

# Laboratory drill rig for PDC bearing and cutter development

*Correlation of accelerated laboratory testing to actual field performance is essential in successful development of polycrystalline diamond cutters (PDCs) and diamond bearing elements for down-hole applications. A laboratory scale drill rig apparatus for the investigation of diamond bearing and drag bit cutter performance has recently been completed. The laboratory scale test rig is capable of producing rotary speeds from 40 to 1500 rpm, normal forces up to 165 kN, torque up to 1900 Nm, and rates of penetration up to 67 m/hr. Drilling tests to evaluate PDC cutters can be conducted using a controlled normal force or controlled rate of penetration. Test methods have been developed to enable accurate comparisons of PDC inserts to be made, typically in one day or less. PDC bit testing shows that we can clearly differentiate cutting efficiency and wear rates based upon changes in the material properties of the PDC inserts. The test rig can also be utilised to measure wear rates and frictional forces in diamond thrust bearings. Full scale PDC bearing experiments indicated that the bearings were capable of much higher loading than previously thought. Correlation between laboratory results and actual field performance will also be discussed. Article by J. Lund, C. Cooley, J. Gonzalez and T. Sexton.*

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The purpose of this work has been to build and deploy a new laboratory drilling machine that will accelerate the development of polycrystalline diamond cutting (PDC) elements used for drilling oil and gas wells.

Since the development of synthetic diamond by Hall the potential for drilling earthen materials with the hardest known material, diamond, has been recognised and pursued. In step with the development of PDC has been the development of laboratory test protocols that have tried to simulate actual drilling conditions and, thereby, provide a metric for gauging cutter development progress.

Through the years several types of testing protocols have been developed and used. Of course, in the end the most reliable assessment of cutter performance has to be testing the cutter on a drill bit in the actual drilling application. This brings with it attendant risks that are often not acceptable when drilling real oil and gas wells. A laboratory test method that mimics the most important dimensions of the actual drilling process continues to be valuable.

The purpose of this paper will be to demonstrate the efficacy of a reduced-scale drilling machine in predicting ultimate field performance of PDC elements. We will also briefly discuss how the same apparatus can be used to gather useful information on other components for down hole use, namely: diamond thrust bearings.

## A brief history

Through the years of PDC development laboratory testing has been used to assess performance. Various laboratory drilling analogs have been tried including lathe, vertical turret lathe, planer, and mechanical testing. [1-4]

It has been the authors' experience that each test taken alone tells us something about eventual cutter field performance, but often omits important aspects of performance that are later discovered during field testing. Through the years field performance remained the accurate and final predictor of ultimate cutter commercial success.

In an effort to obtain the most faithful simulation of drilling possible, full scale laboratory drilling test facilities have been built by TerraTek, Schlumberger, Amoco, University of Tulsa, Hughes Christensen and Reed Hycalog. Because of the scale of the equipment required to undertake this work, investigations are expensive, mostly proprietary and investigate specific topics of interest to the owners of the equipment or the contracting party. [5-9]

Results of the very first full scale experiments were given in terms of torque and weight generated at various penetrations rates in various rock types and whether or not the cutters self destructed. The goal of early testing was to check the rudiments of durability (are these cutters going to immediately self destruct?) and to determine basic performance. For example, what rate of penetration results with a given weight, rotary speed and bit design.

Endurance testing of PDC, which would require drilling long distances and consuming a vast amount of rock, appears to have been too costly and results have not been published to date to the authors' knowledge.

Full scale field test facilities have also been built. The authors know of two facilities that are available for contract use: GTI Catoosa Test Facility and the Rocky Mountain Oil Field Testing Center. Although the results would be interesting and valuable, the cost associated with contracting these facilities normally cannot be justified by PDC manufacturers for the purpose of PDC cutter performance evaluation.

Glowka [10], and Ersoy [11,12] developed reduced scale drilling equipment to look into PDC drilling endurance among other things. Glowka used his drill rig to look into the endurance of PDC as a function of distance drilled. Ersoy has used his drilling apparatus to determine the drilling parameters for optimum drilling efficiency. He has also evaluated PDC performance for longer drilling distances. PDC was compared to cemented tungsten carbide and large differences in performance were noted. Comparisons between different types or grades of PDC were not published.

**Benefits of drill rig testing**

Of the many methods used for PDC cutter testing the laboratory drill rig has several distinct features which make it a particularly interesting and useful test. Tests like the lathe wear test and vertical boring mill typically are run at a constant depth of cut and because the cutters in these tests follow a linear path across the rock or other abrasive media the depth of cut and the associated cutting force will decrease as the cutter wears. Because a constant depth of cut is maintained on the drilling machine regardless of cutter wear, forces will actually increase as wear takes place. Force that increases as a function of continued wear is a more accurate analog of a drill bit in the field.

The laboratory drill rig test also produces a cutter path that is very similar to a full scale drill bit in that the cutters are rotated in a circular path around the center of rotation of the bit. Because multiple cutters are used on the drill bit there are also cutter interactions that alter the distribution of forces acting on the individual cutters. This produces a more realistic load distribution

on the cutter which can affect the wear mechanisms acting on the cutters. In the lathe and vertical boring mill tests the cutting edge is parallel to the surface of the work piece and may not truly simulate the cutting action of a drill bit.

The lathe and vertical boring mill are designed for precision machining work and are usually manufactured to be quite stiff to reduce deflection of the cutting element. The drill rig on the other hand is significantly more compliant, which is a better representation of the downhole drilling environment, where severe vibrations and dynamic events can severely limit the life of PDC cutters.

**Design of the laboratory drill rig**

The laboratory drill rig was designed to facilitate the testing of both PDC cutters and diamond thrust bearings. A servo-hydraulic system is used to provide the thrust while an electric servo motor provides the rotary motion. Both of these systems are computer controlled, allowing the test parameters to be controlled within very close tolerances. Safety limits are built into the system to protect the machine and operator in the event of an unexpected overload. Table 1 lists the capacities of the laboratory drill rig and Fig 1 shows a photograph of the drill rig. The X and Y positions of the rock and gantry are controlled via electronic servo motors allowing accurate positioning of the drill bit/rock interface.

There are two modes of operation for PDC cutter testing. In the primary mode ROP and RPM are fixed and vertical force is varied to sustain ROP. In the secondary mode the vertical force and RPM are fixed and the resulting ROP is measured (torque limited). For PDC bearing testing the secondary mode is the preferred test method.

**PDC cutter testing**

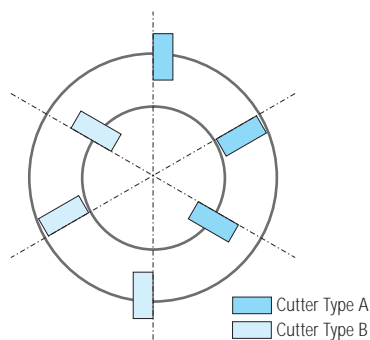
Once the drill rig was operational the next task was to determine the best way to utilise it to evaluate PDC performance. It was necessary to design and build a suitable drill bit to hold the cutters during the drill tests. Multiple bit options were evaluated and a decision was made to use a coring style bit. This was deemed to be the best option because the centre area of the bit where the cutting speed approaches zero is removed. The bits have dimensions of approximately 86 mm diameter with a core diameter

Parameter	Capacity
Max rotary power	44.7 kW
Vertical feed rate	0.3 - 67 m/hr
Stroke	1.02 m
Max vertical force	164.6 kN
Rotational speed	40 - 1500 rpm
Torque on bit	1898 N.m @ 100 rpm (14.2 kW) 879 N.m @ 500 rpm (28.3 kW) 439 N.m @ 1000 rpm (35.8 kW)
Coolant flow	83.3 l/min max flow - closed loop system
Rock size	0.91 m x 0.91 m x 0.91 m (cube)

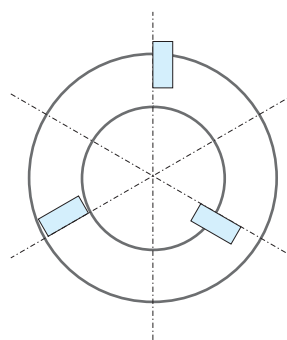
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Table 1 Drill rig capacities



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Fig 1 Photograph of laboratory drill rig



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Fig 2 Cutter locations on 6-cutter core bit



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Fig 3 Cutter locations for 3-cutter core bit

of approximately 48 mm and are manufactured using tungsten carbide matrix. The bits were designed with a flat cutting profile. The first bit style was designed with 6 - 16 mm cutters placing the cutters in two groups of 3 at redundant radial positions as shown in Fig 2. In each group of three the cutters were placed so that one would cut the outside gage diameter (OD), one would cut the inside gage diameter (ID) and the third was placed in-between the two. This style of bit allows direct comparison of two cutter types in a single drilling test, eliminating the effects of variance in the testing procedures.

The second bit style was designed with 3-16 mm cutters placing one cutter to cut the OD gage, a second cutter to cut the ID gage and a third cutter positioned between the other two as shown in Fig 3. This type of bit is useful for making performance measurements on one type of cutter.

All of the cutters on both bit styles were set at 15° backrake with 5° of side rake. Prior to testing all cutters were brazed into the bit body and the vertical height of each cutter was measured. The maximum acceptable variation in cutter height was set at 0.127 mm to limit the amount of variation between tests. If one or more of the cutters were out of tolerance the cutter(s) was/were re-brazed to bring it/them within the tolerance. If more than one re-brazing cycle was required the cutter was replaced to reduce the effects of thermal cycling on the test results.

**Test parameters**

Barre Granite was chosen as the rock type for the initial test program because of its hard and abrasive nature. Historical evidence shows that granite rocks are widely used to create wear in laboratory tests of PDC cutters. [4,10]

All testing was performed using a rotary speed of 350 rpm and a controlled rate of penetration of 4.6 m/hr resulting in a depth of cut of 0.22 mm per revolution. Using a constant rate of penetration

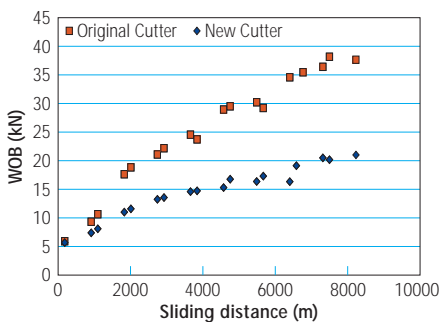
facilitates control of the total sliding distance the cutters travel and allows comparisons to be made between tests. This sliding wear model has been commonly used in the industry [13]. With the constant rate of penetration test method additional weight is applied to the bit to maintain the prescribed rate of penetration as the cutter wearflat grows. In order to cool the bit and flush cuttings out of the drilled hole water was pumped through the drillstring at a rate of 37 l/min.

**Test results**

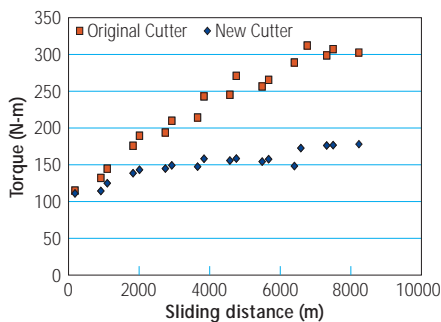
The key for any laboratory test is that the results produced in the lab are representative of how the cutter will perform in the field. The drill rig test developed here shows a very good correlation with field performance.

During the laboratory drill rig test, the weight on bit and torque required to maintain the preset constant rate of penetration will typically increase. The increases in these forces are an indicator of the wear state of the PDC cutters. These measurements can also be used to calculate a specific energy for the rock removal process. Specific energy is a measure of the energy required to remove a unit volume of rock and is often compared to the unconfined compressive strength of the rock being cut. This specific energy measurement has also been related to drilling efficiency which is an important measure for the economics of mining and oil and gas well drilling [12, 15].

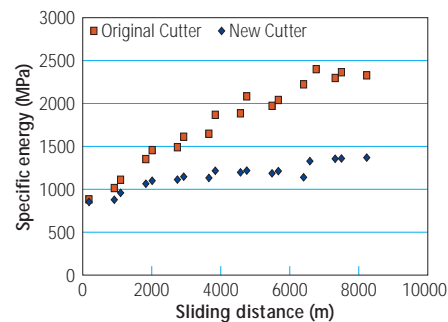
A baseline test was performed first to determine the cutter performance on the laboratory drill rig. This test was performed using the 3-cutter bit and drilling 9 holes in the Barre Granite. Each hole resulted in a total sliding distance of 914 m for a total of 8.2 km of sliding for each cutter on the bit. After completion of the first test the cutters were removed from the bit and a new set of test cutters were brazed into the bit body. The weight on bit, torque and specific energy comparisons for the two tests are shown in Figs 4-6.



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Fig 4 Weight on bit comparisons for original and new cutters recorded in drill rig tests



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Fig 5 Torque comparisons for original and new cutters recorded in drill rig tests



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Fig 6 Specific Energy comparisons for original and new cutters calculated from drill rig tests



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Fig 7 Wear on original cutters after 8.2 km of sliding distance



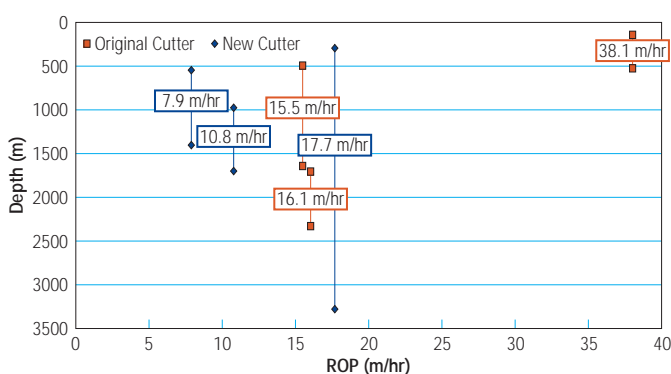
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Fig 8 Wear on new cutters after 8.2 km of sliding distance

Figs 7 and 8 show the cutter wear after completion of the tests. Examination of the data and comparison of the wear on each of the cutters shows a significant improvement in performance of the new cutters vs. the original cutters. Comparison of the specific energy for the original cutter shows a 160% increase in specific energy as the sliding distance and the associated cutter wear area increases. The specific energy for the new cutter increased at a much slower rate with an overall increase of 60% during the test.

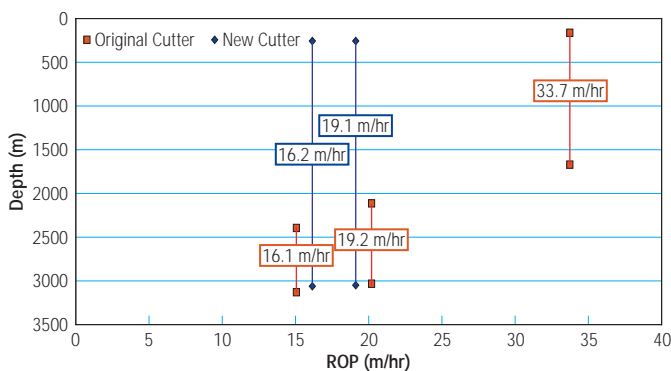
Based on the laboratory test results a decision was made to release cutters for field testing. Testing was performed in established areas where the performance of the original cutter was documented and the drilling programs were well defined. Testing was performed using 200 mm and 222 mm drill bits in two different areas in the United States. The test results in the first area showed mixed results as shown in Fig 9. Two of the runs on the new cutters were slower than the runs with original cutters but one of the runs drilled twice the distance of the bits with the original cutters at a higher rate of penetration.

The second group of field tests bits showed significant improvement over the bits with the original cutters as shown in Fig 10. In these tests the total footage drilled doubled while maintaining similar rates of penetration.

These results show that the results of the laboratory drill rig tests are indicative of field performance in at least some applications. Because of all of the possible variables inherent in field testing it may not always be possible to differentiate performance differences with a small number of bit runs and a large number of field runs may be required.



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Fig 9 Field test results from test area #1



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Fig 10 Field test results from test area #2

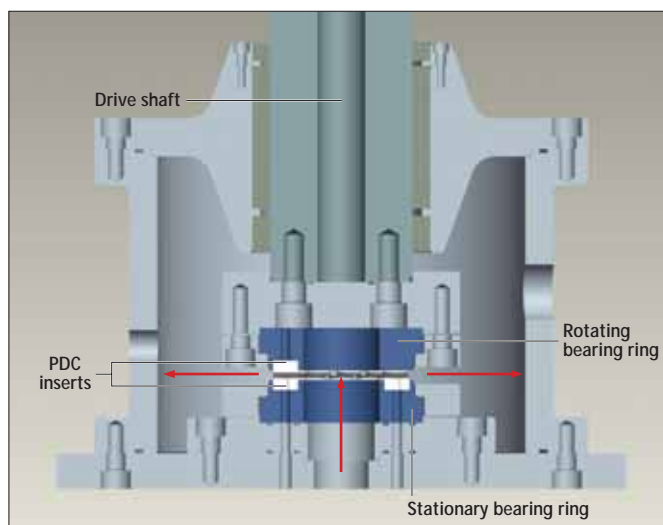
### PDC thrust bearing testing

PDC thrust bearings are used in some down-hole drilling tools to take up the axial loads associated with rotational components. These bearings prove to be effective in applications where high loads and/or speeds require a robust thrust bearing. In addition, the ultra-hard diamond wear surfaces in PDC thrust bearings hold up very well in the presence of abrasives in the drilling fluid, which often serves as a coolant and lubricant for the drilling tool's bearing section.

To help predict the performance of PDC thrust bearings in down-hole applications, the bearing test described below was developed. This test makes possible the simulation of loads and speeds seen by the bearings in down-hole use.

### Thrust bearing test setup

PDC thrust bearings are tested in the apparatus shown in Fig 11. This bearing test assembly is mounted to a rigid steel table located under the drill rig gantry adjacent to the granite drilling test block. To accommodate bearing testing, the drill string is disconnected from the drill bit assembly and attached to the bearing test drive shaft.



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Fig 11 PDC thrust bearing test apparatus



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Fig 12 PDC bearing test ring

Axial force and rotation are transferred through the drive shaft to the rotating PDC bearing ring. Cooling oil is circulated through the bearing assembly as is indicated by the red arrows in Fig 11. An example of a PDC bearing test ring can be seen in Fig 12.

During bearing testing, torque, axial load, and speed are monitored and recorded. In addition, the thickness of the stationary bearing is recorded before and after each test to determine the amount of diamond wear that occurs during the test. To help accelerate testing, larger axial loads than those expected in use can be applied to help provide measurable wear rates in a short period of time.

### Thrust bearing test results

Several thrust bearing tests were conducted at different axial loads to determine the effect of load on bearing wear rates. Speed, test duration, and cooling flow rates were the same for each test. Results from these tests can be seen in Table 2.

As can be seen in Table 2, diamond wear is significantly affected by the axial load on the PDC thrust bearing.

A second round of thrust bearing tests was conducted to determine the effect of diamond composition or diamond feed on bearing wear. Bearings with different diamond feeds, labelled A, B, and C, were tested at a constant speed, load, cooling flow rate, and for the same amount of time. Diamond wear, measured on the stationary bearing ring, is summarised in Table 3.

It is evident from the data shown in Table 3 that modifying the diamond composition has a large affect on the wear characteristics of PDC thrust bearings. Test data gathered in the thrust bearing test stand can be very useful in tailoring the diamond composition to meet the needs of demanding down-hole bearing applications. In addition, data regarding the relationship between bearing loads and diamond wear rates can be used to help predict bearing performance during use.

### Conclusions

The laboratory drill rig has been shown to be a useful tool for the evaluation of PDC cutters and bearings in that it adds another tool to speed the development of new products. Reliable laboratory evaluation techniques that correlate well with field performance are crucial to reduce development time. Initial testing has shown strong correlation between laboratory drill rig test results and actual field performance. ♦

Axial load (kN)	Diamond wear (mm)
26.69	0.00000
44.48	0.00635
66.72	0.01140

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Table 2 Stationary PDC bearing wear at various axial loads

Diamond feed	Diamond wear (mm)
A	0.10200
B	0.04060
C	0.00762

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Table 3 Stationary PDC bearing wear with different diamond feeds

#### ♦ Acknowledgments

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