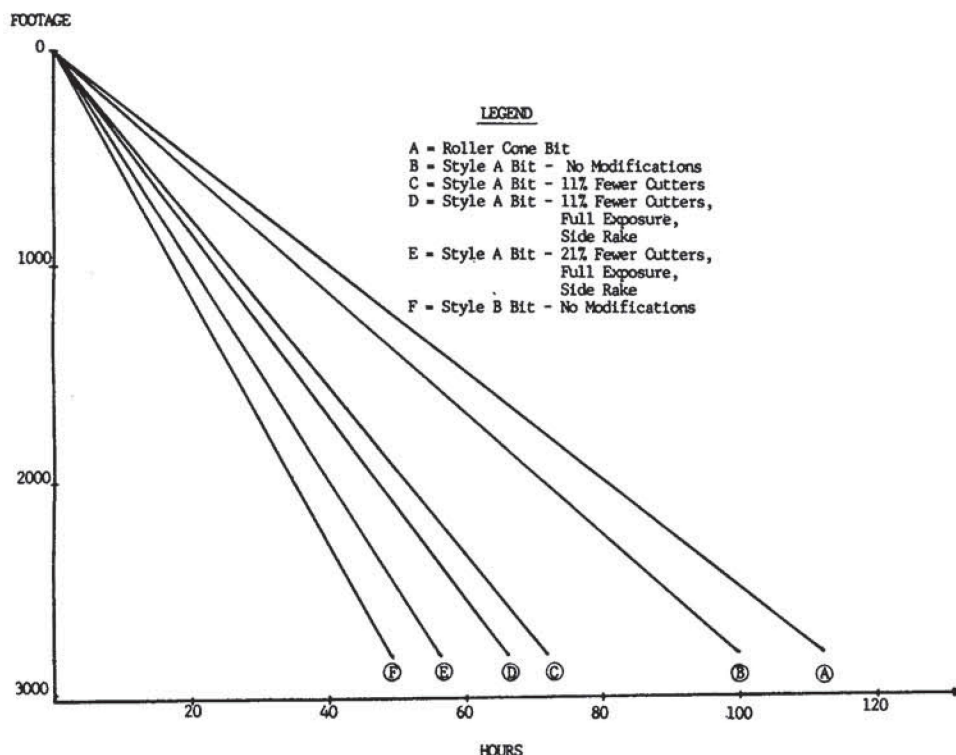


Fig. 7—Rotating time for various bit designs in the Hilliard shale, Green River basin.

[9.0 m/h], which represents a 63% increase in penetration rate over the round cutters and a 96% increase over roller-cone bits.

On the basis of the above results, the best PDC bit selection appears to be a Style B bit to drill the Hilliard and First Frontier. The remaining interval (through the Aspen) should be drilled with a Style A bit profile and chisel-shaped cutters. A Style A bit body is recommended because of its greater durability in hard formations; however, no other profiles were reported to have been tried at this time. Fig. 8 indicates total rotating time for several bit programs on actual wells drilled in the Green River basin.

**Powder River Basin.** Like the Green River basin, wells in the Powder River basin were drilled primarily with roller-cone bits until 1982. Within the Powder River basin, the same formations are usually encountered in all portions of the field. This paper will focus on the results obtained in Township 45N, Range 75W, and in Township 40N, Range 72W. The formations in these two areas are basically the same, although they are encountered at different depths from surface. This is a mountainous area, and the formation tops come in at about the same place when measured from the same elevation, but at different depths from surface. The formations of interest begin with variegated sands and shales above the Teapot and continue down through the Muddy. Specific formations normally encountered (beginning with the Teapot) from top to bottom are the Teapot, Parkman, Sussex, Shannon, Niobrara, Carlile, First through Third Frontiers, Mowry, and Muddy. These formations are predominantly shale sections, with some sand stringers, sandstones, and bentonite stringers.

Depending on the total depth of the well, there are two bit programs used in the Powder River basin that were used for this study. One uses 7 $\frac{7}{8}$ -in. [20-cm] bits through all the formations previously mentioned. The other program uses 8 $\frac{3}{4}$ -in. [22.2-cm] bits down to the First Frontier and 6 $\frac{1}{8}$ -in. [15.6-cm] bits through the Muddy.

Before PDC bits were used, the interval normally was drilled with very-soft- to soft-formation, journal-bearing insert bits (IADC Code 437, 517, and 537).

For this paper, the interval being discussed will be split into three sections. The first is the interval from approximately 1,500 to 2,000 ft [457 to 610 m] above the Teapot down to the top of the Teapot. The second section begins with the Teapot and goes to the top of the First Frontier. The last section consists of the Frontiers, the Mowry, and the Muddy. Fig. 9 shows the evolution of PDC bit designs and penetration rates compared to roller-cone bits used in each section.

The section above the Teapot is generally fast drilling. Until about 1,500 to 2,000 ft [457 to 610 m] above the Teapot, these formations are drilled at penetration rates of 50 to 100+ ft/hr [15.2 to 30.5+ m/h]. Afterward, the penetration rates of the roller-cone bits slow down. Overall averages for this last 1,500 to 2,000 ft [457 to 610 m] are around 35 ft/hr [10.7 m/h].

Although PDC bits have been shown to drill the top hole sections as fast as the 50 to 100 ft/hr [15.2 to 30.5 m/h] drilled by the roller-cone bits, the added bit cost does not justify the use of PDC bits until the roller bits slow down to less than 40 to 50 ft/hr [12.2 to 15.2 m]. The first PDC bit in this test that drilled the section just above the Teapot was a Style A bit profile with no modifications. This bit could not attain the penetration rates of roller-cone bits; however, the bit did continue through



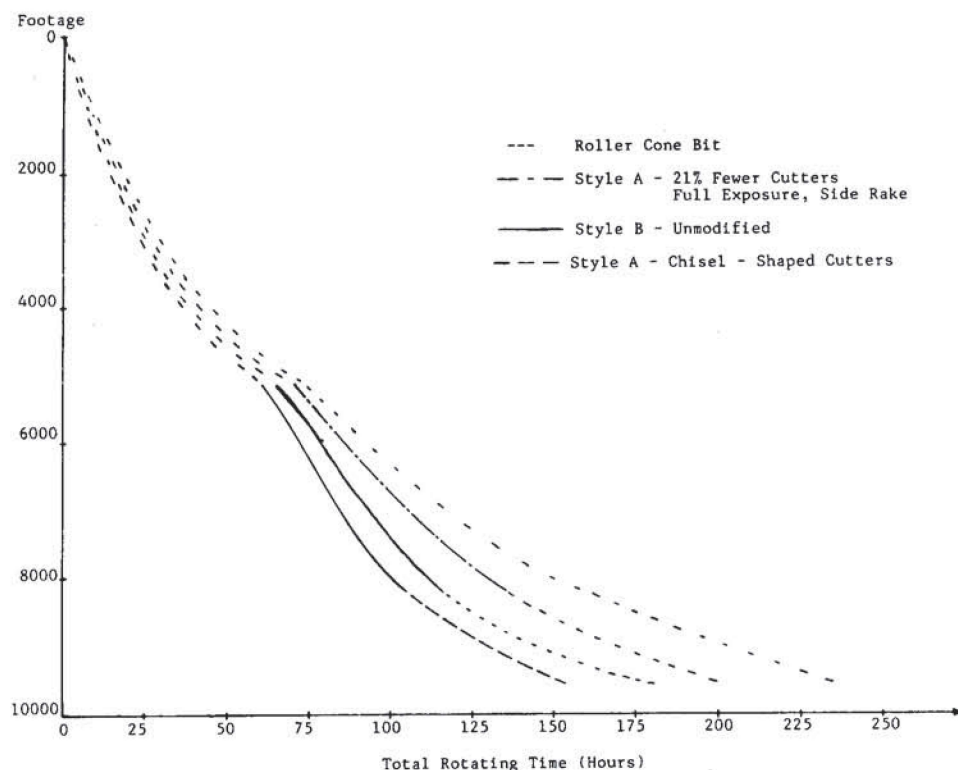


Fig. 8—Total rotating time for various bit programs used in wells drilled in the Green River basin.

to the Frontier. Performance was 32.1 ft/hr [9.8 m/h], compared with 35 ft/hr [10.7 m/h] for the offset roller-cone bits.

Obviously, without modifications, the standard Style A bit would not be cost-effective above the Teapot. The first modification was to reduce the cutter density by 10% and to add full cutter exposure and side rake to a Style A bit profile. This increased the penetration rate by 33% to 42.8 ft/hr [13.0 m/h], which did exceed the average penetration rate of the roller-cone bits. Next, the Style B profile (with no modifications) was tested. This was very successful and increased the penetration rate over the modified Style A profile by 49% to 63.7 ft/hr [19.4 m/h]. Obviously, the increased load per cutter on this more aggressive profile enhanced the penetration rate. Thus, the next step was to modify the Style B profile to penetrate the formation further. Chisel-shaped cutters were used, and this raised the rate of penetration to 73.3 ft/hr [22.3 m/h]—a 15% increase. The final stage in PDC bit evolution studied in this section was to go to an even more aggressive profile in combination with the chisel-shaped cutters. A Style C bit profile with chisel-shaped cutters was tested; it drilled to the top of the Teapot at a penetration rate of 85 ft/hr [25.9 m/h], an increase in penetration rate of 16% over the Style B profile.

Fig. 9 shows clearly that the various design changes increased the penetration rates of the PDC bits studied in the 1,500- to 2,000-ft [457- to 610-m] section above the Teapot. From the original design (Style A, unmodified) to the existing design used (Style C with chisel-shaped cutters), the penetration rate increased by 165%.

Fig. 9 also shows the evolution of bit designs in the section from the top of the Teapot to the top of the First

Frontier. The Style A profile (unmodified) showed an increase in penetration rate of 21% over the roller bits (18 to 21 ft/hr [5.5 to 6.4 m/h]). The Style B profile further increased the penetration rate by 38%, to 30 ft/hr [9.1 m/h]. The chisel-shaped cutters on the Style B bit increased the penetration rate by another 17%, to 35 ft/hr [10.7 m/h].

The last section studied is somewhat different from the previous two sections. This section, from the top of the First Frontier to the top of the Muddy, was drilled with 6½-in. [15.6-cm] bits on the wells studied. The drilling rate slows down drastically in this section to 3.2 ft/hr [1.0 m/h] for roller-cone bits. Fig. 9 shows a slight increase of 16% in penetration rate, to 3.7 ft/hr [1.1 m/h], when the Style A bit profile (unmodified) was used. In addition, the Style A bits lasted more than 100 hours while the roller-cone bits lasted only 40 to 50 hours. Thus, bit life as well as penetration rate played a major role in making the Style A bit cost-effective. The most dramatic penetration rate increase of all occurred when the Style A bit was modified to have full cutter exposure in combination with chisel-shaped cutters. This bit drilled the section from the top of the First Frontier, through the Mowry, and into the top of the Muddy at a penetration rate of 16.5 ft/hr [5.0 m/h]. It drilled a total of 951 ft [290 m] in 57½ hours to achieve this penetration rate, a 346% increase over the unmodified Style A bit.

Tests are still being conducted in this area, but the optimum bit program to date can be extracted from Fig. 9. A Style C bit with chisel-shaped cutters should be used first. This bit drills as fast as roller-cone bits in the very top interval, and faster than roller-cone bits beginning approximately 1,500 to 2,000 ft [457 to 610 m] above the

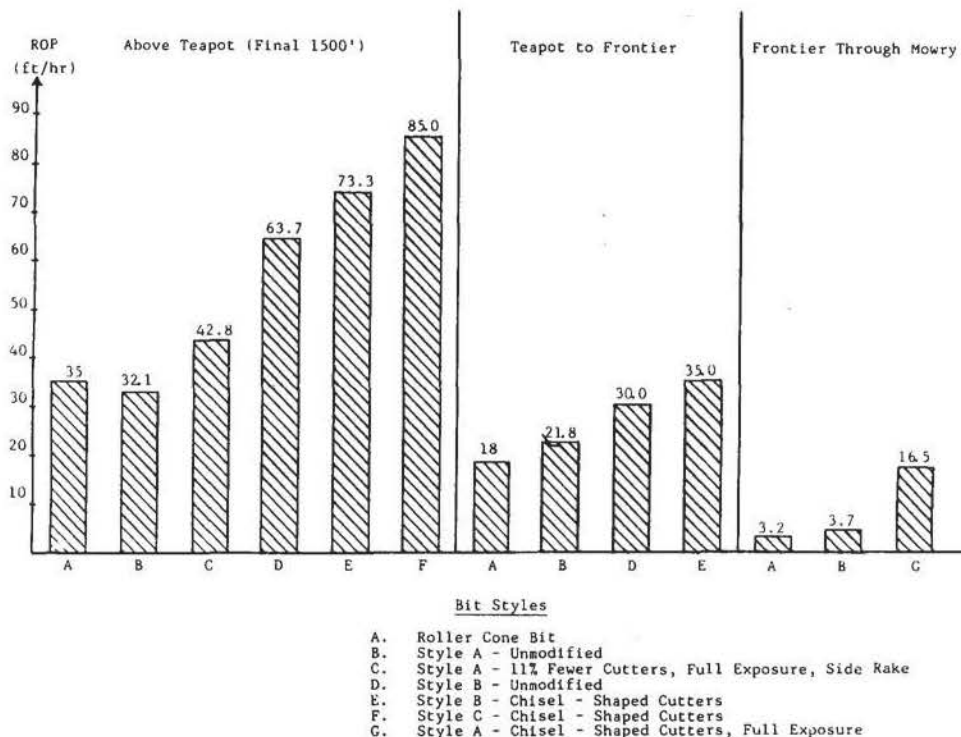


Fig. 9—Penetration rates for various bit styles in different formations in the Powder River basin.

Teapot. Therefore, drilling conditions on each well will determine the optimal depth to run the Style C bit into the hole; this usually occurs when penetration rates for roller-cone bits drop below 40 ft/hr [12 m/h]. Next, the Style B bit with chisel-shaped cutters should be used to drill down to the Frontier. From this point it is obvious that the Style A bit with chisel-shaped cutters and full cutter exposure should be used to drill to the Muddy. Because of its durability, it seems best to stay with the Style A bit in the bottom sections to achieve the necessary bit life for a cost-effective performance; however, rounder-profile bits with chisel-shaped cutters have not been tested to date in this application.

### Conclusions

1. Continuing development of PDC bit designs has increased penetration rates in Rocky Mountain drilling.
2. Drilling in both the Green River and Powder River basins responds with higher penetration rates to increased unit cutter loading on PDC bits.
3. Enhanced cleaning features have a positive effect on PDC bit performance, but not as much as increased cutter loading.
4. The chisel-shaped cutter has proved to be the most influential new feature added to PDC bits to improve penetration rates and drill sections that are marginally economical with PDC bits containing round cutters.

Additional tests are necessary before the optimum bit program can be developed for drilling in the Green River and Powder River basins. However, in the last 2 years, the addition of new bit profiles and changes in orientation, placement, and shape of the cutters in PDC bits has greatly increased drilling efficiency in the Rocky Mountain region.

### Acknowledgments

We thank Randy Smith of Energetics and Tom Schledwitz of Exeter for their contributions to PDC applications from both an operator's and a contractor's point of view. We also thank all the Strata Bit Corp. employees who assisted in preparing this paper.

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### SI Metric Conversion Factor

$$\text{ft} \times 3.048^* \quad \text{E-01} = \text{m}$$

\*Conversion factor is exact.

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