RI 9594

REPORT OF INVESTIGATIONS/1995

The Reduction of Airborne Dust Generated by Roof Bolt Drill Bits Through the Use of Water

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior
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By Laxman S. Sundae, David A. Summers, Douglas Wright,
and Bruce K. Cantrell

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
ft	foot
kPa	kilopascal
L	liter
lb	pound
kN	kilonewton
m	meter
m/min	meter per minute
mg/cm^3	milligram per cubic centimeter
mm	millimeter
pct	percent
rpm	revolution per minute
s	second

OTHER ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

MSA	Mine Safety Appliances
PDC	polycrystalline diamond compact
RAM	real-time aerosol monitor
ROP	rate of penetration
UMR	University of Missouri - Rolla
USBM	U.S. Bureau of Mines
WC-Co	tungsten carbide

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

THE REDUCTION OF AIRBORNE DUST GENERATED BY ROOF BOLT DRILL BITS THROUGH THE USE OF WATER

By Laxman S. Sundae,[1] David A. Summers,[2] Douglas Wright,[3] and Bruce K. Cantrell[4]

ABSTRACT

In the vast majority of American coal mines, roof bolt holes are drilled dry, mainly because of mine operator concern with the spent water creating adverse working conditions. Wet drilling, however, can increase drilling rates and the effective lifetime of the drill bits used.

This study, carried out as part of an ongoing cooperative research program between the U.S. Bureau of Mines and the University of Missouri-Rolla, shows that the large volumes of water conventionally used in wet drilling are not necessary, and the performance benefits from wet drilling can be achieved with total volume flows on the order of 0.4 L per hole. This conclusion is validated based on the measured respirable dust generated in drilling Berea sandstone. The results are confirmed using a variety of bit shapes, which are also shown to have a significant effect on penetration rate.

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[1] Mining engineer. Twin Cities Research Center, U.S. Bureau of Mines, Minneapolis, MN

[2] Curators' Professor, University of Missouri - Rolla. Rolla,MO.

[3] Graduate student, University of Missouri - Rolla.

[4] Supervisory physical scientist, Twin Cities Research Center.

INTRODUCTION

Approximately 2,400 roof-bolting machines are currently employed in the approximately 1,300 underground coal mines now active in the United States. In all but 120 of these mines, bolters are operated dry with no water added to the bits for cooling or clearing the cuttings. Operating the bits without water increases the wear rate, so that three to ten times more drill bits will be required than if the bits were water cooled. This results in an excess expense of some $5-7 million per year for the bit cost alone. This increased wear is caused by thermal cracking and reduced abrasion resistance of carbide bits at the higher temperatures reached when drilling dry (*1-4*)[5]. Dry drilling also generates more respirable dust, with consequently greater dust control problems (*5*).

In the mines where water is used to cool and flush the bits ("wet" drilling), it is usually supplied at line pressure through the stem of the drill steel and is discharged onto the bit through rough openings drilled at the end of the steel. In order to keep the bit cool, large quantities of water are used. Excessive water flow in the bit-rock contact area has the disadvantage of interfering with the effective removal of cuttings from the vicinity of the bits' cutting edges. This large volume discharge is of great concern to mine operators because spent water on mine roadways can create large mud pits from 0.05- to 1.0 m deep, which interfere with the movement of personnel and haulage equipment.

This study was carried out between the U.S. Bureau of Mines (USBM) and the University of Missouri-Rolla (UMR) to demonstrate that proper installation and placement of waterjets on the drill bit will cool the bit while effectively removing the cuttings from the bit-rock contact area. It is comprised of two complementary investigations. Laboratory tests were conducted at the High Pressure WaterJet Laboratory of the Rock Mechanics and Explosives Research Center, UMR, and a series of in-mine tests were conducted in several mines with test bits to compare penetration rate and bit life. The laboratory investigation

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[5]Italic numbers in parentheses refer to items in the list of references at the end of this report.

first determined the minimum amount of water required to cool the bits to avoid thermal cracking of tungsten carbide (WC-Co) inserts and thermal degradation of polycrystalline diamond compact (PDC) bits. Then, waterjets on a PDC bit were examined

for their ability to eliminate respirable airborne dust, or aerosol, generated duiring mine roof bolting operations.

TEST EQUIPMENT

The laboratory drill test facility, together with the drilling mechanism, the aerosol measuring equipment, and the testing procedure for this investigation, has been described in detail in earlier reports and publications *(6-8)*. The equipment is comprised of a hydraulic ram which elevates a platform carrying a rotary motor and drilling steel along a set of guide rails (figure 1). Instruments record the forces required to advance and turn the bit, and the rate of penetration (ROP) is timed. A block of rock is mounted above the assembly, and the entire frame is surrounded by a plexiglass cover to contain the dusty atmosphere created during a drilling test. Samples of the respirable dust are drawn off for analysis using a Model RAM-1 real-time aerosol monitor (RAM) (*9*) and a gravimetric filter sampler using a 37-mm MSA filter. For these tests, the drill setup was modified from the previous work by reversing the direction of drilling (i.e., upwards rather than downwards) to more accurately approximate the roof-bolt drilling conditions encountered in underground mines.

PDC AND WC-Co BITS

Test bit configurations used in this study (figure 2) are similar to those of earlier studies (*6,8*). The first four bit types employ the water stream flushing design currently in use in mines, while the fifth is specifically designed for this series of tests using water jets for flushing. There are a considerable number of differences in the design and physical characteristics between the test bits, these are summarized in table 1.

Berea sandstone was used in previous studies, and this rock was again selected because of its homogeneity, its known properties, and to allow correlation with the results of the earlier work (*6*). Because of economic considerations, the rock for this series was obtained from a different quarry than the earlier material, in this case some 15 miles west of Bloomington, Indiana.

EXPERIMENTAL DESIGN AND TEST PROCEDURES

The test matrix used in the laboratory investigation is summarized in table 2. The change in stream flow rate through the PDC bit and its affect on both the amount of dust generated and the penetration rate achieved was examined. WC-Co bits were tested concurrently at the minimum water flow for purposes of comparing both the rate of penetration and respirable dust generations. A total of 67 tests was carried out, with the holes drilled at a rotational speed of 500 rpm, and a feed thrust of 14.24 kN (3200 lbs). Drilling time was measured with a stop watch. Hole depths, volumes, and ROP were determined. Because of funding limitations it was not possible to acquire more sophisticated metering equipment to more accurately control the volume of water supplied to the bit.

DISCUSSION OF RESULTS

Test results for dry and wet drilling are shown in Appendices A and B. Appendix B shows the actual volume of water used in drilling each test suite of five or six holes. A second series of in-mine tests was conducted to verify laboratory test results.

The RAM aerosol monitoring instrument was calibrated before the tests were started, after which two preliminary tests were performed using the PDC bits to check on the calibration and the accuracy of measurement (Appendix A). During the test series, measurements of drilling parameters and airborne respirable dust were recorded simultaneously for each of the test holes drilled. Test results for the drilling parameters were then summarized (table 3) and plotted to show the effect of the parameter change on ROP (figures 3-5) and on the quantities of dust generated (figures 9-12). The American Conference of Governmental Industrial Hygienists defines airborne respirable dust as a log-normal distribution curve with 50 pct of the particles having an aerodynamic diameter of 3.5 μm or less, and a geometric standard deviation of sg = 1.5 (I).

PENETRATION RATE

Laboratory Tests

When the data on the performance of the bits is compared, both dry and wet, it is clear that when drilling dry (figure 3) the triangular shaped bit with the U-shaped apex provides the fastest drilling speed. However, when the ROP is plotted for the wet drilling this advantage disappears (figure 4) and there is no longer a clear difference in performance between PDC bits and the triangular bit with the U-shaped apex. A relative comparison of the enhancement in bit performance with water (figure 5) shows that the performance of the latter bit is slightly reduced although the difference lies within the scatter of the data. The greatest individual test ROP occurred with PDC bits when water assisted (see appendix B).

When cutting through the rock the triangular bit with the U-shaped apex leaves a 3-mm-diameter core in the center of the hole. This core is removed by the upward shearing action of the drill bit. Thus, the bit does not attack the full face ahead of the tool. In contrast, the triangular bit without this central core has the longest drilling time, or slowest ROP. Interestingly, the PDC bit design developed at UMR has the same design philosophy as the U-shaped triangular bit but only functions effectively when water jets are used to keep it clean.

Field Trials

The higher drilling rate of the triangular bit with the U-shaped apex is significant and of potential value in mining. The results with jet assist for the PDC bits have equivalent potential but would, in many mines, require more modification to the drilling device which would necessitate long-term application. Thus, only the first four bits were field tested. In order to assess the validity of the laboratory results, a series of more than 75 tests were conducted in a northern Michigan underground copper mine. A time study made during the in-mine testing showed that the U-shaped bit design was able to collar a hole in 7-10 s less than trapezoidal and triangular-shaped inserts. It took 10-12 s less to drill a 6.0-ft-deep hole when the bits were new. This represents a total savings of 17-20 s per hole, a 30 pct overall reduction in drilling time (figure 6). The comparison becomes even greater during the operational life of the bits since, over a length of 50 m the average time to drill with the U-shaped apex was 55 s, while it increased to 75 s for the standard trapezoidal bit and to 85 s for the triangular bit. After drilling some 22 holes, the relative times were 62 s, 91 s and 108 s, with a 40 pct gain in drilling time and an overall gain of over 50 pct in performance with the best bit shape.

During this field trial, the PDC bit was not able to achieve the same penetration rates as the other bits, probably because of its much higher rake angle, therefore, the results have not been included.

Field trials were also conducted in three coal fields. The strength of the roof rock varied considerably during these trials, making comparisons difficult. It also became clear that the tip, rake and clearance angles of the bit have significant effects on the ROP and may have a co-variable effect on bit life. It was difficult to identify a single rock property which could be used to predict performance since, in some cases, the strength of the rock appeared most critical, while in others it was easier to correlate performance to the hardness of the rock formation. (These test results are described separately.)

Field tests were conducted with triangular and trapezoidal bits to compare life expectancy with wet and dry drilling methods. At the first test mine located in a southeastern Utah coal field, with wet drilling trapezoidal bits achieved 2 to 3 times greater life than the triangular bit. At a second test site in southern Illinois, with dry drilling, trapezoidal bits achieved twice as much bit life. The later mine was impressed with bit performance, and adopted it for routine roof bolt drilling. The mine has reported a 20 pct reduction in bit cost over past the 2-year period.

Dry and Wet Drilling

Also monitored was the effect of change in the amount of water flowing over the bits as a means of eliminating respirable dust. The results of the initial trials suggested that it is possible to obtain equivalent results if only 20 pct of the water normally used on mine bolting machines were applied. Because of the additional water pressure, it was necessary to increase the compressed air pressure to 275 kPa for this part of the program. Because of the differences in flow channels and sizes, there was some difference in the amounts of water consumed by the different bit designs as shown in Appendix B.

The performance of the bits was improved when water was added (figure 5), with the exception of the U-shaped bit. It is possible, due to the way that bit operates, that water was not as successful at reaching the cutting area as it was for the other designs. In the case of the other bit designs, a significant improvement in performance was achieved when water was added to the bit. It is interesting to note that the data shows no reduction in the penetration rate as the amount of water was reduced. This can be seen in the performance of both the conventional PDC bit using the streamflow and the PDC bit using jet nozzles (figure 8).

It can be clearly seen from the above two curves that it is possible to cut the water flow to a PDC bit from 9.5 L to 0.41 L a drop of 95.7 pct in the amount of water used - without any loss in drilling performance. Because of the small amount of water used, it will be adsorbed on the sides of the hole and in the dust generated. It is possible that the small quantity may overcome the major objections operators have had about the use of water as an assist to the mechanical drilling of rock.

AIRBORNE DUST MEASUREMENTS

Airborne dust measurements were made by using both a USBM-modified continuous dust monitor based on a real-time aerosol monitor (RAM) and a gravimetric sampler with a 90-mm MSA filter. The RAM is a nephelometer that measures instantaneous concentrations of dust in a sample airstream. USBM modifications to the RAM allow measuring, monitoring and recording of the concentrations of the airborne dust generated in the drilling enclosure on a "real-time" basis. The MSA filter was used to measure an average concentration of aerosol generated by each bit. Each airborne dust measurement was taken while bit performance was being monitored.

The data clearly shows that a 40 pct reduction in respirable aerosol was achieved with the PDC bit when compared with the WC-Co bit (figure 9). This reduction is less than that found in previous work by the USBM (5), probably because these tests were conducted in a harder sandstone. Evidence of this was shown by the damage to the PDC bit cutting edge during dry drilling.

When water was added to the drill bits (figure 11), the amount of respirable dust generated was reduced by more than 98 pct. Since each bit delivered a different amount of water, it is not possible to relate the difference in the amount of dust generated by each bit type. Furthermore, if only less than 2 pct of the airborne dust was allowed to escape into the mine atmosphere, this value would be well below the regulatory limits, and would suggest that there is not a great deal to be gained by much further development.

At the end of each test in wet drilling, all the bits were cool to hand touch because of the decrease in the frictional temperature in the bit-rock contact area. Because of the lack of a frictionally generated rise in temperature, carbide and PDC inserts will maintain their greater room temperature hardness and abrasion resistance. This, in turn, maintains the cutting edge at its original level of sharpness for a much longer period.

DUAL BENEFITS OF WATER JETS

The use of a jet assist with the PDC bit has two demonstrable benefits. First, the waterjets use only 5 pct of the water used in conventional bit cooling and still generate a 10 pct higher drilling ROP. At the same time (figure 11) the waterjet at these volumes will reduce the overall dust generated in a drilling operation by about 98 pct. Increased jet pressure removes cuttings more efficiently with 95 pct less water. There is a slight increase in airborne dust with the new bit design, since it shears off a central section of the rock mass rather than grinding it off as with the conventional PDC design. This results in a coarser fraction of dust, which appeared as a sand slurry of cuttings found at the bottom of the test chamber. This was anticipated at the beginning of the tests.

These results establish that increased jet pressure removes cuttings with 95 pct less water than is used conventionally.

This same result cannot be achieved as effectively using a stream flow since the additional pressure allows the jet to penetrate along the cutting surface, dampening the dust before it becomes airborne, simultaneously easing the cutting.

COMMPARISON OF RAM AND GRAVIMETRIC FILTER DATA

It is assumed that there is some difference in the background dust available for measurements and in the degree of accuracy of the two measuring methods. Despite these differences, there was good correlation between the data from the two methods (figure 12). Regression analysis of test results from the two systems showed a 0.74 correlation. It was concluded that either the RAM or the filter data would be an effective method for measuring dry dust measurements. More accurate correlations are unlikely since one instrument is geared to instantaneous readings while the other provides an average. Because the RAM does not function in the presence of water, no comparative data between the two could be assayed with the wet drilling data.

RELATIONSHIP BETWEEN BIT PERFORMANCE AND AEROSOL

This study indicates that there are remarkable similarities between an increase in penetration rate and a decrease in airborne dust generated while using water as a cooling and wetting agent for each bit type, with or without jet action. At present, it has not been possible to quantify this relationship mathematically.

CONCLUSIONS AND RECOMMENDATIONS

Test results show that a triangular-shaped insert with a U-shaped apex collars and drills much faster than a conventional triangular shaped insert. The presence of water at the bit-rock interface prevents temperature rise caused by friction, maintains the sharpness of cutting edges, and results in higher penetration rates. All test bits had a higher ROP when water was added as a coolant.

Wet drilling resulted in a 98 pct reduction in airborne dust with each bit, whether PDC or WC-Co. Under both wet and dry conditions conventional PDC bits produced about 40 pct less dust than other test bits. Despite the differences in performance characteristics of WC-Co bits, there is no statistically valid difference in the quantity of airborne dust generated by the three types of WC-Co bits, either with wet or dry drilling.

Two series of tests were conducted to compare the performance of the PDC bit with stream flow and with waterjet assist. In each case the bit with the jets consumed at least 60 pct less water, had a higher ROP, and produced a slightly higher amount of respirable dust.

There is a small increase in the amount of airborne dust generated when the water jet used to assist drilling is reduced by 98 pct. This increase may be important to highlight the accuracy of measurement techniques, theoretical calculations or wetting characteristics of rock constituents. This relatively minuscule amount of airborne dust left in the air has either no practical bearing on mining operations or very little effect on the quantity of airborne dust generated overall.

It has been shown that relatively small amounts of water, if properly directed onto bit cutting surfaces, can enhance the performance of WC-Co drill bits. Use of water as a coolant is essential to reap the benefits of PDC bits. The small quantities of water which have been found to be effective will not generate the muddy floors which are a concern to mine operators, particularly those with fireclay floors. It is therefore recommended that a program be developed to introduce low-volume waterjet systems into roof bolting operations.

ACKNOWLEDGEMENTS

This work was carried out at the High Pressure Waterjet Laboratory of the Rock Mechanics and Explosives Research Center, Rolla, MO. We gratefully acknowledge the assistance of Robert Fossey and Jo Blaine of Rolla, MO in the preparation of this report. The authors gratefully acknowledge the technical assistance of Lance Van Elsen, Student Engineer, and Sue Stine, Physical Science Technician at TCRC for their assistance in data analysis and editorial comments during preparation of this manuscript. The USBM is also grateful to Scot Herr, Chief Mining Engineer, White Range Copper Co., White Pine, MI, for permission to conduct in-mine tests. The USBM is also indebted to Steve

Nance, Tungco Inc., Hanson, KY for manufacturing test bits at no cost for this study.

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Oct. 1994, ____pp. RI, U.S. Bureau of Mines, 1994.

TABLES

Table 1. - Physical characteristics of the test bits.

Bit type	Design features				
	No. of faces	Tip angle, deg	Rake angle, deg	Clearance angle, deg	Stream/ jet
PDC..............	2	85°	20°	0	Stream
Triangular.......	2	85°	0	15°	Stream
Triangular-U.....	2	85°	0	15°	Stream
Trapezoidial.....	4	70°	0	23°	Stream
PDC with jet.....	2	85°	20°	5°	Jet

Table 2. - Test Matrix showing the number of tests planned for each wet and dry drilling test.

Bit type	Estimated use of water, L				
	0.0 (dry)	9.5	1.9	0.95	0.47[1]
PDC..............	5[1]	5	5	5	0
Triangular.......	0	0	0	5	0
Triangular-U.....	0	0	0	5	0
Trapezoidial.....	0	0	0	5	0
PDC with jet.....	0	0	0	0	5

[1]Nominal quantity of water supplied through jet nozzles

Table 3. - Summary of Dry and Wet Drilling Results.

Bit type	Number of tests	Water Pressure (kPA)	Air Pressure (kPA)	Water Volume (L)	Average ROP (m/min)
		DRY DRILLING TESTS			
PDC..............	12	0	165	0	0.56
Triangular.......	5	0	154[1]	0	0.51
Triangular-U.....	4	0	138	0	0.61
Trapezoidial.....	5	0	138	0	0.54
PDC with jet.....	n/a	n/a	n/a	n/a	n/a
		WET DRILLING TESTS			
PDC..............	5	480	275	9.5	0.58
PDC..............	10	475	275	1.4	0.61
Triangular.......	5	523	240	0.95	0.55
Triangular-U.....	5	520	260	1.1	0.60
Trapezoidal......	5	525	260	1.2	0.56
PDC with jet.....	10	500	270	0.44	0.61

[1]Averaged

Appendix A. - Dry drilling test results

Test number	Distance, cm	Water pressure, kPA	Air pressure, kPA	Drilling time, s	ROP m/min
		PDC BIT			
1......	12.8	0	165	14.19	0.54
2......	12.7	0	165	13.73	0.55
3......	12.9	0	165	13.34	0.58
4......	13.1	0	165	14.05	0.56
5......	12.7	0	165	13.91	0.55
6......	12.7	0	165	13.89	0.55
7......	12.8	0	165	13.11	0.59
8......	12.6	0	165	14.16	0.53
9......	13.0	0	165	13.11	0.59
10.....	12.72	0	165	13.12	0.58
11.....	12.73	0	165	13.11	0.58
12.....	12.75	0	165	14.01	0.55
Mean...	0	0	0	0	0.56
SD[1]....	0	0	0	0	0.02
		TRIANGULAR BIT			
1......	12.8	0	138	15.15	0.51
2......	13.3	0	138	15.24	0.53
3......	12.9	0	165	14.39	0.54
4......	12.3	0	165	15.29	0.48
5......	13.2	0	165	15.55	0.51
Mean...	0	0	0	0	0.51
SD.....	0	0	0	0	0.02
		TRIANGULAR BIT WITH U-SHAPED APEX			
1......	13.0	0	138	13.11	0.59
2......	13.5	0	138	0	0
3......	13.5	0	138	13.23	0.61
4......	13.0	0	138	12.92	0.60
5......	13.4	0	138	12.99	0.61
Mean...	0	0	0	0	0.61
SD.....	0	0	0	0	0.01

Appendix A. - Dry drilling test results (continued)

Test number	Distance, cm	Water pressure, kPA	Air pressure, kPA	Drilling time, s	ROP m/min
TRAPEZOIDAL BIT					
1......	13.0	0	138	14.37	0.53
2......	13.2	0	138	14.38	0.55
3......	13.0	0	138	14.60	0.53
4......	12.8	0	138	14.09	0.54
5......	12.79	0	138	14.42	0.53
Mean...	0	0	0	0	0.54
SD.....	0	0	0	0	0.01

[1]Standard Deviation

Appendix B. - Wet drilling test results

Test number	Distance, cm	Water pressure, kPA	Air pressure, kPA	Drilling time, s	ROP m/min
PDC BIT WITH 9.5 LITERS OF WATER					
1......	12.7	480	275	13.88	0.55
2......	12.5	480	275	13.70	0.55
3......	12.5	480	275	12.25	0.61
4......	12.6	480	275	12.54	0.60
5......	12.6	480	275	12.79	0.59
Mean...	0	0	0	0	0.58
SD[1]....	0	0	0	0	0.03
PDC BIT WITH 1.5 LITERS OF WATER					
1......	13.0	470	275	12.89	0.61
2......	12.8	470	275	13.00	0.59
3......	12.8	470	275	12.78	0.60
4......	13.0	470	275	12.90	0.60
5......	12.79	470	275	12.85	0.60
Mean...	0	0	0	0	0.60
SD.....	0	0	0	0	0.006
REPEAT TEST, PDC BIT WITH 1.3 LITERS OF WATER					
1......	11.8	480	275	12.5	0.57
2......	12.6	480	275	11.95	0.63
3......	12.8	480	275	12.46	0.62
4......	12.8	480	275	12.02	0.64
5......	12.8	480	275	12.27	0.63
Mean...	0	0	0	0	0.62
SD.....	0	0	0	0	0.03
TRIANGULAR BIT WITH 0.95 LITERS OF WATER					
1......	12.0	520	240	13.34	0.54
2......	11.5	520	240	13.24	0.52
3......	13.0	525	240	13.42	0.58
4......	12.0	525	240	13.18	0.55
5......	12.1	525	240	13.26	0.55
Mean...	0	0	0	0	0.55
SD.....	0	0	0	0	0.02

Appendix B. - Wet drilling test results (continued)

Test number	Distance, cm	Water pressure, kPA	Air pressure, kPA	Drilling time, s	ROP m/min
TRIANGULAR BIT WITH U-SHAPED APEX WITH 1.1 LITERS OF WATER					
1......	12.0	520	260	12.2	0.59
2......	12.1	520	260	11.78	0.62
3......	12.0	520	260	12.09	0.60
4......	12.0	520	260	11.99	0.60
5......	12.1	520	260	12.72	0.57
Mean...	0	0	0	0	0.60
SD.....	0	0	0	0	0.02
TRAPEZOIDAL BIT WITH 1.2 LITERS OF WATER					
1......	12.0	525	260	12.79	0.56
2......	12.0	525	260	13.16	0.55
3......	12.0	525	260	12.90	0.56
4......	12.0	525	260	12.63	0.57
5......	12.0	525	260	12.48	0.58
Mean...	0	0	0	0	0.56
SD[1]....	0	0	0	0	0.01
PDC BIT WITH JET ASSIST USING 0.41 LITERS OF WATER					
1......	12.4	520	430	11.38	0.65
2......	12.0	520	430	11.67	0.62
3......	11.6	520	430	12.06	0.58
4......	12.4	520	430	11.91	0.62
5......	12.0	520	430	11.5	0.62
Mean...	0	0	0	0	0.62
SD.....	0	0	0	0	0.03
REPEAT TEST, PDC BIT WITH JET ASSIST USING 0.47 LITERS OF WATER					
1......	11.5	480	480	11.58	0.60
2......	11.5	480	480	11.01	0.63
3......	11.6	480	480	11.59	0.60
4......	11.8	515	515	11.99	0.59
5......	11.6	515	515	11.66	0.60
Mean...	0	0	0	0	0.60
SD.....	0	0	0	0	0.01

Figure 1

General layout of test equipment.

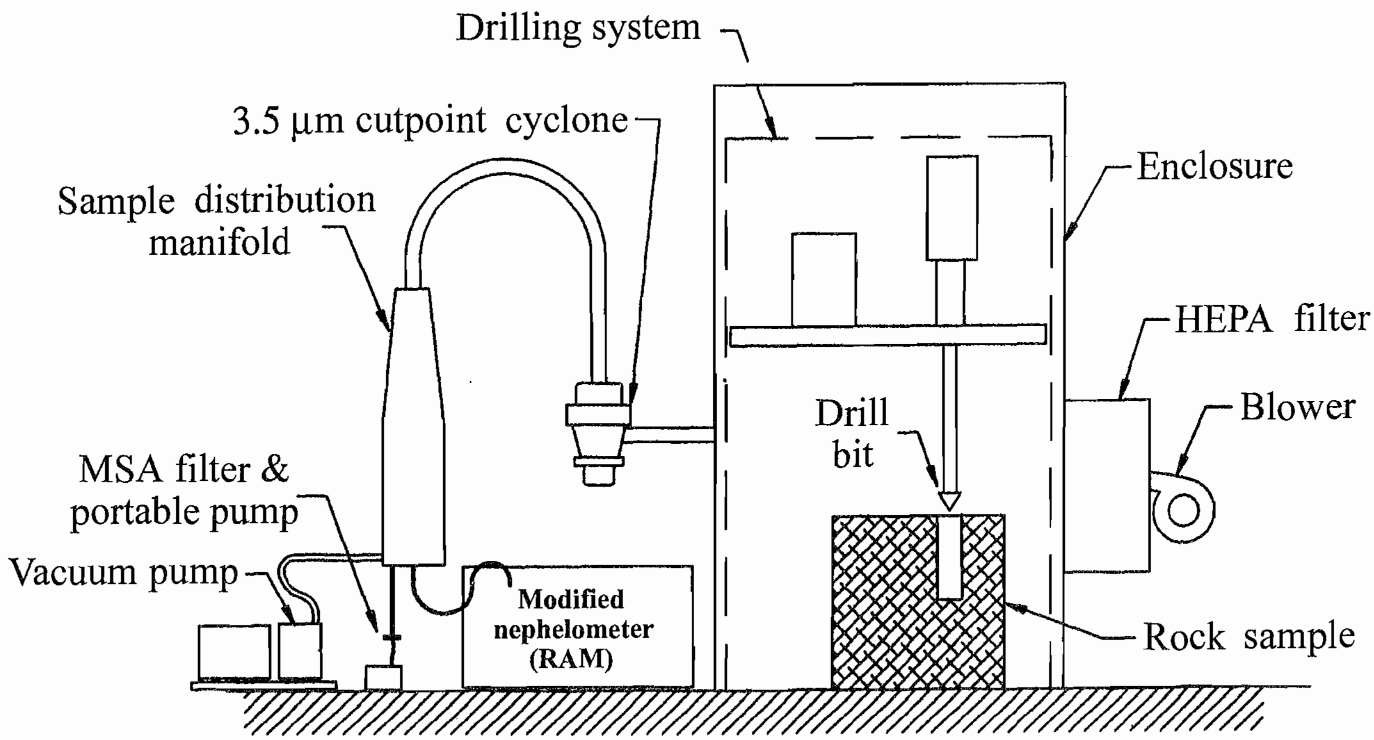


Figure 2

Different designs of bits tested.

Figure 3
Relative Penetration Rates of Different Drill Designs Operated Dry

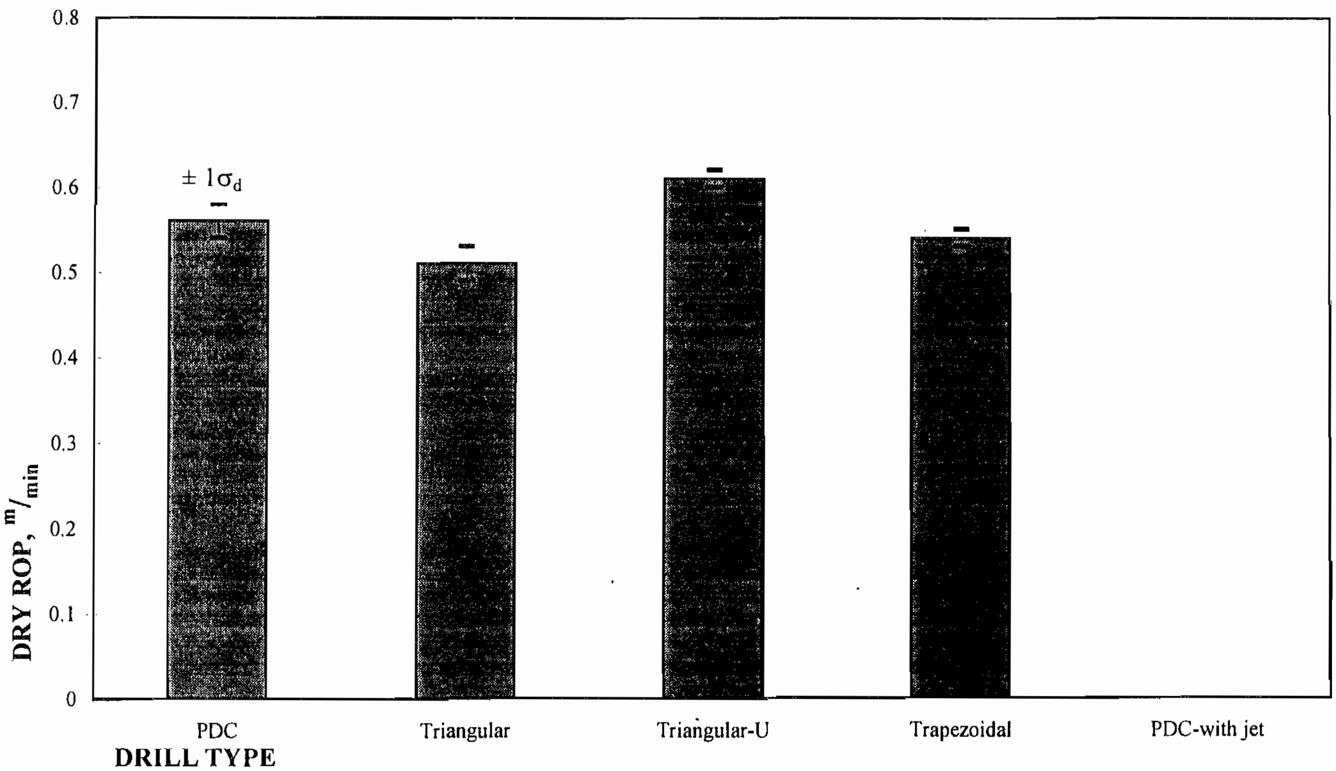


Figure 4
Relative Penetration Rates of Different Drill Designs Operated Wet

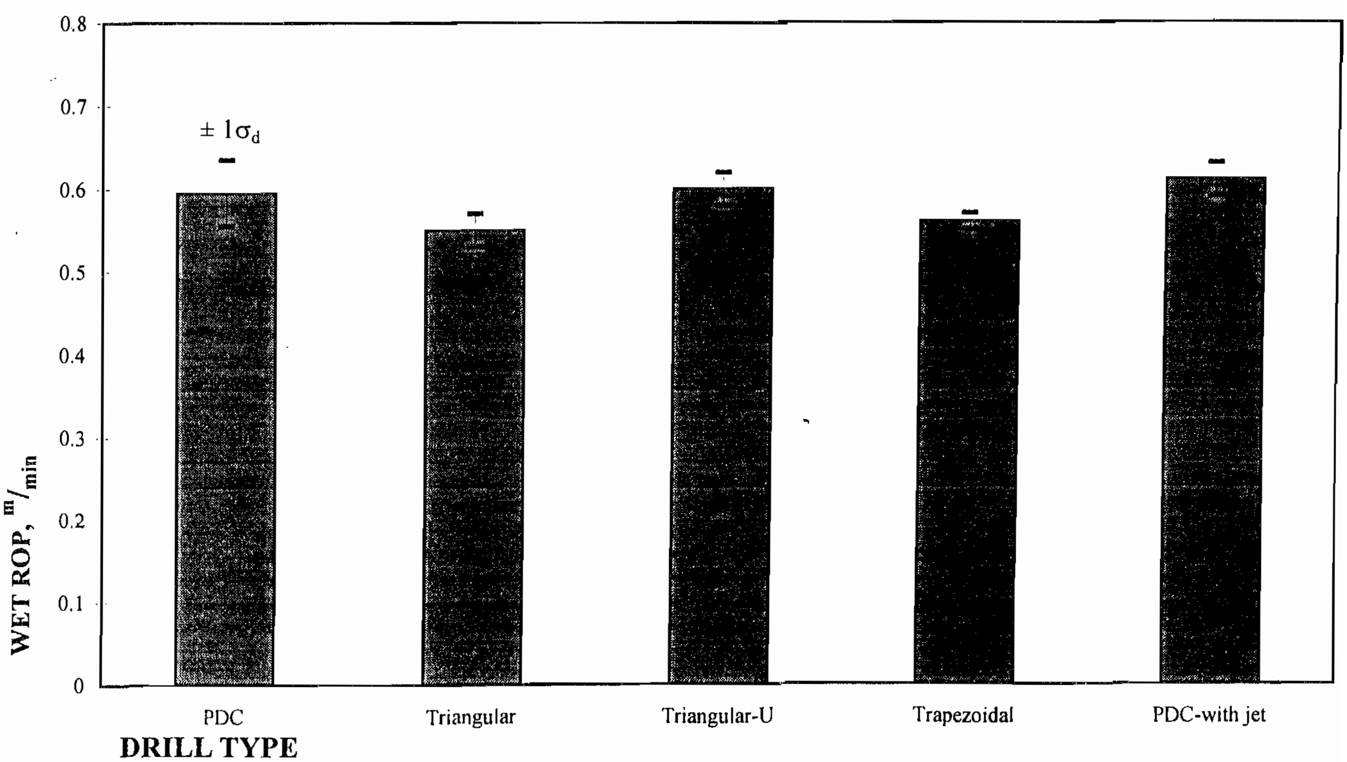


Figure 5
Relative Gain in ROP When Water is Added to a Bit

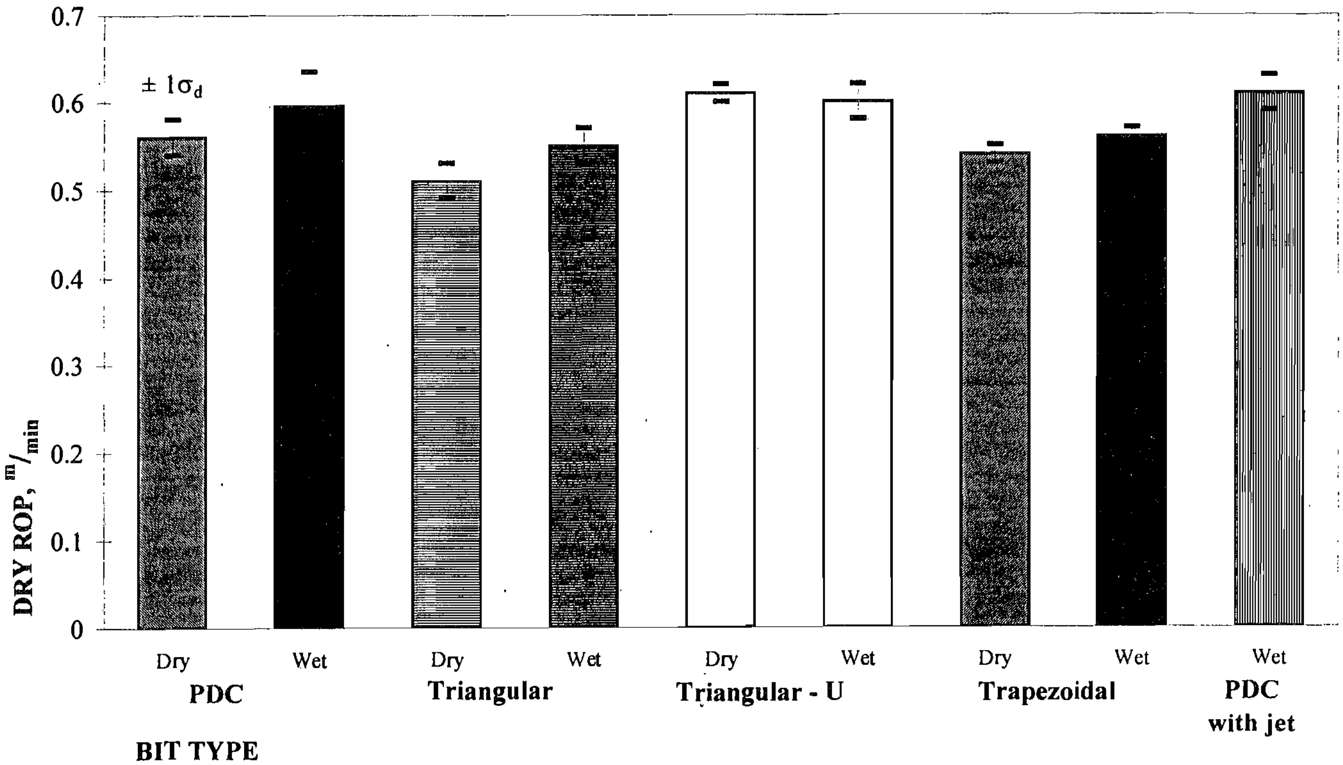


Figure 6
Comparative Bit Performance in Drilling 1.8m Holes in a Mine

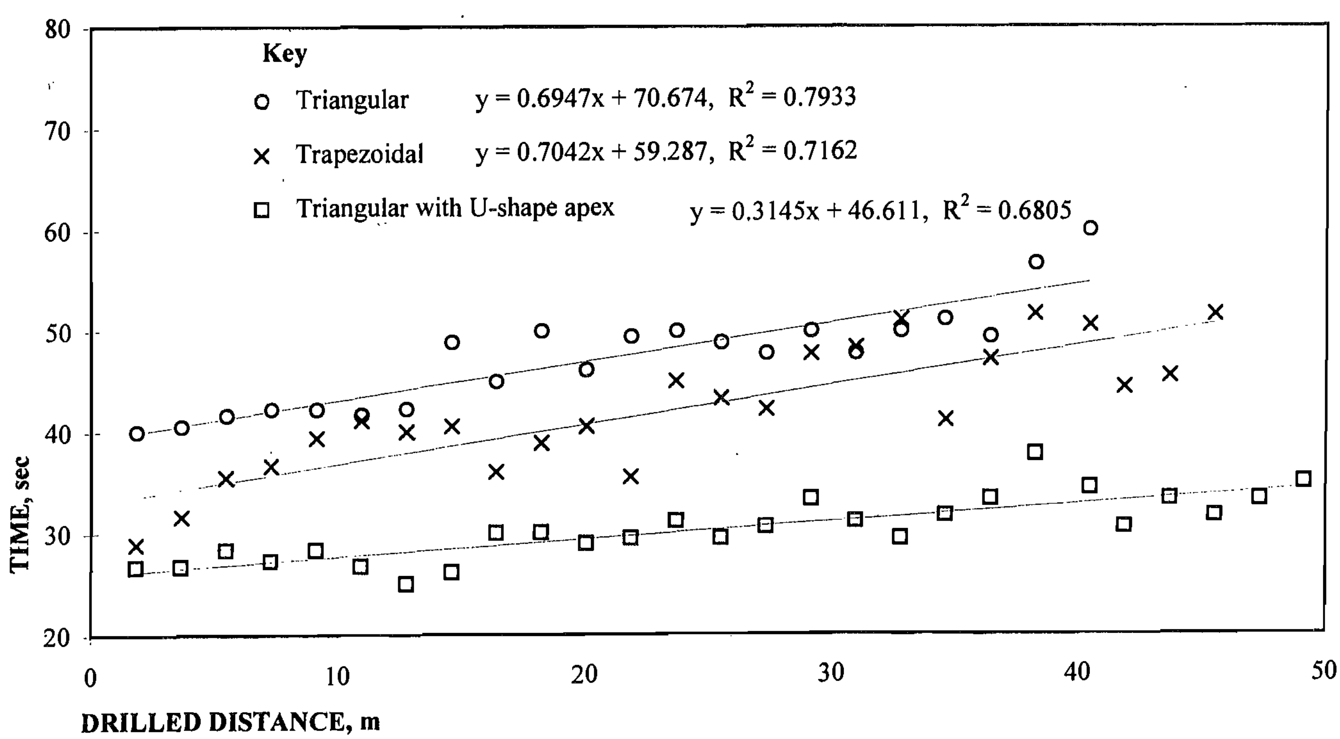


Figure 7
Penetration Rate for a Stream Cooled PDC Bit With Various Flows

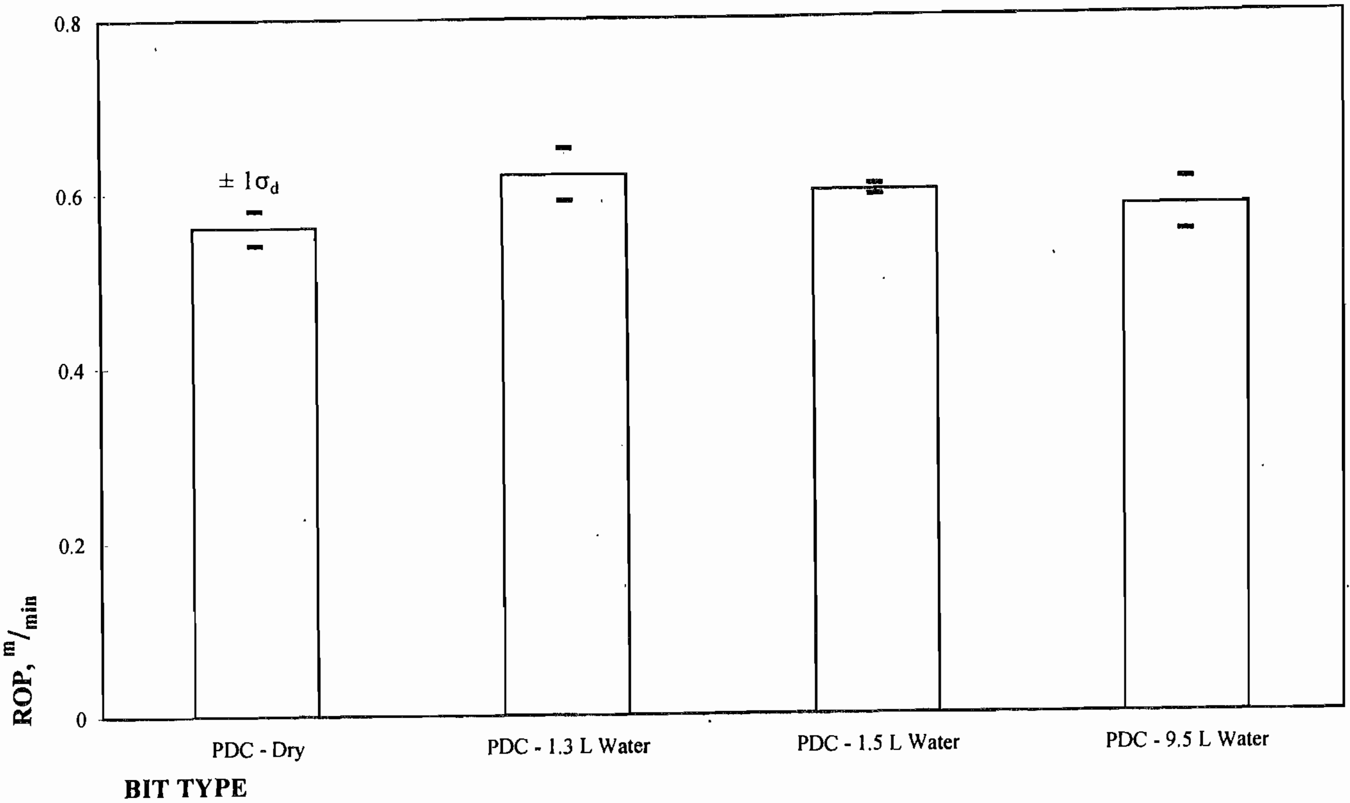


Figure 8
Comparative ROP for Stream and Jet Cooled PDC Bits

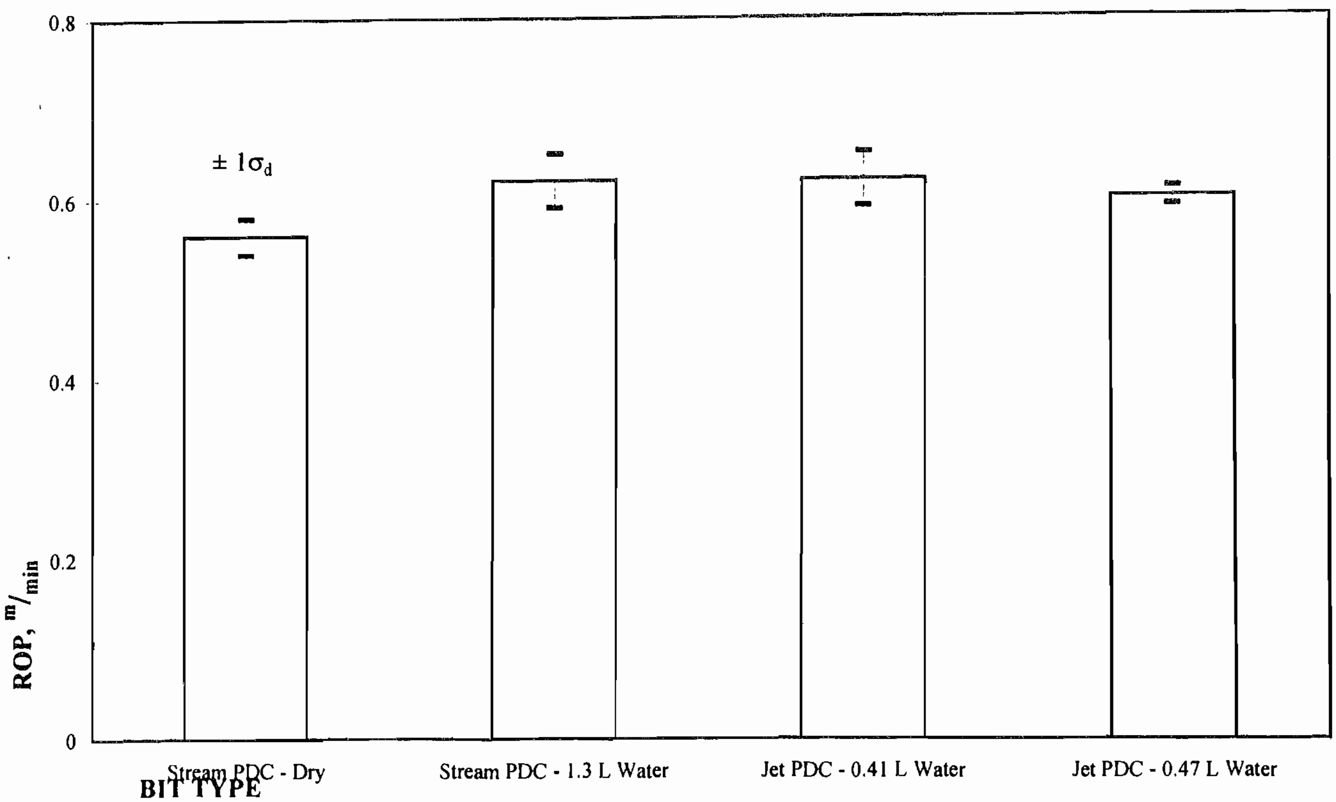


Figure 9
Respirable Aerosol Values From the Filter Data For Various Drill Bits During Dry Drilling

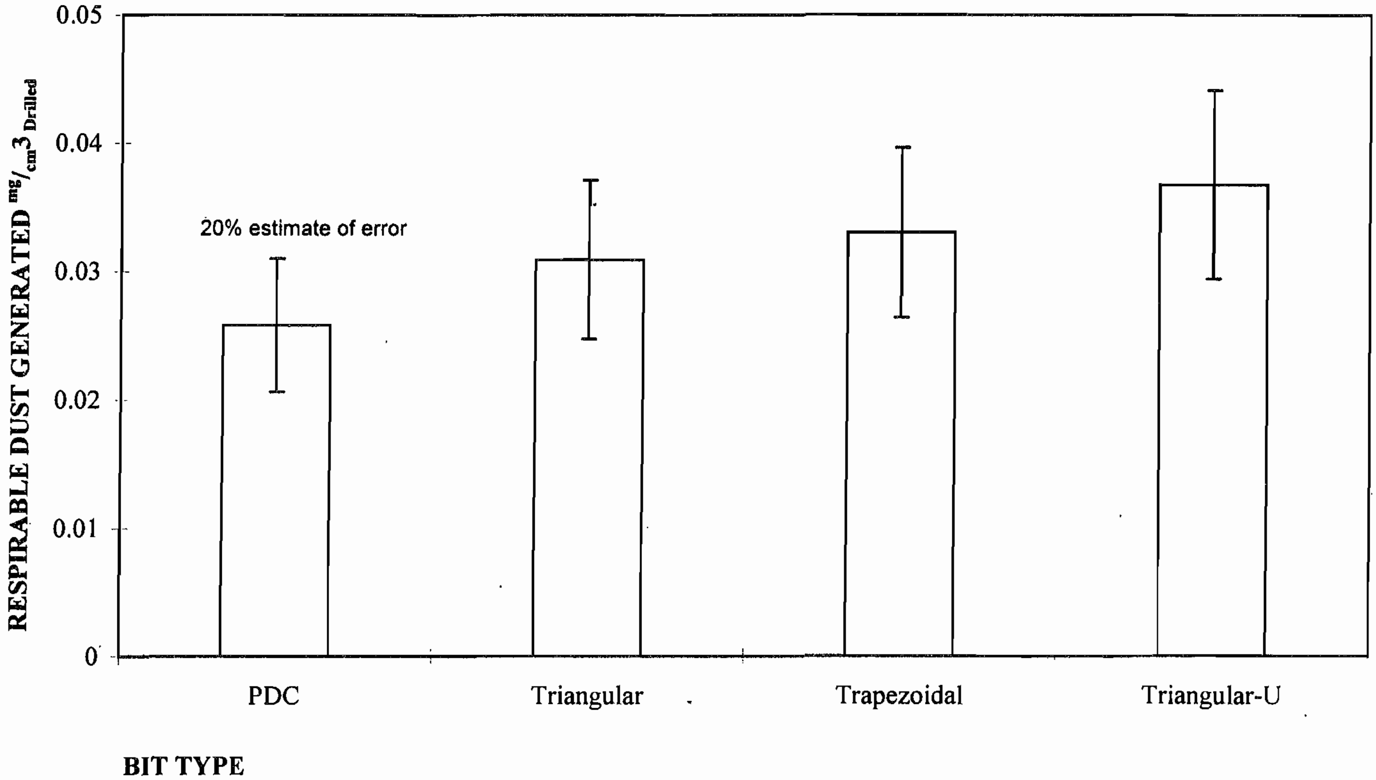


Figure 10
Respirable Aerosol Values From the RAM Data for Various Drill Bits During Dry Drilling

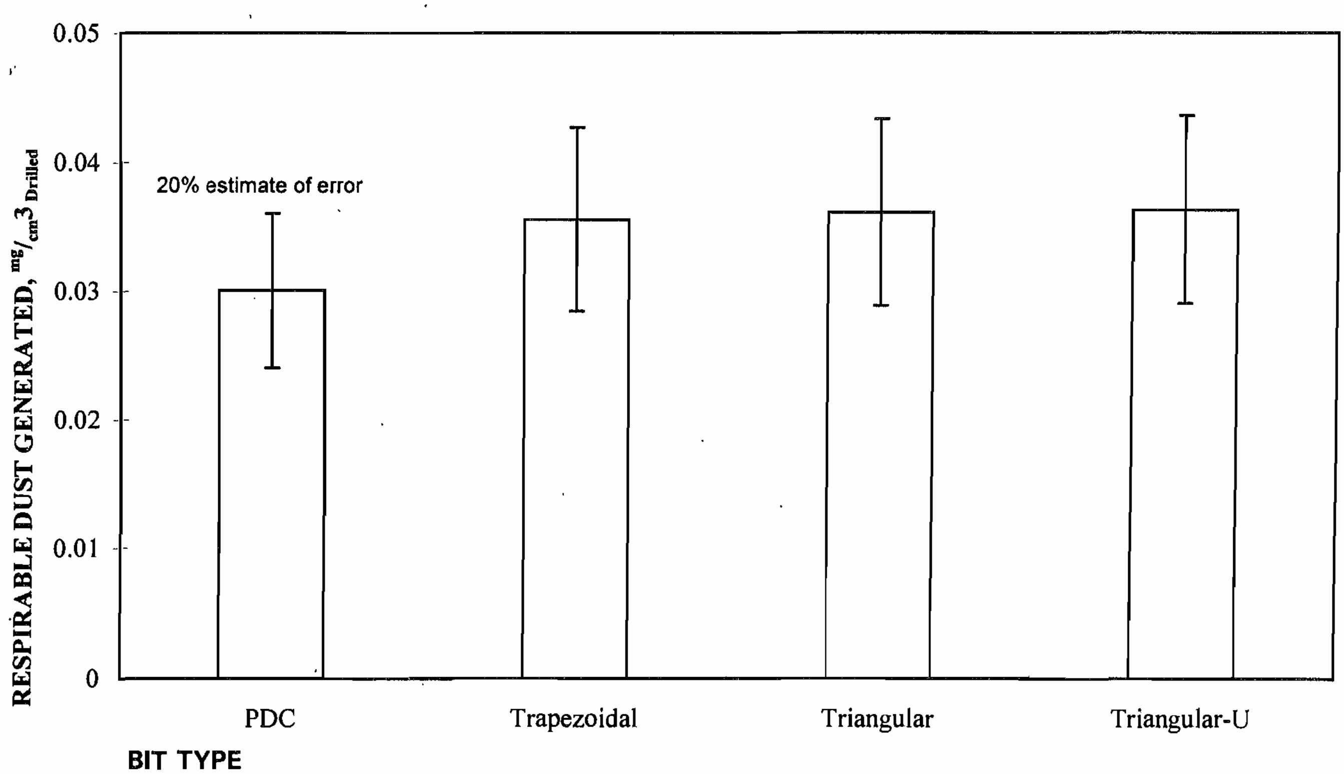


Figure 11
Relative Dust Aerosols with Wet and Dry Drilling for the Various Bit Types

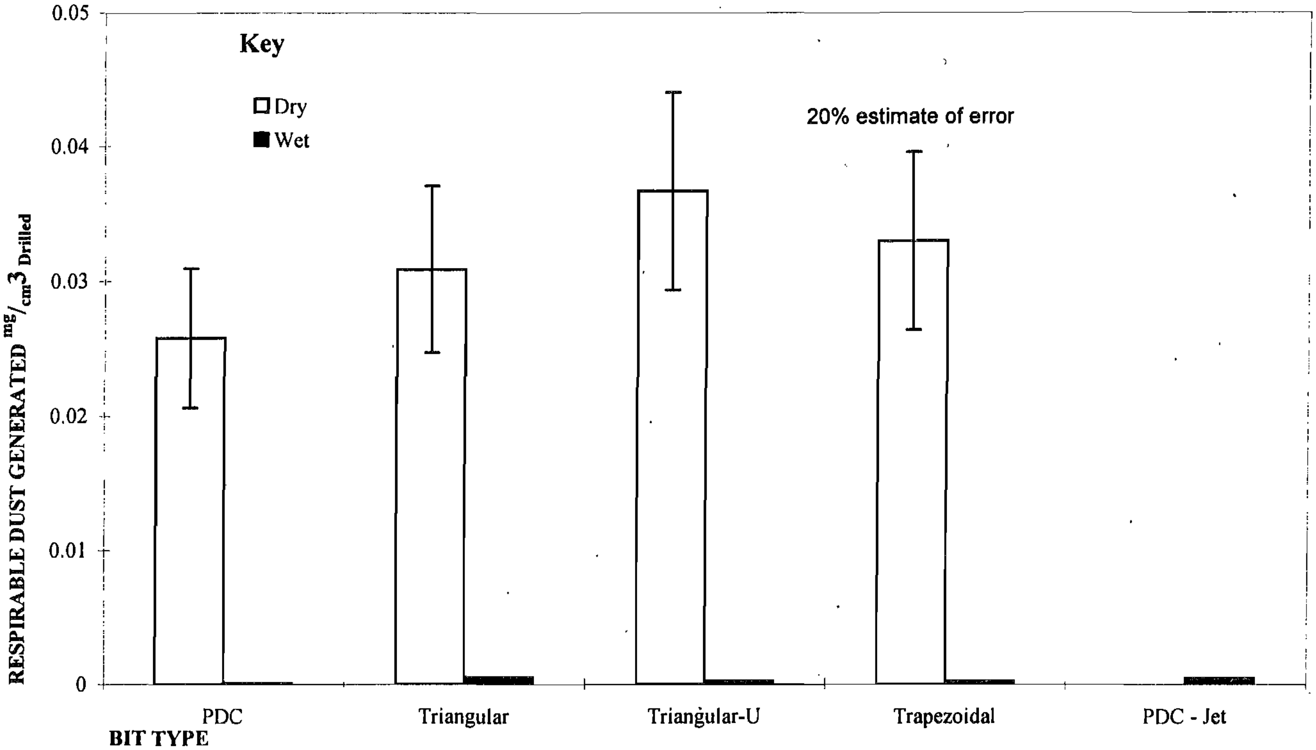
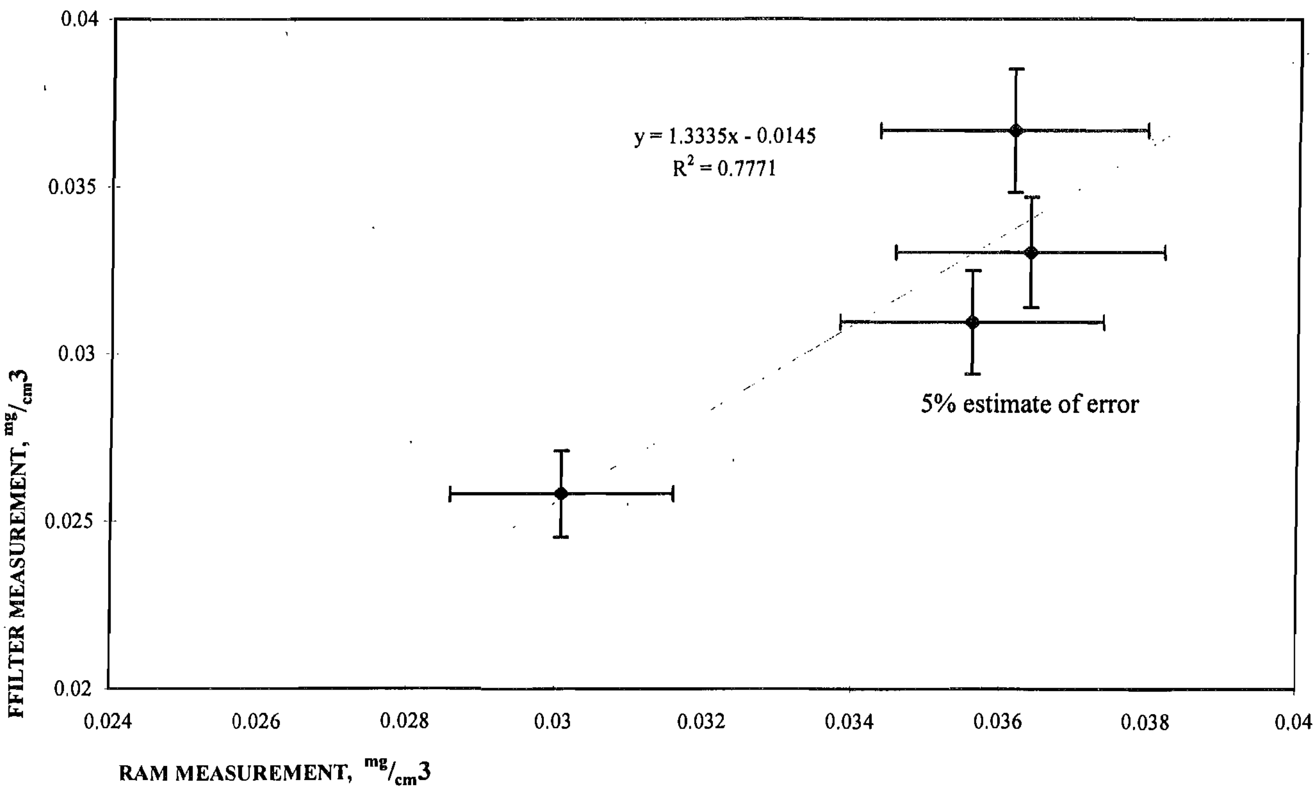


Figure 12
Correlation Between RAM and Filter Measurements



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