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IMPROVEMENT OF DRILLING CAPABILITIES OF PDC CUTTERS IN HARD FORMATION

Final Report

Work Performed for the Department of Energy
Under Contract No. DE-AC19-80BC10364

Date Published—August 1982

Diamond Oil Well Drilling Company
Midland, Texas

National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
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IMPROVEMENT OF DRILLING CAPABILITIES OF PDC CUTTERS IN HARD FORMATION

Final Report

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UNITED STATES DEPARTMENT OF ENERGY

FOREWORD

The work covered in this report was performed under the Drilling Research Program of the U.S. Department of Energy. The Project was monitored by the Bartlesville Energy Technology Center, Bartlesville, Oklahoma. The purpose of the work was to advance the technology for drilling hard formations with Polycrystalline Diamond Compact (PDC) drill bits. These type bits have often shown excellent performance in soft and medium formations. If the operating horizon of the PDC bits can be expanded to include hard rocks, the petroleum industry will realize increased efficiency, faster drilling rates and reduced drilling cost.

C. Ray Williams
Technical Project Officer
Bartlesville Energy Technology Center

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ABSTRACT

This report describes the work performed by Diamond Oil Well Drilling Company (DOWDCO) under a cost-sharing contract with the U.S. Department of Energy. Fifteen bits were designed, fabricated and field tested in an effort to improve Polycrystalline Diamond Compact (PDC) bits for hard formations. Some conclusions are presented regarding design of hard formation bits. The performance is described for the 15 bits tested. Some bit design layouts and photographs are shown. The work is considered to be successful and some excellent results were obtained. Bit No. 9 drilled 5,949 feet averaging 33 ft/hr and Bit No. 16 drilled 1,100 feet of hard rock averaging 8.7 ft/hr.

Problems that were encountered early were resolved and coring penetration rates ranging from two to six times faster than conventional diamond core bits were achieved. The full-face PDC drill bits showed improved penetration over roller cone bits when drilling medium and hard formations but breakage of the nose cutters occurred when extremely hard formations were encountered.

INTRODUCTION

In a 1980 proposal to the Department of Energy (DOE), Diamond Oil Well Drilling Company (DOWDCO) suggested several techniques which might expand the capability of Polycrystalline Diamond Compact (PDC) bits for drilling in hard formations and/or reducing bit costs. The state-of-the-art at that time for PDC bits usually showed excellent performance in soft and medium formations but were not always reliable for hard formations. In September 1980, DOWDCO and DOE entered into a cost-sharing contract to test various concepts for developing PDC core and drill bits for hard formations. The objective was to develop PDC bits that would be effective in coring and drilling hard formations.

The overall approach for this work was to identify the requirements needed to improve and optimize the performance of PDC hard-formation coring and drilling bits, to determine practical solutions to the problems identified, to design and fabricate bits using new concepts and, finally, to field test these bits while thoroughly documenting their performance.

A total of 18 experimental bits were designed, built and tested during this contract but three bits were not for hard formation and did not qualify for DOE participation. Most of these bits performed well in a myriad of formations. Photographs and design patterns for many of these bits are presented in this report.

Various designs and concepts were tested as the opportunities occurred for field testing. This sometimes makes it appear that progress was sporadic but each test provided new information. Consequently, a separate write-up is presented for each bit.

DISCUSSION

DOWDCO designed, constructed and tested the 18 bits discussed herein and has completed its contracted obligations with the DOE. The original contract was to test 12 bits in one year; however, adequate field testing opportunities in various hard formation did not occur during the first year and a no-cost six-month extension was granted. One concept which had been planned for testing was a bit with a removable cutter plate. This was intended to facilitate removal of damaged studs and allow re-use of the bit body. DOWDCO was unable to test this concept because PDC cutters on steel studs could not be obtained. However, stud replacement became a reality on the DOE Multiwell experiment (MWX) where cutters were replaced and the bits re-used repeatedly.

The reason for testing hard formation bit concepts on core bits was because core bits are pulled after drilling about 60 feet or less. The core bits could then be inspected for wear patterns. Conversely, drill bits are normally used to destruction and it is often difficult to evaluate the wear characteristics. This system provided good information during the building of the first bits. Most of the first core bits performed well but the first full-face PDC drill bit (No. 6) did not. However, the second full-face bit (No. 9) drilled 5,949 feet and averaged 33 ft/hr -- an excellent performance.

The testing of the small PDC cutters proved acceptable considering the small diamond cutting area on the bits. The large bases on the small cutters that were tested restricted the number of cutters that could be installed on each bit. DOWDCO still plans to test small cutters with small bases even though this contract is completed.

Finally, the performance of both the experimental core and drill bits (No. 14-18) in the DOE MWX wells was also excellent. It was estimated that DOE saved approximately $300,000 which is about 2½ times what DOE invested in this cost-shared work. Obviously DOWDCO has advanced their capability to drill hard formation and, through the information in this report, the state-of-the-art for the petroleum industry will be advanced.

CONCLUSIONS

During the performance of this work, DOWDCO has arrived at the following conclusions regarding the manufacture of hard formation drill bits.

1. The design of PDC bits is greatly facilitated by use of a computer design program.

2. Each PDC cutter should be designed to remove equal volume.

3. Drilling with lower hydrostatic pressure reduces rock strength and greatly speeds penetration rates.

4. PDC cutters are circular in shape but when inclined at negative rake (usually -25 degrees) all computer representations must be shown as ellipses. Three axis programs must be developed.

5. The PDC cutters should be installed at an angle at the ID and OD of the bit to maintain gauge size.

6. Cracking of PDC cutters may occur because of vibration if bit weight is too light.

7. A pin and notch technique should be used during construction to assure proper alignment of each PDC cutter.

8. The PDC studs should be buried deeply in the steel matrix of the bit for hard rock drilling.

9. Use as many PDC cutters on the bit face as possible for hard rock drilling.

10. Hydraulics of 2 to 3 hp/in^2 provide improved cleaning and cooling of PDC bits.

11. When drilling faster than 15 ft/hr, 3 hydraulic horsepower is required.

12. Using the "chin" technique assures consistent depth placement of the cutters.

13. Grinding of PDC gauge cutters provides additional gauge protection.

DESCRIPTION AND PERFORMANCE OF EXPERIMENTAL BITS

Bit No. 1

Bit No. 1 was a 6½ inch by 3 inch PDC core bit. It was tested in the moderately hard Wolfcamp formation near Wellman in West Texas. Good comparative data is available because pressure coring PDC bits and conventional diamond bits were also used in coring the well. Data is also available from a nearby well drilled with conventional water base mud and roller bits.

The operator's objective for the well was to determine oil saturation of the field as accurately as possible. For this reason, foam drilling fluid was selected to provide a near zero psi differential and PDC bits were selected for their increased cutting rates to reduce filtrate invasion time. This created an unique opportunity to test the effects of a low differential pressure as well as foam drilling fluid on PDC bit performance. The nearby comparative well was drilled with a 3,000 psi differential.

The objectives of this experimental PDC core bit were:

1. To test a new improved PDC bit;

2. To drill (core) in the hard Wolfcamp formation:

3. To test the effects of reduced differential pressure on PDC-bit drilling;

4. To determine how PDC bits may be improved.

PDC Bit No. 1 (before coring) is shown in Figure 1. Observation of bit wear on this test led to the decision to pre-grind the PDC cutters which are subject to cutting the gauge of the hole. This provides more wear surface on the cutting element so that "wear down" is reduced and the bit will stay "in gauge" much longer. This concept is shown in Figure 2.

This bit also was built using a design which DOWDCO describes as a half-Torus matrix design. It is believed that this is a stable design for drilling straight holes. A cross section of the bit showing the half-Torus is in Figure 3.

Test Results and Conclusions

1. The PDC bit cored at rates as high as 60 ft/hr; averaging 39 ft/hr.

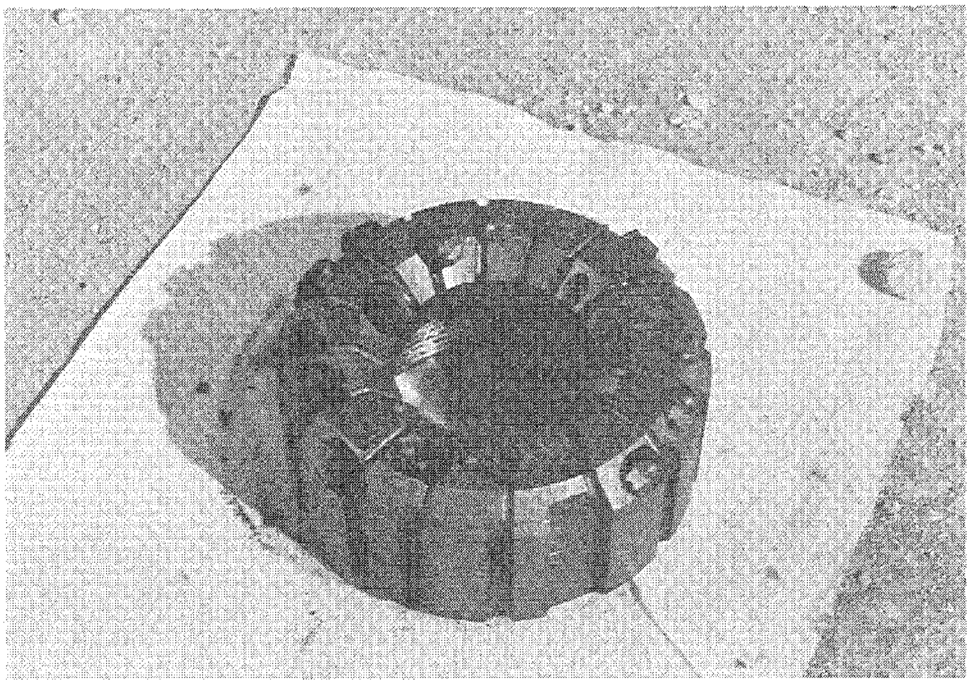


FIGURE 1
Field Picture of PDC Bit No. 1
Used to Core With Foam

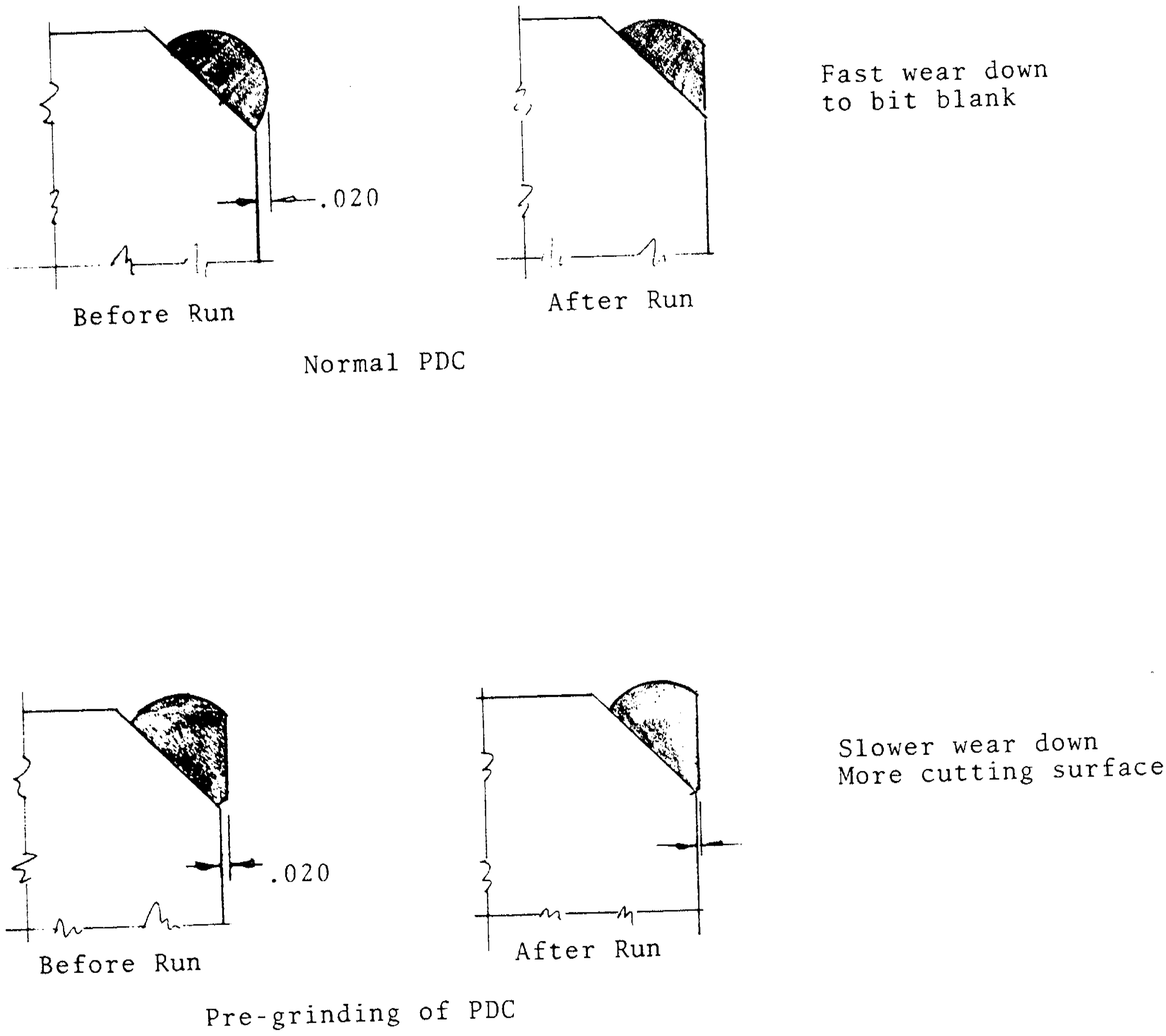


FIGURE 2
Schematic Showing Pre-Grinding
Reduces Gauge Wear

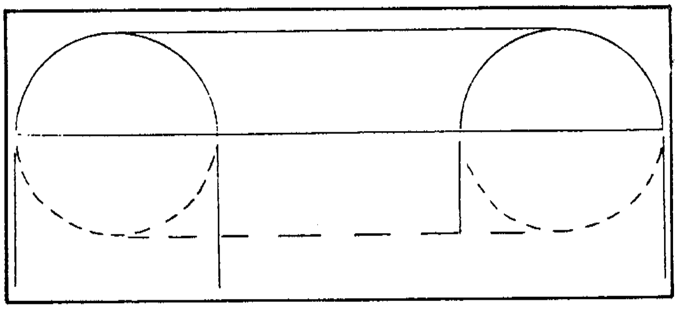


FIGURE 3
Half Torus Shape - Cross Section

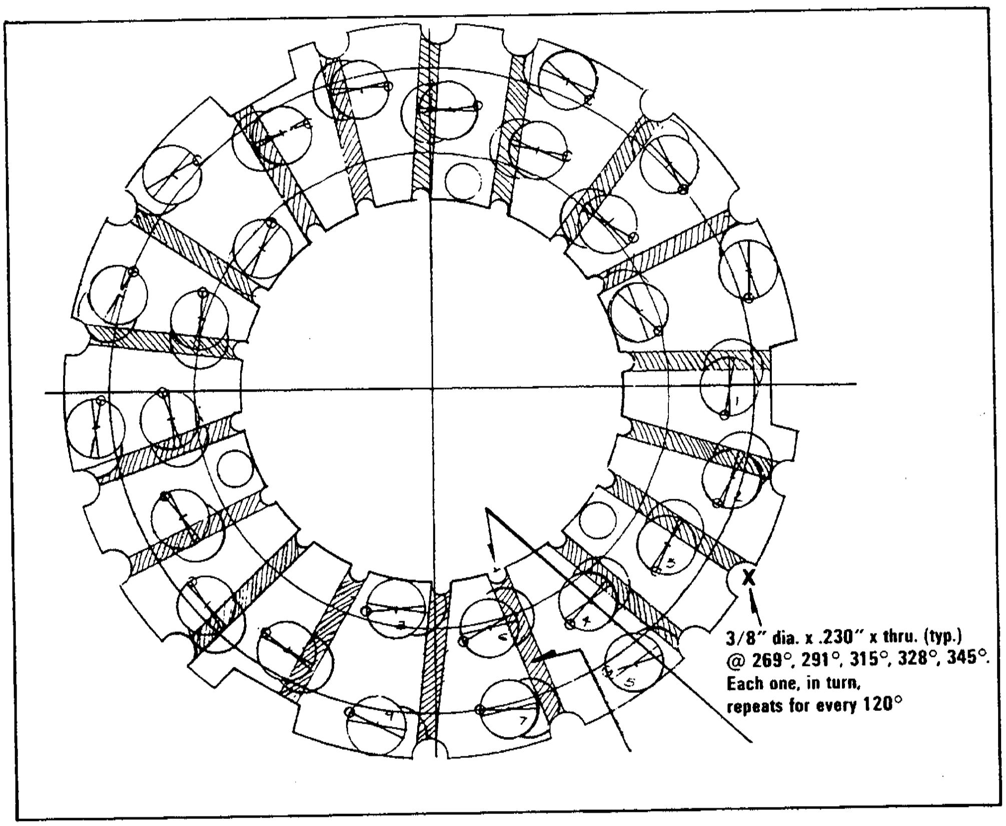


FIGURE 4
PDC Core Bit Design

2. Conventional diamond core bits drilled at rates of 11 ft/hr.

3. Offset wells drilling with approximately 3,000 psi differential pressure with roller bits drilled at 12 ft/hr.

4. It was concluded that reduced differential pressure reduces rock strength and greatly speeds drilling.

5. The core bit showed little wear. Possibly the bit could have drilled as much as 200 feet in this formation.

Computer PDC Design Programs

The design of PDC bits can be greatly facilitated by use of a computer design program. A computer with a plotting terminal and proper software will allow rapid testing of PDC design concepts.

Since PDC cutters are circular in shape but inclined at a negative rake, generally of 25 degrees, all computer representations of them must be ellipses. These features require that the design program be able to compute and draw ellipses on the plotter in any position.

Conventional analytic geometry mathematics has been developed only for ellipses with major axes either parallel to the X axis or the Y axis. DOWDCO developed some special software to rotate the axes of ellipses to give the computer software complete flexibility in handling ellipses. All of the vital considerations of the PDC core bits can be drafted on the plotter to show the special relationships to exact scale. This program can reduce error and improper placement of PDC cutters and water courses.

Bit No. 2

The objective for the second PDC bit was to develop a PDC core bit to drill in a somewhat harder rock than the Wolfcamp where conventional diamond core bits drilled 11 ft/hr. For this test, the Canyon sand was selected which drills from 1 to 4 ft/hr with conventional diamond bits.

This PDC core bit, a three scraper bit, was built to core the Canyon sand in Nolan County, Texas. This was a 7-13/16 inch by 4.25 inch core bit. A similar design (see Table 1) drilled 15 ft/hr in granite at Terra Tek Drilling Laboratories. Each of the blades does not follow a logical sequence around the bit, but folds back such that nine PDC studs can fit in one 120 degree segment of the bit. This design is to allow the largest feasible number of PDC studs on the bit for hard rock drilling.

This bit was designed to drill at the maximum rate of 60 ft/hr and operate with a pressure drop across the bit of 150 psi during operations. This design requires 280-300 gal of mud flow per minute and produces mud velocities approaching 140-150 ft/sec, to cool and clean the PDC cutters.

TABLE 1--Drilling Data for PDC at Terra Tek

DOWDCO PDC Core Bit 4.25 in. x 7-13/16 in.
Sierra White Granite (psi 30,000)

Time	Ft/hr	Bit Weight	Torque	RPM	Flow	Mud Pressure
729.969	11.72	12440.1	919.0	80.6	305.3	311.7
730.117	11.81	12446.3	925.2	80.6	308.8	290.0
732.168	11.90	12595.4	949.5	80.3	305.8	264.5
742.133	14.65	13334.3	1019.9	80.4	308.1	323.8
743.902	13.52	13309.4	1011.5	80.6	309.0	297.8

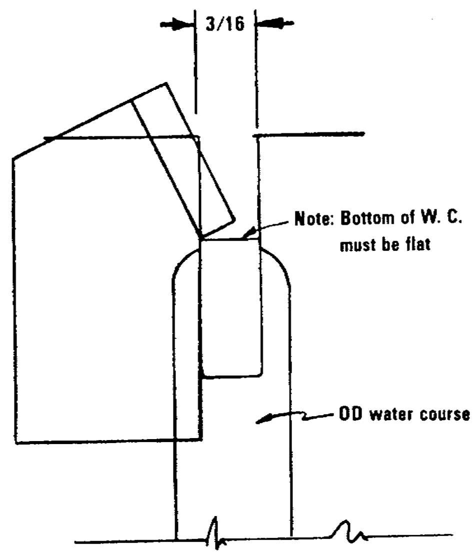
A design drawing of PDC Bit No. 2 is shown in Figure 4. The bit drilled uniformly and evenly through 59 feet of relatively hard Canyon sand from 5,224 to 5,283 feet. It drilled as fast as 60 ft/hr and averaged 12 ft/hr. Some unexpected shale streaks cored very slowly causing the low average. Only two of the PDC cutters wore appreciably. The problem was due to poor quality control on positioning of these cutters. They were inadvertently positioned higher than the other cutters which caused excessive force and more wear. Weight-on-bit was from 8,000 to 20,000 pounds. Offset conventional diamond bits cored at 3.04 ft/hr.

The quality control problems prompted DOWDCO to develop a technique called "chin" to locate the PDC cutters. This technique is shown in Figure No. 5.

Bit No. 3

Experimental Bit No. 3 was built to also core the canyon sand. Bit size was 7-27/32 by 4¼ inches. The new "chin" technique was used to accurately position the PDC cutters. The bit was designed to improve cleaning and cooling of the cutters and to provide better cleaning at the ID and OD of the core bit. A new technique of placing the cutters on an angle instead of vertical was tested in this bit. (See Figure 6.) A concept using a pin and notch to assure alignment was tested.

PDC Bit No. 3 drilled 120 feet of Canyon formation but the zone was chiefly shale. This bit drilled 4 ft/hr. The offset conventional diamond bit drilled less shale at 2.4 ft/hr. Mud flow rates of 240-280 gal/min were used which provided 50-100 psi pressure drop across the bit. Weight-on-bit was a maximum of 12,000 pounds.



W.C. is Water Course

FIGURE 5
Chin Technique

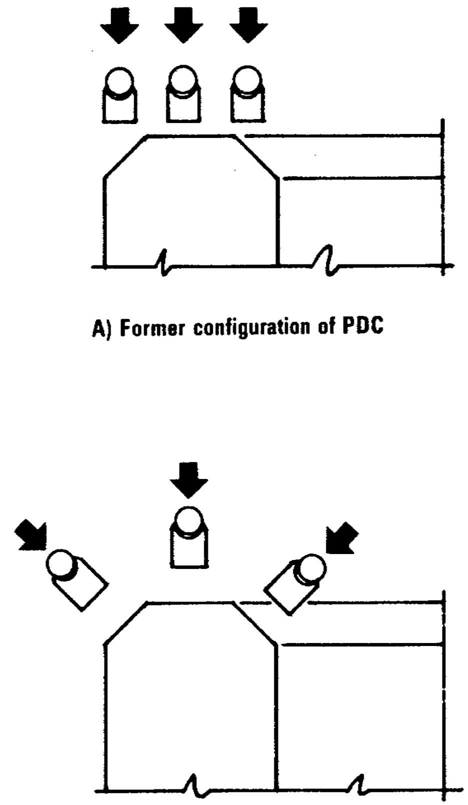


FIGURE 6
Positioning of PDC in Bits

The results with Bit No. 3 were much superior to those of Bit No. 2 because of placing PDC cutters at the OD and ID of the bit at an angle. This allows more cutting edge to be available to maintain gauge. This was effective in providing more footage per bit while still maintaining gauge.

A phenomenon of cracking of the OD PDC cutters occurred in Bit No. 3. This may have been caused by bit vibration while coring which has been observed previously with conventional diamond bits when insufficient weight is used on the bit.

Field testing of PDC core Bits No. 2 and 3 in the hard abrasive Canyon sand was significant. Both the drilling rate and footage drilled in this hard rock were improved. Drill rates of three to five times faster than conventional diamond bits and footages of up to 300 feet per bit were achieved.

Conclusions

The field testing of Bits No. 2 and 3 have proved some design concepts. Through this testing, it has been determined that several design factors are very important when drilling with PDC core bits. These conclusions are as follows:

1. Locating PDC cutters in water courses such that adequate mud flow is available for cooling and removal of cuttings.

2. PDC cutters require accurate placement. DOWDCO has established the use of "chin" position of cutters for accurate placement. (See Figure 5.)

3. Outer cutters (ID and OD) are much more effective in maintaining gauge if placed in the matrix at an angle. (See Figure 6.)

4. Grinding of the ID and OD gauge cutters to produce more cutting edge gives improved PDC cutter life.

5. Counter-sinking of PDC cutters into the matrix with the back side against the matrix ensures support when cutting hard rock.

6. Keying the PDC cutters in position during braising assures proper position.

7. Computer analysis of PDC cutters to ensure equal volume of cut is very successful.

Bit No. 4

Experimental PDC Bit No. 4 was built employing the findings outlined in the above conclusions. Bit size is 6½ by 3 inches. (See Figure 7.) This bit was similar to Bit No. 3 except that it had four PDC cutters on the OD which had been ground to provide up to three times the OD protection.

Unfortunately, this bit was improperly threaded and the threads and six PDC cutters were damaged when attempting to screw the bit on the core barrel. The threads were later repaired and the bit was run in a different well to determine how much the bit would drill with the cutters being damaged. The bit only cored 48 feet before it was completely worn out.

Bit No. 5

Bit No. 3 had experienced some cracking of the PDC cutters. It was postulated that this was caused by indadequate weight-on-bit which allowed excessive vibration. Since Bit No. 3 had shown positive results, it was decided that the design should receive further testing.

DOWDCO built PDC Bit No. 5 using the same design as Bit No. 3. This bit cored 147 feet of lime formation in a well in Pontotoc County, Oklahoma. It averaged 13.9 ft/hr or five times faster than a conventional diamond core bit which averaged 2.8 ft/hr in the same hole. This bit is shown in Figure 8. It was kept in the field for additional drilling and ultimately cored a total of 300 feet.

Bit No. 6

Experimental PDC Bit No. 6 was DOWDCO's first full-face drill bit. Efforts were made to use the information learned from the previous hard formation core bits to build a full-face bit which would be highly effective in hard formation. Also, numerous designs were considered for the center portion of the bit and to obtain a stable design which would not cause hole deviation.

This was a 7-7/8 inch drill bit. (See Figure 9.) It was designed with five 11/32 jets to provide adequate cooling and cleaning. The design was for a mud flow rate of 300 gal/min with a 400 psi pressure drop across the bit. DOWDCO designed the bit for 2 hp/in^2 on the bottom of the bit.

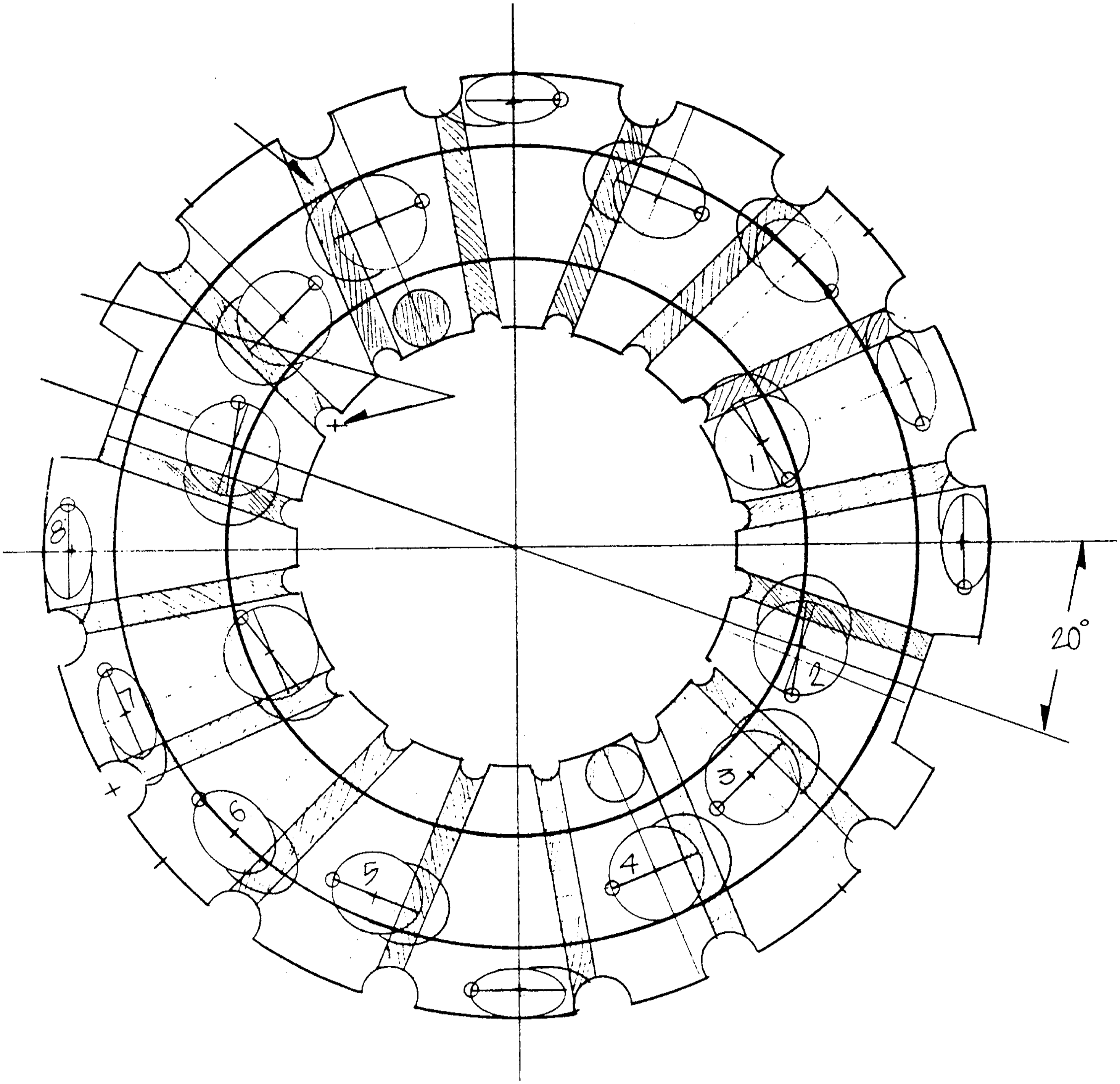


FIGURE 7
Bit No. 4

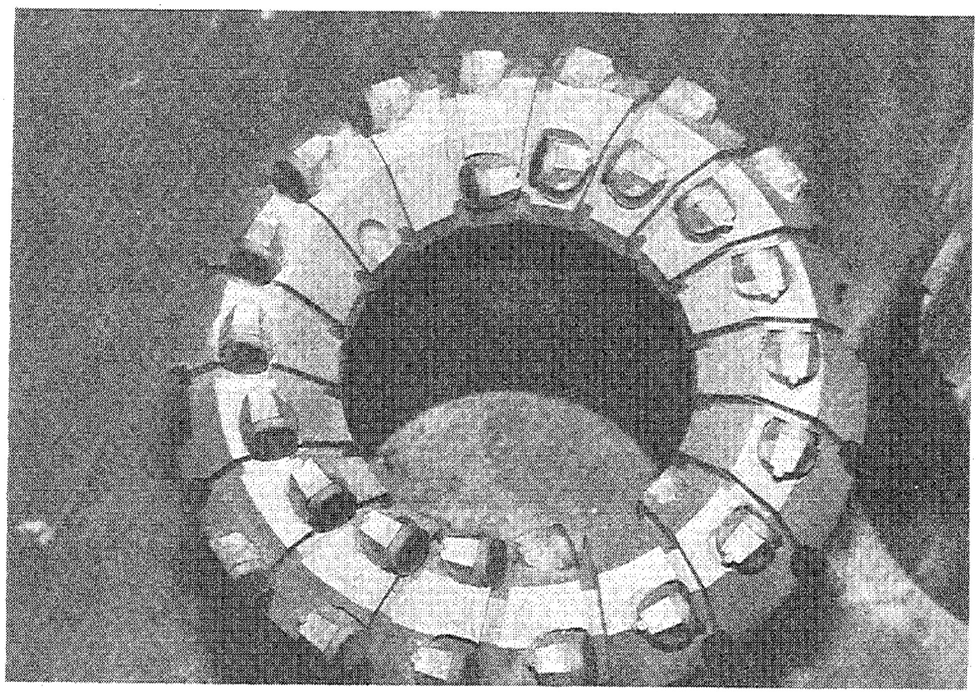


FIGURE 8
Bit No. 5 Which Cored 147 Feet

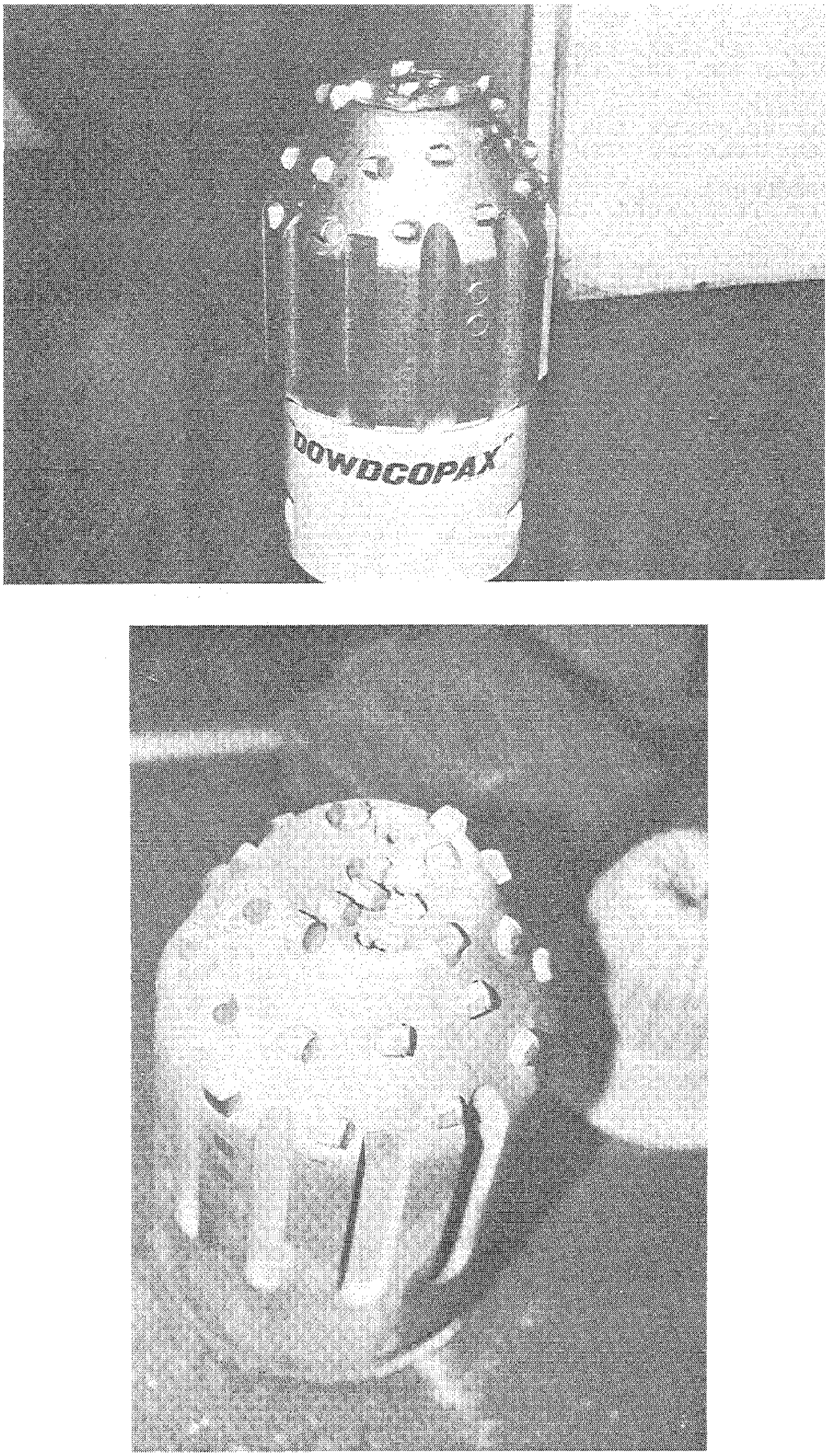


FIGURE 9
Full Hole PDC Drill Bit

Bit No. 6 was tested near Bryan, Texas but its performance was not satisfactory. It drilled 340 feet and averaged 10 ft/hr. That was not a fast rate for those formations so the bit was pulled out of the hole. The rig facilities were not optimum and it was surmised that the drill collar weight may have been inadequate; however, PDC bits normally use less weight than roller cone bits. When it was pulled, the bit showed very little wear and the operator kept the bit for testing at a different location.

The bit was used again near Lamesa, Texas and stopped drilling shortly after being run. The center of the bit had "washed out". DOWDCO had used a silver-solder process to install the jets. The jets are now installed by welding and this problem has not recurred.

Bit No. 7

PDC Bit No. 7 was a core bit which was designed to core unconsolidated sand and increase the amount of formation recovery. The principal design factor was to obtain good bit cleaning while pumping low volumes of fluid. The bit was designed to core at 120 ft/hr. In conjunction with this test, a special core barrel was designed and built. However, the DOE Technical Project Officer adjudged that this work in soft formation did not comply with the purpose of the contract and the results of the testing are not included in this report.

Bit No. 8

One of the objectives of the DOE contract was to test various types of PDC cutters. One of the proposed techniques was to test the concept of using a much smaller PDC cutter element. This bit employs a cutter with a face that is one-half as large as a standard size PDC cutter. This concept was to test the known technology of conventional diamond bits: bits with small diamonds drill hard rock best. Figure No. 10 shows the relative size of the two cutters.

The cutting action of this bit was first tested by drilling into a graphite block to determine the cutting pattern. The bit cuts numerous small grooves. This may provide a more reliable performance in extra hard rock.

The bit was a 7-7/8 inch by 4 inch core bit which used 21 PDC cutters per blade. A design drawing is shown in Figure No. 11. Note that the design uses two full-circle spirals which DOWDCO calls "blades". DOWDCO uses a PDC blade concept where a blade consists of a numer of cutters which cut out the complete bottom of the hole in one revolution. Seldom are more than two blades used on a core bit. Each PDC in the blade is positioned such that it cuts an equal volume. The three axis are positioned by a computer program for visual inspection and machining.

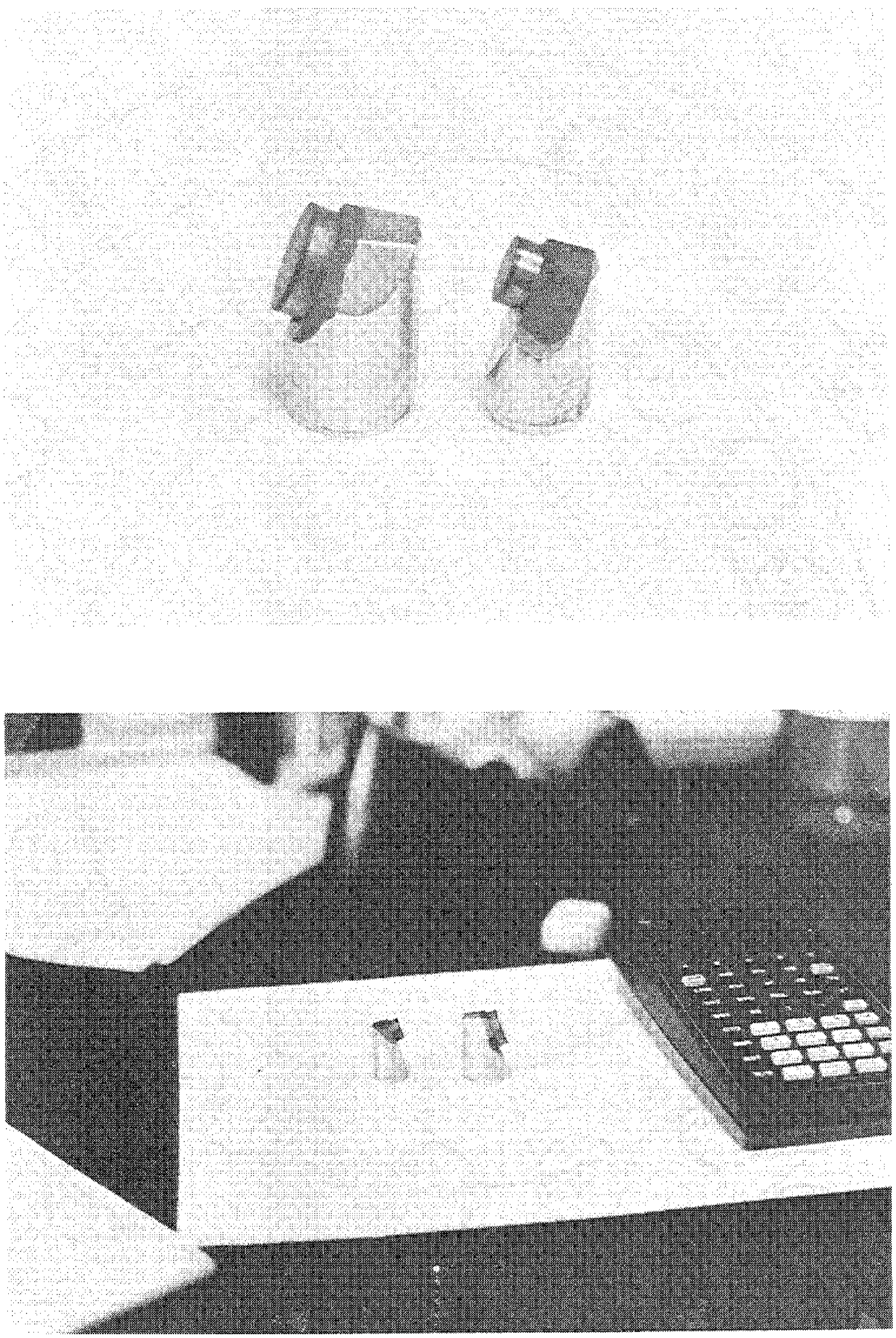


FIGURE 10
Two Comparisons of Large and Small PDC Studs

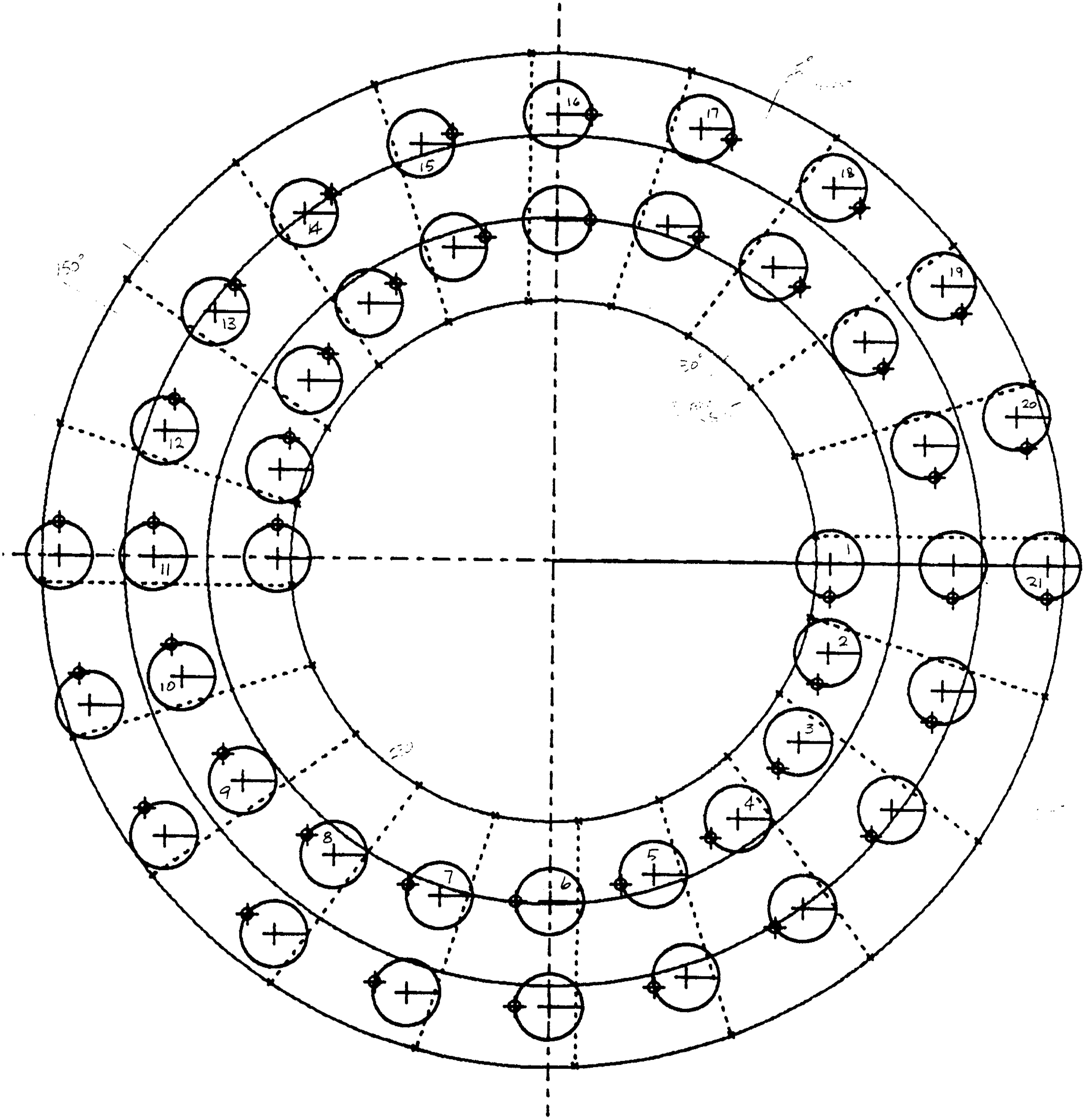


FIGURE 11
7-7/8 by 4 inch Core Bit with 21 Small PDC Cutters Per Blade

Bit No. 8 was used in a hard formation in Oklahoma. It cored 78 feet of core at 10.5 ft/hr where a conventional diamond bit cored 30 feet at 1.9 ft/hr. This is a 600 percent increase in penetration rate. The PDC cutters were still in good shape after the coring job except that one cutter was broken. (See Figure 12.)

These small PDC cutters are mounted on studs which have a base that is nearly as large as those for standard size cutters. These large bases limit the number of cutters which can be placed on a bit and DOWDCO believes that the cutting ability of a bit with small PDC cutters can be improved by using studs with small bases. This concept will soon be tested.

Bit No. 9

PDC Bit No. 9 was a $6\frac{1}{4}$ inch full-face drill bit which showed remarkable success. The bit was used three times to finish the lower portion of three wells. The drilling depth ranged from 6,000 to 8,000 feet in limey formations near Laredo, Texas. It drilled a total of 5,949 feet and averaged 33 ft/hr. The new bit is shown in Figure No. 13 and Figure No. 14 shows the same bit after being used in the three wells.

Bit No. 10

This PDC bit was a 7-7/8 inch full-face drill bit. It was built similar to the prevously described $6\frac{1}{4}$ inch Bit No. 9 which was highly successful. Bit No. 10 was tested in the Austin Chalk formation near Bryan, Texas where other PDC bits have shown poor results. Unfortunately, the rig operations limited rotary speed to about 40 RPM and mud pump rate was only 130 GPM. These are not optimum values yet the bit drilled 448 feet at 18 ft/hr and was reportedly "like new" when it was pulled from the well. The operator kept the bit for use in a future well.

Bit No. 11

This was a $6\frac{1}{2}$ inch full-face drill bit with small PDC cutting elements. The design layout is shown in Figure 15. It was used in an Oklahoma well where the roller cone bits had drilled an undergauge hole. Unfortunately, the PDC bit was used to ream about 2,000 feet of the hole and had "lost gauge" when it had reamed to bottom. It was used for a short interval and reportedly performed well but had to be removed. The bit was returned to DOWDCO but could not be repaired.

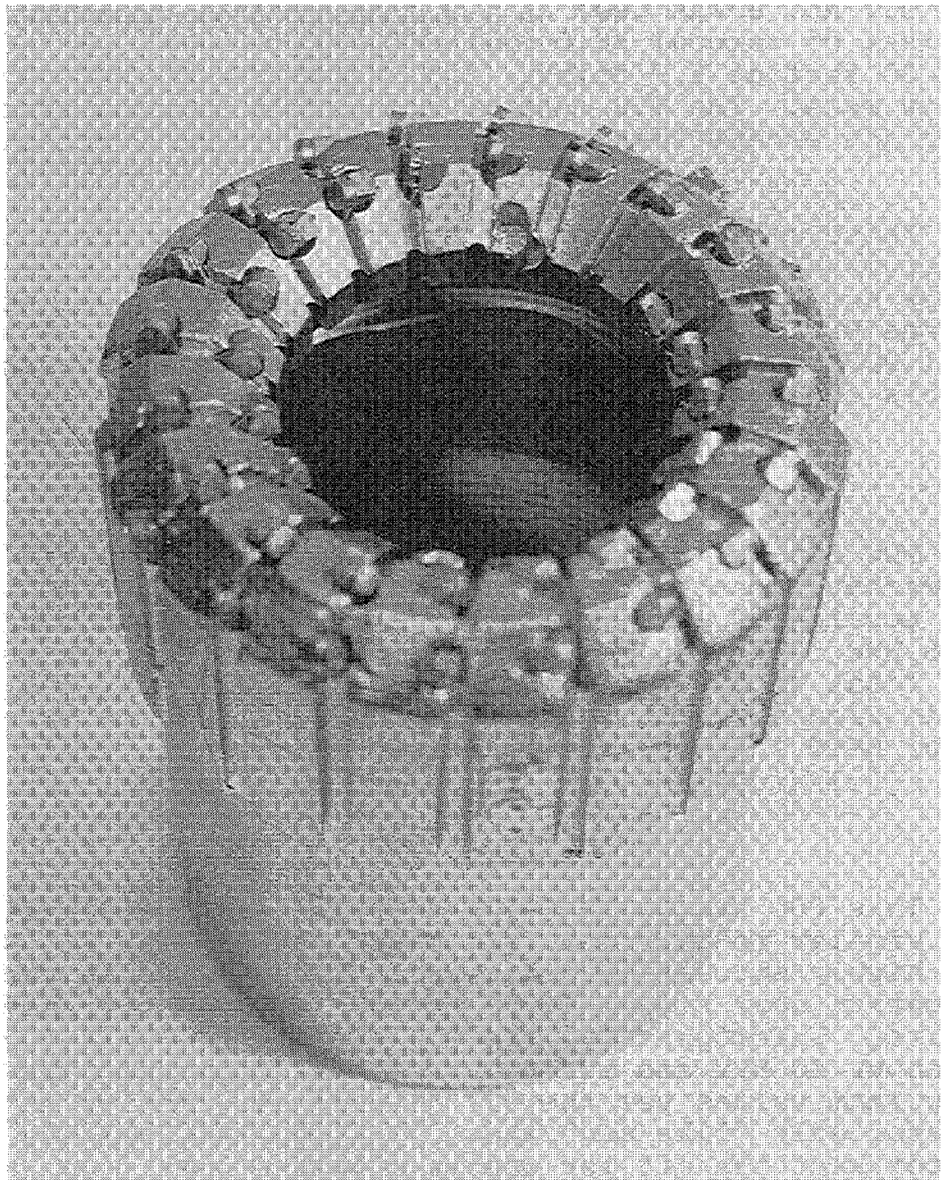


FIGURE 12
7-7/8 by 4 inch Bit with Small PDC Cutters
Cored at 10.5 ft/hr

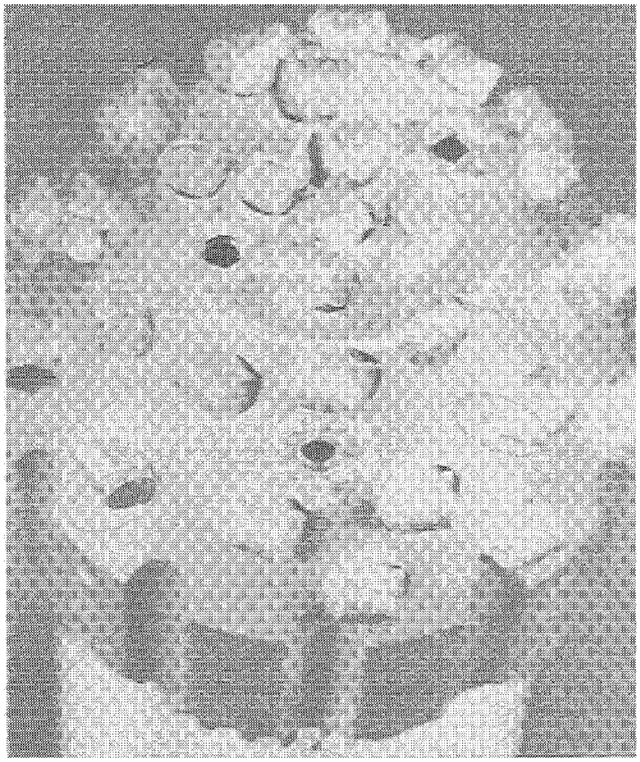


FIGURE 13
New $6\frac{1}{4}$ PDC Bit

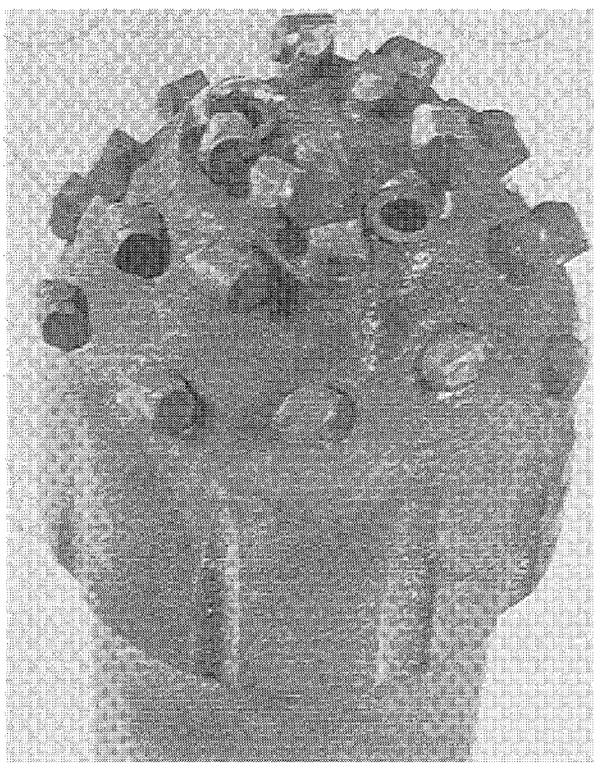


FIGURE 14
Bit in Figure 13
After Drilling 5,949 Feet, Averaging 33 ft/hr

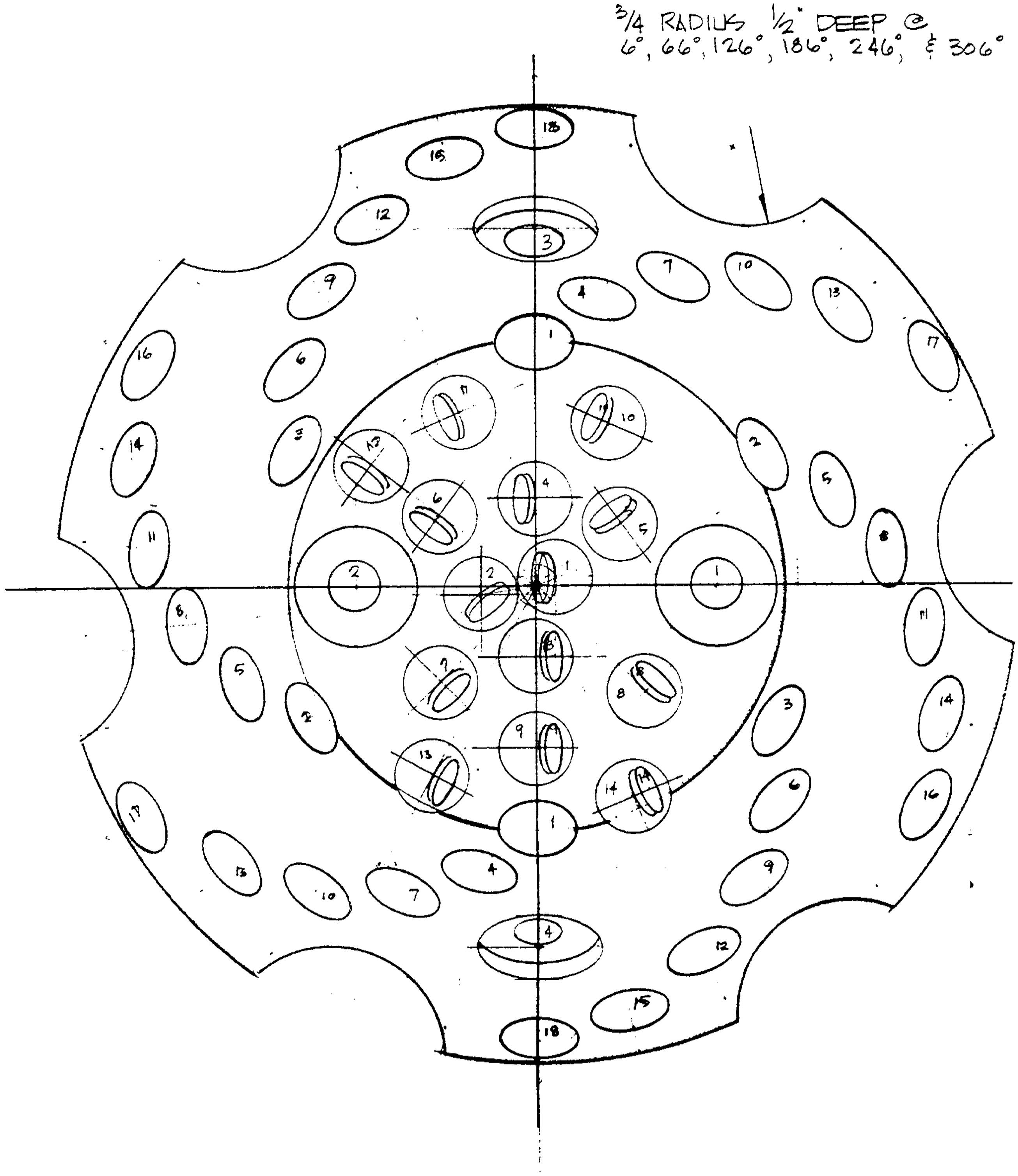


FIGURE 15
Design Layout for 6½ Inch Bit No. 11

Bit No. 12

This was a full-face, 7-7/8 inch PDC drill bit which DOWDCO built for a special application. It was a bit designed for the purpose of "side-tracking" a hole. It was used with a mud turbine and a bent sub to change the direction of a hole. However, as with Bit No. 7, the DOE Technical Project Officer adjudged that this work did not comply with the intent of the contract (to develop technology for drilling hard formations) and the results of the testing are not included. An interested reader should contact DOWDCO concerning this work.

Bit No. 13

This bit was an improved version of Bit No. 12, a side-track bit. Bit No. 12 apparently suffered some broken studs and DOWDCO embedded the studs deeper in the matrix for Bit No. 13. However, this work did not comply with the DOE contract and specific information is not given in this report.

Bit No. 14

The Department of Energy Fossil Energy Division performed some experimental research through its Western Gas Sands Project (WGSP). This work is entitled the "Multiwell Experiment" (MWX). It consisted of an extensive logging and coring program to study the characteristics of the Mesaverde formation in Garfield County near Rifle, Colorado. Both the WGSP and Drilling Technology Project are monitored for DOE by the Bartlesville Energy Technology Center (BETC). Since the Mesaverde formation is considered hard drilling, the MWX project provided an excellent opportunity for a coordinating effort between the projects. Further, the MWX wells were to be drilled using oil base drilling mud which causes slower drilling and coring. Experimental Bits No. 14, 15 and 16 were designed and used in this environment. This was an opportunity to determine whether PDC core bits can drill these formations faster and more economically than conventional diamond bits.

Bit No. 14 was an 8-3/4 by 4 inch core bit using the small PDC cutters tested in Bit No. 8. It is shown in Figure 16. These cutters still had the large bases discussed earlier and the bit had to be built with a minimal number of cutting surfaces, yet it provided a satisfactory penetration rate. This bit can be compared to Bit No. 15 which is shown in Figure 17. The amount of cutting surface is noticeably less.

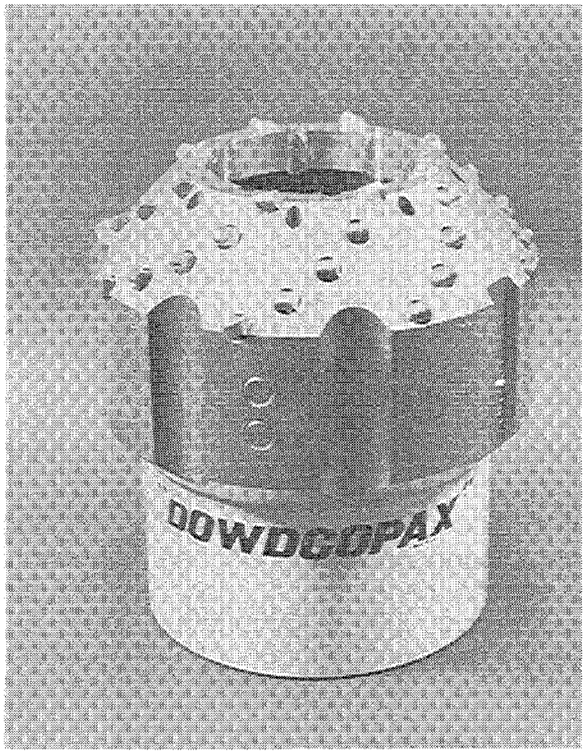


FIGURE 16
8-3/4 by 4 inch Core Bit with Small PDC Cutters

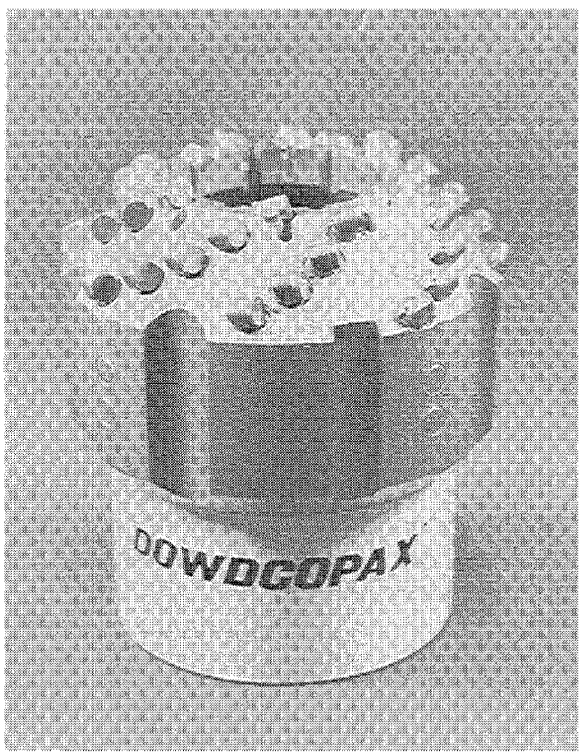


FIGURE 17
Same Size Bit as Figure 16 With
Standard Size PDC Cutters

A conventional diamond core bit (not DOWDCO's) was used first in MWX Well No. 1. It cored at a rate of 3 ft/hr. Bit No. 14 was then run and it cored at an average rate of 20 ft/hr. Bit No. 14 cored 180 feet before being sent to the shop for replacement of five worn PDC cutters. After being repaired, Bit No. 14 was used as a back up because Bit No. 15 and an identical bit were providing excellent performance and the large cutters gave longer service.

Bit No. 15

This was an 8-3/4 inch by 4 inch core bit similar to Bit No. 14 except that it was built with standard size PDC cutters. It is shown in Figure 17. This bit performed so well that the DOE Contractor, CER Corporation, purchased a second bit of the exact design and these two bits were used throughout the coring operation. These two bits were repaired once each by replacing four to six PDC cutters and returned for additional coring.

These bits averaged coring rates which were 252 percent faster than conventional diamond bits and cut 2,160 feet of core. This is considered to be exceptional performance. Also, these bits were repaired and used again in MWX Well No. 2 where they cored an additional 887 feet averaging 8.3 ft/hr.

Copies of 39 coring reports are in the DOE Monthly Reports but are too numerous to include in this report. A summary of these data is presented in Table No. 2. The PDC core bits always showed faster drill rates than conventional diamond core bits used in this well or on nearby wells. It is believed that this record shows considerable improvement in the state-of-the-art for PDC bits which was the objective of the DOE contract.

TABLE NO. 2
CORING RECORD FOR MWX NO. 1
8-3/4 BY 4 INCH CORE BITS

Core #	Depth From	Depth To	Depth Cored Per Record	Hours Coring	Avg. Drill Rate Ft/Hr
1	4,405	4,465	60	3	20
2	4,465	4,525	60	3.1	19.35
3	4,525	4,585	60	4.41	13.6
4	4,585	4,645	60	3.2	18.75
5	4,645	4,705	60	4.00	15.00
6	4,702	4,762	60	8.36	7.17
7	4,762	4,822	60	8.28	7.24
8	4,822	4,882	60	7.3	8.22
9	4,882	4,942	60	3	20.00
10	4,942	5,002	60	7.57	7.9
11	5,002	5,062	60	5.55	10.81
12	5,062	5,120	58	8	7.5
*13	5,120	5,180	60	12.25	4.89
*14	5,180	5,204	24	10.75	2.23
15	5,204	5,264	60	3.5	17.17
16	5,264	5,324	60	8.43	7.14
17	5,324	5,384	60	6.5	9.23
18	5,384	5,444	60	8.38	7.15
**19	5,424	5,484	60	10	6.00
**20	5,484	5,534	50	8	7.5
21	5,534	5,592	58	9.91	5.85
22	5,592	5,652	60	14.2	4.22
23	5,652	5,712	60	16.49	4.14
24	5,712	5,772	60	4.66	12.87
25	5,772	5,825	53	14.03	8.41
26	5,825	5,885	60	5.34	11.23
27	5,885	5,933	48	6.68	7.17
28	5,933	5,993	60	6.41	9.36
29	5,993	6,054	60	10.75	5.58
30	6,054	6,114	60	4.88	12.29
31	6,114	6,119	5	1.26	4.76
32	6,119	6,168	49	8	6.3
33	6,168	6,258	90	10.25	8.78
34	6,258	6,348	90	11.5	5.2
35	6,348	6,438	90	14.8	6.08
36	6,438	6,528	90	13.26	6.78
37	6,528	6,618	90	21.5	4.18
38	6,618	6,689	70	17	4.11
*39	6,689	6,779	90	22	4.0

Average drill rate for PDC core bits 9.33 ft/hr
Average drill rate for diamond core bits 3.70
Average improvement of PDC bit 252%

*Indicates where conventional core bits were used.
**Indicates where oriented cores were taken and depth correction.

Bit No. 16

After the excellent performance of the PDC core bits in MWX No. 1, it was decided to test a full face PDC bit versus roller cone bits. Bit No. 16 was designed, built and donated to the MWX experiment. It is an 8-3/4 inch bit and is shown in Figure No. 18.

Bit No. 16 was run below the extended coring operation. It drilled 1,100 feet in 126 hours, averaging 8.7 ft/hr. For comparison, it was immediately followed by a roller cone bit which drilled 24 feet at an average rate of 3 ft/hr. Coring was then resumed for 90 feet.

After the core was taken, Bit No. 16 was rerun in the hole and drilled only 24 feet before it quit drilling. An extremely hard section had been encountered and six PDC studs were broken from the bit's nose. A J-33 roller cone bit was run which averaged 2 ft/hr indicating the very hard formation.

Bit No. 16 gave excellent performance in the firm to hard formations and its design may be optimum for these type formations. However, this bit has a sharply rounded nose and the PDC stud breakage may indicate that this design will not tolerate streaks of ultra-hard formation. After the early success of this bit, DOWDCO built a duplicate and tested it in the deep Anadarko Basin where it also suffered broken nose cutters.

Bit No. 17

This was an 8-3/4 inch full-face PDC bit which was built for MWX Well No. 2. The bit was expected to drill in medium hard rock but encountered hard drilling. It drilled 125 feet at 6 ft/hr. Once again the nose cutters were broken.

Bit No. 18

Another 8-3/4 inch full-face bit was tested in the MWX Well No. 2. It was used three times at three different depths and drilled a total of 438 feet averaging 5.4 ft/hr. This compared with a diamond bit which drilled in two similar intervals at rates of 2.1 and 2.4 ft/hr. The bit can also be compared with two roller cone bits which drilled at the same depths. A J-33 bit drilled at 4.0 ft/hr and an S-33 drilled at 3.2 ft/hr.

FIGURE 18
8-3/4 inch PDC Drill Bit for MWX No. 1

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