Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DURABILITY IMPROVEMENT AND MANUFACTURING COST REDUCTION OF POLYCRYSTALLINE DIAMOND COMPACT BITS FOR GEOTHERMAL WELL DRILLING

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Key Words: drilling, geothermal well, PDC bit, durability test, cost reduction

ABSTRACT

The objective of this research was to develop polycrystalline diamond compact (PDC) bits for deep geothermal well drilling, focusing on long bit life and high cost-performance. Laboratory drilling and durability tests have been conducted using 142.88 mm-dia (5-5/8 in.) PDC full-face bits. During early stages of this work, the durability of 142.88 mm-dia bit was only 10 m (33.3 ft) when drilling hard and abrasive granite. Finally, the life of the 142.88 mm-dia bit reached 40 m (133 ft) when drilling granite. Performance improvements were due to several factors, such as selection of adequate PDC cutters, arrangement of PDC cutters on the bit face, and the number of PDC cutters mounted on the bit.

To reduce manufacturing cost of the PDC bit, two kinds of new PDC cutters were developed. Cross sections of these cutters are fan shaped and horse's foot shaped respectively. The amount of PDC material used for these cutters is less than that of normal PDC cutters, for which cross-sections are circular. Series of three types of PDC bits, core bits of 66 mm-dia (2.6 in.) and full-face bits of 66 mm-dia and 142.88 mm-dia,, have been manufactured with these new cutters. Through a series of laboratory drilling tests with these bits, it has become clear that manufacturing costs of these bits would be expected to decrease without affecting their durability.

1. INTRODUCTION

The thermal stability of roller cone bits is relatively low. Bit-lives often decrease considerably when drilling geothermal wells with formation temperatures above 350-deg C. On the other hand, the application of PDC bits for geothermal well drilling is limited due to insufficient cutter strength, even though they have sufficient thermal stability (up to 700-deg C). However, the application of PDC bits for drilling oil wells is widespread. It has been determined that the durability and cost performance of PDC bits is excellent, compared to conventional three-cone bits, for formations consisting of soft and medium rock with limited fractures and fissures.

We have conducted laboratory drilling and durability tests to develop PDC full-face bits for geothermal well drilling (Karasawa and Ohno, 1995, Karasawa et al., 1996), and the following data have been obtained.

- Full face PDC bits with different face forms, such as concave, convex, and flat, have been made and their stability examined revealing that their concavity stability and durability exceeds bits with flat and convex styles
- Cutting forces are minimized at a rake angle of -10-deg within -10 to -40-deg, and back rake and side rake angles of -10-deg provide the optimum penetration rate.
- The influence of PDC cutter size for drillability has been examined within range from 5.5 mm-dia to 13.2 mm-dia. Generally, the smaller cutter has better drilling stability at high rotation speed, but the larger cutter has better drill performance. Cutter damage of larger cutters are less than that of smaller cutters and the rate of penetration of large cutters are higher than that of smaller cutters.

This report presents the results of the indoor drilling experiments aiming toward the further improvement of durability and manufacturing cost reduction of the PDC bits.

2. DRILLING TEST MACHINE AND TEST PROCEDURE

2.1 Test Machine and Procedure

A drilling test machine was used for development and evaluation of full face PDC bits. The maximum bit load, torque, and rotation speed of the machine are 300 kN, 3 kN-m, 500 rpm respectively. Fresh water was normally used as circulation fluid.

Rock samples for all tests consisted of Sori granite with a uni-axial compressive strength range of 145-162 MPa. Because of sample size restrictions (up to 50 x 50 x 80cm (W x D x H)), the units continuous drilling length was only about 70 cm. Therefore, durability tests were conducted while cycling the units continuous drilling capability.

During the test, the bit load was maintained at a constant penetration rate of 2 cm/min, with a rotation speed of 100 rpm and a fluid circulation rate of 110 l/min. The bit load was gradually increased until a constant penetration rate of 2 cm/min could not be maintained, even though a large bit load was applied. We considered the time when the penetration rate decreased below the value of 2 cm/min as the life of bit tested.

Based on previous experiments, PDC cutters of 8.2 mm-dia were selected to make the bits used for the durability and manufacturing cost reduction test for the PDC bit. Full-face bits of 142.88 mm-dia were used for durability tests. The general specifications of these bits are presented in Table 1.

2.2 A Preliminary Test

Before starting the test, initial durability improvements and cost reductions were made regarding PDC bits. The fundamental drilling test was conducted with our most recently manufactured full PDC bit.

The bit was 142.88 mm in diameter and had 75 PDC cutters of 6.6 mm-dia. mounted on the bit face. We made this bit to evaluate effects of cutter diameter on drillability. Specifications of the bit are shown as No.1 in Table 1. The data obtained from this bit are shown in Figure 2. A constant rotation speed of 200 rpm was used, which was different from drilling conditions of other bits listed in Table 2. It is obvious that the bit weight showed a steep rise early in the test, and that the value exceeded 110 kN when the drilled length reached 10 meters. At the same time, the penetration rate of this bit could not maintain the constant rate of 2 cm/min, therefore, we considered the bit had reached its life.

The following became clear from the observation of the bit after the durability test. During the test, the wear of the cutters increased rapidly and many wear spots on the cutters, set around the nose and on the gage, were observed after 10 meters of drilling. From the results of the test, it became clear that the bit design must be improved and PDC cutters with higher strength are necessary to improve the bit performance significantly for hard rock drilling.

3. EXPERIMENTAL RESULTS AND DISCUSSION OF DURABILITY IMPROVEMTNS FOR PDC BITS

3.1 Performance of Polished PDC Cutter

It is well known that polishing the face of a PDC cutter is one method used to improve the cutter strength. Bit No. 2 in Table 1 was redesigned and fabricated using polished cutters.

The main improvements of this bit were:

- Polished PDC cutters instead of conventional PDC cutters used.
- The increase and rearrangement of an additional six cutters set around the nose.
- A change in the configuration of the bit body (increase of the radius of the nose).

The durability of this bit was evaluated at constant rotation speed of 100 rpm using the Sori granite. Performance of bit No. 2 is presented in Figure 3. Bit weight was increased rather moderately compared to that of bit No.1 (Figure 2) and exceeded 100 kN when the length drilled reached 17m. It is obvious that bit No. 2 performed better, with respect to the length drilled and the penetration per revolution at the end of testing, as compared to bit No. 1. After the tests, considerable wear spotting, on the cutters set around the nose, was observed. The performance of the 142.88 mm-dia bit was improved with applications of polished PDC cutters, but there was room for improvement with respect to the arrangement of cutters and the number of cutters set on the bit body.

3.2 Effect of PDC Cutter Numbers Mounted on The Bit Body

Based on the result of the examination of the polished PDC cutter, the design of the bit was improved to increase the number of cutters. Figure 4 compares the arrangement of PDC cutters to (a) bit No.2 and (b) the newly manufactured bit No.3 (Table1). Ninty-one cutters were used for bit No.3, an increase of 35 % when compared to bit No.2. The surface area for cutters on new bit No.3 was enlarged by increasing the curvature of the bit-face. This allowed us to mount additional cutters. The number of cutters used in one array on the outside of the bit face was increased from 8 to 10. The cutter number increase on the bit may facilitate a weight decrease on each cutter resulting in less abrasion and damage to the cutters.
Throughout the drilling tests of the PDC bits, we observed that severe abrasion occurred on cutters at the bit nose. Therefore, we increased the array of cutters on the bit nose from previous single array of bit No.2 (Figure 5-a) to two arrays for bit No.3 (Figure 5-b). The intention of this change was to decrease the stress concentration applied to cutters at the nose of the bit during the rock drilling.

Figure 6 shows the performance of the bit. Bit weight was raised gradually with respect to the length drilled and the rate of penetration was almost constant at 2 cm/min. The total drilled length, which relates to bit life, reached about 26 m, and bit weight at the end of the test was 120 kN.

After durability test, a careful observation of cutter wear was conducted. No wear was seen at the bit center. The wear was observed at nose and on the gauge of the bit, but it was not severe compared to bit No.2, as described above. The increase and rearrangement of cutters achieved a significant improvement in the bit's durability. Even though the bit performed well, two of ten cutters at the gauge of the bit dropped out during the drill test, which might have the effected the results.

3.3 Examination of Newly Developed PDC Cutters

As a result of our tests, it became clear that the performance of the PDC bit is affected greatly by the arrangement and number of PDC cutters. The quality of cutter itself is also very important for good performance. Several years ago, we examined on characteristics of several kinds of cutters and selected a desirable type for the bit. Because technical innovation is very rapid, we decided to re-examine the performance of PDC cutters themselves.

Two full-face 66 mm-dia bits were manufactured using the current and newly developed cutters. Drilling tests using these bits on the Sroi granite were conducted using a constant penetration rate of 2 cm/min. During the tests, the load on the later showed a lower value as compared to that of the former bit at the same drill length.

Photographs of both bits after the drilling experiment are shown in Figure 7. 7(a) shows the bit with current PDC cutters and 7(b) shows the bit with newly developed PDC cutters. The degree of wear on the newly developed cutters appears to be less than that of current cutters.

A 142.88 mm-dia bit was then developed with new cutters. Its specifications are shown as bit No.4 in Table 1. 98 cutters of 8.2 mm-dia were installed on this bit. The number of cutters at nose and gauge of bit was increased compared to bit No.3. Figure 8 shows the performance of durability tests using this bit. As can be seen in the figure, the length drilled with the bit reached about 40 m before the bit weight exceeded 140 kN, while maintaining the constant penetration rate of about 2 cm/min (1.2 m/h).

We believe that increasing the number of cutters has led to sufficient durability improvements on the PDC bit. Each load subjected on individual PDC cutters may be decreased to some extent compared to that of previous bit with fewer PDC cutters. To effectively drill hard and abrasive rocks with PDC cutters, an adequate force on each cutter must exist, therefore, we would like to continue investigation on the proper relation between the number of PDC cutters set on the bit body and the bit life.

4. AN ATTEMPT TO DECREASE THE MANUFACTURING COST OF THE PDC BIT

4.1 Drilling Cost Comparison of Old and New PDC Bits

As described above, increasing the number of PDC cutters and revising their arrangement has prolonged the life of PDC bits. However, increasing the number of PDC cutters resulted in a rise in bit cost. The cost of PDC cutters occupies a significant part of bit manufacturing costs. Therefore, we examined methods to reduce the manufacturing cost of PDC bit.

We have manufactured 4 PDC bits of 142.88 mm-dia. (Table 1), and manufacturing costs of later bit is rather high compared to previous one, because the later one uses many more PDC cutters. The price of these bits ranges between about 1.8 and 3.0 million yen. On the other hand, the durability of these bits has been improved year after year. The simple drilling cost of a PDC bit was calculated by dividing the bit manufacturing cost by the distance excavated by the bit in Sori Granite, as observed in the laboratory experiments.

Table 2 shows that the drilling cost decreases with an increase of bit life. However, the manufacturing cost of the PDC bit is extremely high in comparison with that of a diamond bit or a three cone bit, even if one takes into consideration the improvement of bit life in the future.

Furthermore, we examined the shape design of the PDC cutter in order to cut down the bit cost. The price of PDC cutter occupies large portion of the manufacturing cost of PDC bit, therefore, the price reduction of PDC cutter itself will bring about the reduced production cost of PDC bit.

4.2 Details of Shape Designs of New PDC Cutters

After finishing the drilling test for the PDC bit, we observed the PDC cutters carefully. When the bit itself reached its life, only a few tips of the cutters were worn. Most PDC cutters were not damaged severely and still looked useable. Therefore, it is thought that bit cost can be reduced by attaching PDC cutters only as necessary for drilling.

We made two kinds of PDC cutters with different shapes shown in Figure 9 (a) a fan-shaped cutter which uses only 1/3 of a circular PDC cutter and Figure 9 (b) shows a semicircular cutter corresponding to 2/3 diameter of circular unit. Both of these two cutters are attached at the direct contact point between the bit and the rock during drilling. The cost of the two kinds of cutters are about 1/3 and 1/2 of the circular cutter respectively.

4.3 Test for Core Bit Using The New Designed Cutter

With the new design, the durability of the cutters can decrease, since the portion welded at the bit body is small compared with the circular cutters. We manufactured a small core bit of 66.0 mm outside diameter and 44.8 mm inside diameter for the durability estimation of new shaped cutters. Figure 10 shows the structure of the bit. Eight fan-shaped cutters were used for this bit.

The results, when drilling granite with this bit, are shown in Figure 11. Since the outside wear of cutters increased, the bit had drilled about 13m of granite when the test was stopped.

Figure 12 shows a photograph of the bit after the test. Although wear was observed on the cutters outside at the edge of the bit, wear of the inside cutters was small and they maintained their original condition. However, a durability of only 10 m recorded for the fan-shaped cutter as compared with 26 m for Bit No. 3 (Table 1) which used the circular cutters. The strength of the fan-shaped cutter is considered to be insufficient compared with the strength of the circular unit.

4.4 Test for Small Diameter Full-Face Bit Using The New Cutter

Next, a PDC full-face bit of 66mm-dia. was manufactured. 18 newly designed cutters, 7 semicircular and 11 fan-shaped, were used for this bit. 6 semicircular cutters were positioned at edge, and one was used at the center of the bit. Figure 13 shows the cutter array.

The durability test results, again using Sori Granite, for the bit is shown in Figure 14. The life of the bit was about 50 m.

Figure 15 shows the damage to the cutters when the test was finished. It was observed that some fan-shaped cutters on the second and third rows from the outside had dropped out. However, wear of the fan-shaped cutter used at the center of the bit was minimal, and did not have drop out. On the other hand, the semicircular cutters at the outside of the bit did not drop out in spite of having been worn to the same degree as the fan-shaped cutters. The reason why this bit reached its life was considered to be the result of bit weight increase and dropping out of the cutters in second and third rows. Therefore, it is recommended that the fan-shaped cutter be used where stress acting on the cutter is small.

The results from the durability test this PDC full-face bit indicates that the semicircular cutter brought about a cost reduction without loss of the bit's performances. Moreover, the fan-shaped cutter also can be used after taking its proper placement into consideration.

4.5 Application of New Designed Cutters

Based on the result of above test, we manufactured a PDC full-face bit with a diameter of 142.88 mm in which the semicircular cutters were attached. This is the same full-face bit, Bit No. 4 in Table 1, discussed above. Ninety-eight cutters were installed on this bit (74 semicircular cutters and 24 circular cutters). The circular cutters were used for a line on the edge of the bit, and two lines on the nose. This was due to the severe cutter damage observed on these lines compared with other placements of cutters through the series of previous drilling tests.

By using the semicircular cutter for 3/4 of the whole cutters, the cost of this bit is reduced by 2/3 compared with the case where only circular cutters are used.

Figure 16 shows the cutter damage on this bit after the durability test. The damage was not as severe, although wear to some extent occurred on the cutter at nose or gauge part. This means there is minimal effect to the durability of the bit when we use semicircular cutter instead of the circular cutter.

It is obvious that the simple drilling cost of bit No. 4 (Table 2), which used the semicircular cutter, is greatly improved. These test results and data evaluations indicate that reduced drilling cost can be attained by using new shapes for PDC cutters without reducing durability of the bit.

5 CONCLUSIONS

We have developed the PDC full-face bit, for drilling geothermal wells, with excellent cost performance, improvement of a bit life, and a reduction in bit manufacture cost.

As for the durability improvement testing for hard rock drilling, the PDC full-face bits with a diameter of 142.88 mm, using PDC cutters with a diameter of 8.2 mm, were manufactured. Laboratory durability revealed that the latest design gave a bit life of about 40 m in hard and abrasive granite. In addition, it has become clear that the bit must be improved with respect to the arrangement of cutters and the number of cutters set on the bit body in the case of hard rock drilling such as in Sori granite.

As for the reduction of bit manufacture cost, efficiency of the PDC cutter itself was examined by changing shape design. Two kinds of PDC cutters, fan-shaped and semicircular, were developed. The PDC bits using these new shaped cutters were manufactured and investigated for durability. Test results showed that the durability of the semicircular cutter is almost the same as the circular cutter. A few problems still remain regarding the durability of the fan-shaped cutter. The manufacturing cost can be cut down to 2/3 of our previous PDC bit by using the new shaped cutter properly, without decreasing the durability of the bit.

6 REFERENCES

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Karasawa, H., Ohno, T., and Kobayashi, H. (1997). Research on Drilling Techniques for Deep Geothermal Wells. Proc. of NEDO International Geothermal Symposium, p. 187-191.

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Figure 1. An example of 142.88 mm dia. PDC Full-Face bit.

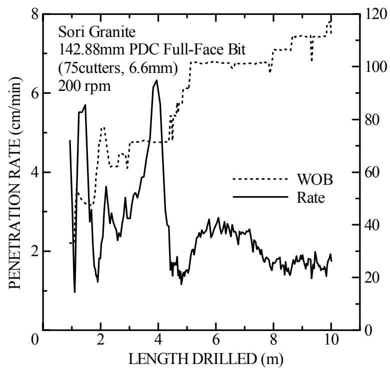


Figure 2. Results of durability test using bit No. 1 in Table 1. The bit life in early stage of development was about 10 m.

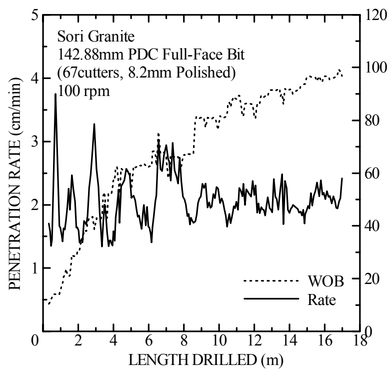
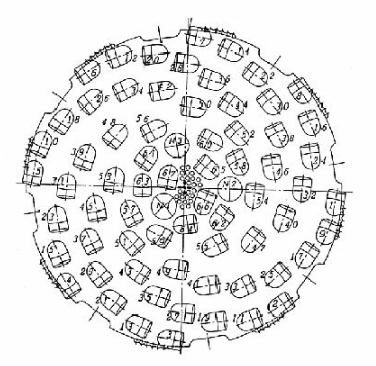
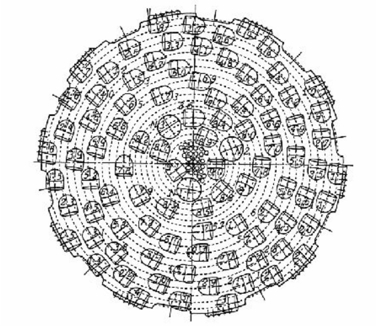


Figure 3. Results of durability tests using bit No. 2 in Table 1. By using polished cutter, bit life was improving to 17 m.

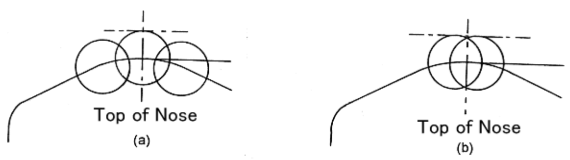


(a) Bit No. 2 in Table 1 (67 cutters)



(b) Bit No. 3 in Table 1 (91 cutters)

Figure 4. The cutter array of PDC full-face bits. The number of cutters at the bit edge was increased from 8 to 10, and the rows of cutters increased by changing the curvature of the surface of the bit.



(a) Bit No. 2 in Table 1 (b) Bit No. 3 in Table 1

Figure 5. The array of cutters at bit nose was increased from previous 1 to new 2. This change was intended to decrease the stress concentration applied to cutters at nose of the bit.

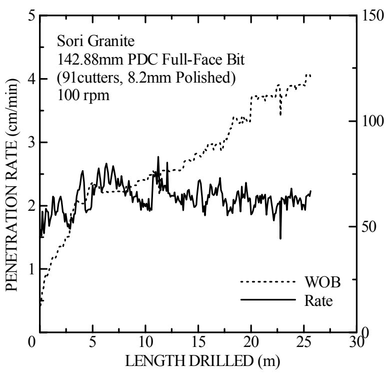
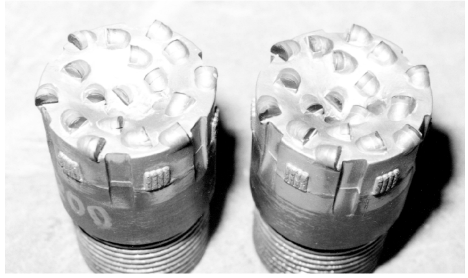


Figure 6. Results of durability tests using bit No. 3 in Table 1. By the arrangement of cutters and the increase of cutters, the bit life extended to 26 m.



(a) The conventional cutter bit (b) The new cutter bit

Figure 7. The 66 mm-dia PDC Full-Face Bit after the durability tests.

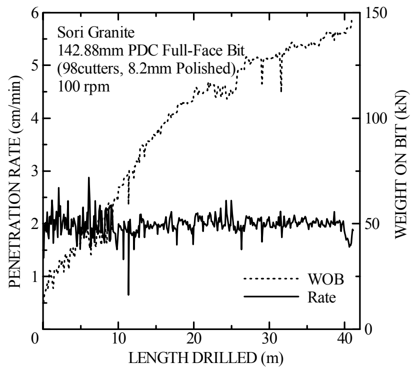
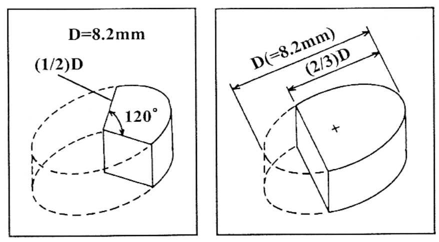


Figure 8. Results of durability test using bit No.4 in Table 1. By using new cutter of high durability compared previous one, the bit life improved up to 40 m.



(a) The fan-shaped cutter (b) The semicircular cutter

Figure 9. Two kinds of new shaped cutters.

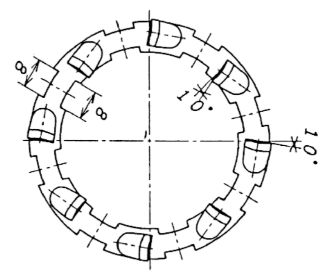


Figure 10. The Cutter arrangement of small diameter (66.0 mm in the outside dia. and 44.8 mm in the inside dia.) PDC core bit using 8 fan-shaped cutters. (Bit No. 1 in Table 3).

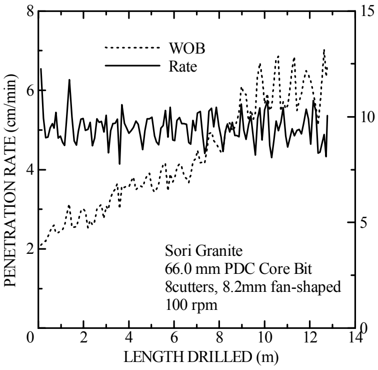


Figure 11. Results of durability test using bit No. 1 in Table 3. The bit life was reached only 13 m.

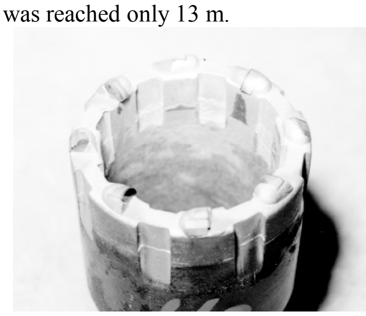


Figure 12. PDC core bit (bit No. 1 in Table 3) after the durability test. Although large amount of wear was observed at the outside cutters, wear on inside cutters was small.

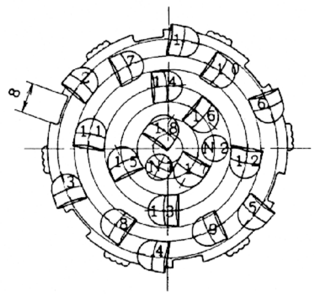


Figure 13. The Cutter arrangement of small diameter (66.0 mm) PDC full-face bit (Bit No. 1 in Table 3). This bit uses 18 PDC cutters, 7 semicircular cutters and 11 fan-shaped cutters. Cutters No. 1 to 6, and No. 18 are semicircular.

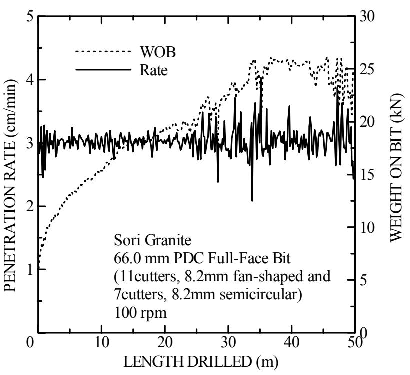


Figure 14. Results of durability test using 66 mm dia. PDC full-face bit (bit No. 2 in Table 3). The bit life extended to about 50 m.

Figure 15. PDC full-face bit (bit No. 2 in Table 3) after the durability test. The fan-shaped cutters on second rows and third rows from the outer side dropped out, but the semicircular cutter at the edge did not dropped out.

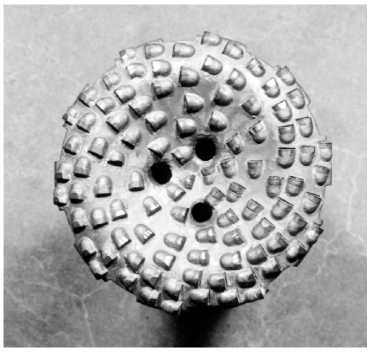


Figure 16. 142.88 mm dia. PDC full-face bit (bit No. 3 in Table 3, same as bit No. 4 in Table 1) after the durability test of 40 m drilling. Bright parts of the cutter are worn out area. There are many worn out cutters at the edge and nose.

Table 1. Description of 142.88 mm dia. PDC full-face bits.

Bit No.	Bit Dia.(mm)	Cutter Dia.(mm)	No. of Cutters	Rake Angles(deg.)
1	142.88	6.6	75	-10
2	142.88	8.2	67	-10
3	142.88	8.2	91	-10
4	142.88	8.2	98	-10

Table 2. Cost analysis of 142.88 mm dia. PDC full-face bits.

Bit No.	Bit-life (m)	Simple Cost ($/ft)	Notes
1	10	333	(Fig. 2)
2	17	227	(Fig. 3)
3	26	182	(Fig. 6)
4	40	83	(Fig. 8)

Table 3. Description of PDC bits using new designed cutters.

No.	Bit Type	Fan-shaped	Semi circular	Circular	Total
1	66 mm dia. core	8			8
2	66 mm dia. full-face	11	7		18
3	142.88 mm dia. full-face		74	24	98