

BREAKTHROUGH IN ROOF BOLT DRILL BIT TECHNOLOGY
PROVIDES
200 TO 600 TIMES GREATER BIT LIFE

BY

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Abstract

Recently developed polycrystalline diamond compact (PDC) roof-bolt drill bits were tested by the U.S. Bureau of Mines in nine coal mines in the Utah, Pennsylvania, and West Virginia Coal fields. Roof rock in these mines consisted of shale, silty shale, silty sandstone, mudstone, and sandstone. Compressive strengths of the rock varied from 6,000 to 32,4000 psi, and the quartz content varied from 10 to 85 pct.

Results from the study show that PDC bits have 200 to 600 times greater life than tungsten carbide-cobalt alloy (WC-Co) bits, thereby reducing drill bit cost by more than 60 pct. In test mines containing shale, limestone, and dolomite as roof rock, PDC bit life ranged from 4,500 to 6,000 ft versus an average of 10 ft for a WC-Co bit. In mines where the roof rock contained 1 or 2 ft of shale, overlaid by hard sandstone, PDC bit life averaged more than 1,000 ft. For optimal PDC bit life, it was determined that drill operators must maintain water pressure at 200 to 300 psi, rotational speed at 450-500 rpm, and thrust below 3,000 lb.

PDC bits have the potential to reduce the coal industry's bit cost by several million dollars per year. In addition, by reducing the number of operations a worker must perform, PDC bits may significantly reduce the number of non-fatal accidents that result in lost-time injuries associated with roof-drilling operations.

Introduction

Roof bolting was introduced in U.S. mines before 1940. In 1968, the U.S. Bureau of Mines estimated that 69 pct of coal mined in the United States was mined under bolted roofs, requiring 55 million roof bolts (1)³. With enactment of the Mine Safety and Health Act (MSHA) of 1966 and its subsequent amendments in 1969 and 1974, roof bolting was adopted as a roof support method by MSHA, which requires and enforces its use as part of mine roof support plans. Regardless of the soundness of roof rock, U.S. coal miners are not permitted to work under unsupported mine roofs until all the roof bolts are installed as described in the mine's MSHA-approved roof bolt plan. Today, virtually all U.S. coal mines use roof bolts as a primary or temporary roof support method (2).

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³ Italic numbers in parentheses refer to items in the list of references the end of this report.

In the majority of mines, 4- to 12-ft-deep holes are drilled 4 to 5 ft apart to install different sizes and types of roof bolts. The depth and spacing of holes is usually determined by a mine's past experience with roof fall and cave-in (2-4). In 1985, the Bureau conducted a survey of 34 dry roof-bolt drilling operations in underground coal mines and found that one out of three of these operations exposed operators to excessive dust (5). Roof-bolting activities also accounted for the largest percentage of lost time injuries in underground coal mines (6). Dull bits, application of excessive force, frequent removal of steel from drill holes to replace dull bits, and changing starter and finishing steel were the primary causes of these injuries.

In medium-hard rock (4,7), it may be possible to drill two or three holes with a single WC-Co roof-bolt drill bit; but, in hard sandstone containing more than 85 pct quartz, 5 to 7 WC-Co bits are required to drill a single hole (3-4). At a cost of \$2.15 per bit, roof bolting is an expensive part of a mining operation, and in some mines requires \$2 per ft in bit costs alone (4).

Since 1979, the Bureau has engaged in research to put PDC technology to use in the mining industry. In 1983, it was demonstrated that diamond-coated bits significantly reduced frictional ignition of methane in coal mines (8). In 1987, it was shown that PDC coatings can enhance the life of conical and radial bits by a factor of 5 to 8 times, depending on the design of the PDC bits (9). In 1989, it was demonstrated that it was possible to cut more than 10,000 ft of a very abrasive rock with a single conical bit with no wear on the bit tip, while the similar WC-Co bit wore off completely after cutting 2,500 ft (10). These tests were repeated with similar results with a spherical PDC bit tip. For roof-bolt drilling applications, the main strength of a PDC insert lies in its superior hardness, greater abrasive resistance, and higher thermal conductivity (3.5 times WC-Co).

Recently, the Bureau initiated a field research project to demonstrate the feasibility of using PDC roof-bolt drill bits. This was done in cooperation with MegaDiamond⁴, a PDC and drill bit manufacturer that has recently designed and fabricated a PDC-coated roof-bolt drill bit. The object of the research was to compare the performance and bit life of PDC and WC-Co bits in a wide variety of roof rock types found in U.S. coal mines. Nine mines were visited in Utah, Pennsylvania, and West Virginia. This paper reports the results of these demonstrations and recommends usage parameters for the PDC roof-bolt drill bits tested.

Acknowledgements

We would like to acknowledge the contributions of Dr. Rolland L. Blake of the U.S. Bureau of Mines for performing chemical analyses, X-ray diffraction analysis, and microscopic examination of mine roof rocks. In addition, the Bureau gratefully acknowledges all nine participating coal companies and their officials for conducting field tests and monitoring bit performance.

Polycrystalline Diamond Compact Bits

The first synthetic diamond was manufactured in 1953 by a group of Swedish scientists at Allemanna Svenska ElektriKA, A.B. There are some indications that synthetic diamonds were also independently made in the former Soviet Union and East Germany, and by the General Electric Company

⁴ Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

(G.E.) in the United States at about the same time. However, G.E. was the first, in 1955, to manufacture synthetic diamonds in large quantities for industrial applications by utilizing a high-pressure, high-temperature process (11).

Since 1981, synthetic diamonds have been made from methane (CH₄), carbon monoxide (CO), and many other hydrocarbons using methods such as chemical vapor deposition and plasma chemical vapor deposition. DuPont synthesizes diamonds and diamond-like carbons using high-velocity explosives. Shock wave research on this process was done at Stanford University and the University of Chicago in 1953. The shock wave from high-velocity explosives generates very high pressure for a very short duration, the phase transformation takes place, and the graphite is converted into diamonds with some graphite impurities (12).

The diamond powder used to manufacture PDC coatings of WC-Co inserts for this research was manufactured using a high-pressure, high-temperature process. The PDC insert coatings were manufactured by MegaDiamond by sintering 1 to 6 μm diameter individual particles at one million psi pressure and temperatures exceeding 2,600° F. MegaDiamond mounts a diamond layer on two transitional layers containing different percentages of diamond and cobalt for impact shock absorption, and to minimize uneven thermal expansion of the WC-Co substrate and diamond layer on the top. Physical properties of natural diamond, PDC, WC-Co, and 4340 steel supplied by MegaDiamond are reported in Table 1. The PDC manufacturing process is described in U.S. Patent No. 4,525,178 and 4,604,206.

Experimental Design and Field Testing

For successful use of PDC and WC-Co bits, literature suggests that temperature limitations of 400° C for WC-Co alloys (13) and 700° for PDC inserts, must be observed (14-15). This restriction can be eliminated by introducing water as a cooling and lubricating agent. Past experience with roof-bolt drill bits, both percussive and rotary drilling, suggests that water also removes cuttings from the hole and cleans the bit tip. For these tests, PDC-coated roof-bolt drill bits were used with 80 to 200 psi water pressure to minimize or eliminate overheating of PDC inserts. The PDC bits were operated at half the cutting speed (420 rpm) and thrust (2,500 lb) required by the WC-Co bits, in order to decrease impact or shock loading of PDC inserts; however, in two tests, the thrust level was 3,500 to 4,000 lb.

The PDC and WC-Co bits used for field testing are shown in Figure 1. To compare the performance and bit life of a 1 1/32-in diameter PDC bit against a 1-in diameter WC-Co bit, these bits were mounted side by side on a twin boom roof bolter. Thrust and rotational speeds were maintained at 2,500 or 3,500 lb and 420 rpm for the PDC bit, while the WC-Co bit operated at 7,000 lb thrust and 750 rpm. Water pressure was maintained at 80 to 200 psi for both drills. Initially the PDC and WC-Co bits were examined after drilling each hole; but after running a few tests at each mine, the bits were examined whenever the location of roof bolters was changed. This was essential to maintain mine production.

Nine mines were selected for the study. Although the criteria used for selection was fairly uniform roof rock with no sandstone layers, mixed roof rock was unavoidable. Table 3 summarizes test results from these mines, together with cost per foot for the holes drilled. During field testing, bits from only one PDC bit manufacturer were used. These bits were purchased at \$140 each. The price of new WC-Co bits varied from \$2.05 to \$3.45 per bit, and the resharpened or regrinds were priced at \$0.75 to \$1.05 per bit. The price comparisons in Table 3 are based on \$140 for PDC bits and \$2.15 for WC-Co bits. For purposes of these calculations, the lower values of bit life for PDC bits were rejected

because during the first stages of field testing, numerous adjustments were made to the thrust, rotational speed, and water pressure to optimize bit life.

Several roof-rock core samples were collected from each mine test area and analyzed for their physical, mechanical, and chemical properties. Petrofabric analysis, X-ray diffraction analysis, chemical analysis, and microscopic examinations of roof rocks from Mines No. 1, 2, 4, 7, 8, and 9 were done to identify rock types and mineral composition. The roof rock geology of Mines No. 3, 5, and 6 was too complex. Here, mudstone and sandstone were grossly interbedded. Samples from these mines were too heterogeneous and could not depict the roof rock conditions accurately for microscopic examination.

Chemical analysis of roof rock was done for the quartz content and the binding matrix. Test results for Mines No. 1, 2, 4, 7, 8, and 9 are in Table 2. The engineering staff of Mine No. 8 determined the silica content of its roof rock using a different method. In both cases the quartz content was 70 pct. Table 2 illustrates the complexity of rock minerals and their influence on rock strength and abrasivity.

Mechanical properties of roof rock were determined by using a servo-controlled 900 KN (200,000-lb) capacity testing machine. The mean value and standard deviation for mechanical properties are in Table 3. During field tests, it was impossible to obtain core samples from the test areas of Mines No. 4, 6, and 7, and physical properties for these roof rocks are unavailable.

Field Results

Western Mines

For initial testing, Mine No. 1, located in a southeastern Utah coal field, met the selection criteria. The roof rock consists of siliceous dolomite with a compressive strength of 32,000 psi. The dolomite contains about 16 pct angular quartz particles, uniformly distributed throughout.

Initially, test bits were examined after drilling each hole. The PDC bit showed no visual wear and the bit surface was cold to the touch. The WC-Co bit showed pits on its culling edge, as shown in Figure 2, and occasionally was too hot to touch. After drilling 15 holes, the drill setting (thrust and rotational speed) and the positions of the PDC and WC-Co bits were interchanged to minimize effects of difference in roof rock from one side of the face to the other, operator bias, and any differences in roof-bolt drills. The roof-bolt operators took extra precautions to avoid impact fracture of PDC inserts.

On the second day, while passing through a clay pocket, the drill speed increased abruptly and the bit impacted the top of a clay pocket at a much higher speed, causing a small chip of the PDC insert to crack off from the bit apex. This fracture did not affect the bit life. The presence or absence of PDC coating on the interior of the insert had no effect on bit life and eliminating PDC coating in this area may reduce bit cost.

During the first trial, 401 holes were drilled with a single PDC bit, with no visual indication of abrasion or other damage. Examination of the cutting edge showed gradual abrasion was occurring at a microscopic level. The abrasion was so uniform that it was undetectable by the unaided eye (Figure 3). During this period, 34 WC-Co bits were consumed in drilling the same number of holes.

The roof rock of Mine No. 2 consisted of shale, silty shale, and sandstone, with a very small number of planes of weakness. The sandstone

contained more than 16 pct quartz, with grain size ranging from 20 to 100 μ m. The mine was unable to maintain 80 psi water pressure with an in-line pump, so a new 150-hp pump was installed, and the water pressure was boosted to 200 psi. This change doubled the bit life, but the PDC bit started to plug up. To eliminate this new problem, the rotational speed of the roof-bolt drill was increased from 300 to 450 rpm, with no adverse affect on the PDC insert. The PDC bit showed no visual wear for 3 days. Later the mine reported this bit drilled 6,000 ft before one of the inserts failed.

The roof rock in Mine No. 3 consisted of mudstone and sandstone, but it was impossible to obtain rock samples for chemical analysis and microscopic examination. Although water pressure higher than 80 psi was unobtainable, the PDC bits were able to drill 2,000 to 4,000 ft, versus a maximum of 30 ft for the WC-Co-bits.

At Mine No. 4, PDC bit life varied from 816 to 3,192 ft. Figure 4 is a map of Mine No. 4 roof-rock formations and shows typical examples of variations in roof-rock formations. Figure 4 shows that roof rock consists of broken layers of mudstone/coal mudstone, inter-bedded mudstone, siltstone, and sandstone mixed with mudstone. The thickness of each layer varies from the location of one drill hole to another. Roof rock in each of the mines also contains numerous major and minor cleavage planes and cleats. Microscopic and macroscopic cracks run in all directions, crossing each other, but cannot be shown on the map.

During the trial period, six drill steels with PDC bits were lost in the drill holes. This occurred when the operators attempted to retrieve stuck bits and the use of excessive force caused the drill steels to break off. This also occurred in other mines that had hard and fractured roof rock, especially Mines No. 8 and 9.

Physical and microscopic examination of the roof rock from Mine No. 5 indicated that the roof rock is very weak. The weakness of this roof rock is confirmed by the superior performance of the WC-Co bit (244 ft). During the first trial, the PDC bit life reached 3,192 ft. Since the roof rock in this mine is quite soft and water pressure is higher than 200 psi, both Wc-Co and PDC bits performed satisfactorily.

Eastern Mines

After completing the first phase of testing in the southeastern Utah coal fields, it was decided to conduct additional tests in eastern coal mines that have sandstone roof rock formations, where quartz content and the strength of roof rock are known to be much higher. Two of the selected mines are located in West Virginia coal fields, and the other two are in the Pennsylvania coal fields. The quartz content of the roof rock in these mines varies from 70 to 85 pct and the compressive strength varies from 27,000 to 28,000 psi. The WC-Co bit life in Mines No. 6 and 7 ranged from 4 in to 10 ft.

Mines No. 6 and 7 were able to maintain thrust between 3,000 and 3,200 lb, rotational speed at 420 to 480 rpm, and water pressure at 200 psi. The roof rock in Mine No. 6 consisted of interbedded mudstone and sandstone, while in Mine No. 7 it consisted entirely of dark grey sandstone. During field testing, the PDC bit life averaged 1,400 ft in Mine No. 6 and 1,080 ft in mine No. 7.

Mine No. 8 provided 200 psi water pressure and between 450 to 480 rpm rotational speed, but was unable to reduce thrust to below 4,000 lb. In this mine, the PDC bit drilled 108 ft, and the WC-Co bit drilled only 4 to 6 in. The roof rock has a compressive strength of 28,400 psi and contains 85 pct quartz. It is highly fractured which caused bits to stick and break. While drilling through hard sandstone, occasionally a protrusion

is left on the back of the PDC insert which creates frictional forces that slow the penetration rate. By filing this protrusion off, it is possible to reuse the bits for an extended period.

Figure 5 illustrates the variation in the silica content of a core sample from the test area in Mine No. 8. The shale changes into sandy shale that is capped by a layer of fine-grained sandstone (30 to 100 μm) within 9 in. The silica content may change gradually or abruptly from the bottom to the top, or from one side to the other, of a drill hole.

Mine No. 9 probably has the strongest and hardest roof rock found in any U.S. coal mine. The shale and quartz sandstone in the roof rock are very uniform in texture with no planes of weakness. The sandstone contains 94.8 pct silica and has a compressive strength of 27,320 psi. The quartz particles are 300 to 1,000 μm long, angular in shape, and interlocked. This mine was included in the test sequence to determine the upper limit for application of the PDC bits.

At Mine No. 9, a continuous miner and two roof bolters were connected to the same water line. When all three of the machines were working at the same time, the water pressure dropped below 10 psi, and in less than 5 minutes, two PDC bits were damaged--the first due to overheating and the second due to overthrusting. Afterwards, attempts were made to maintain the water pressure at 250 psi and two more PDC bits were tested. The last two PDC bits achieved a bit life of 72 and 88 ft. This mine is using resharpened bits, and at the current pricing level, PDC bits were found to be uncompetitive at this location.

Comments on Field Results

In Mines No.1 through 5, it was impossible to measure thrust precisely because of a lack of an accurate pressure gauge. To insure accuracy, in Mines No. 6 through 9, the thrust was measured by using a load cell, which is considered adequate to determine and adjust the thrust for PDC bits.

At each mine, numerous attempts were made to compare the penetration rates of PDC and WC-Co bits, but it was impossible to make a fair comparison because the cutting edge of the WC-Co bit became dull or worn-out after drilling 10 to 15 ft. The cutting edge of the PDC bit remained sharp even when it was experiencing gradual microscopic abrasion on its periphery. The PDC bits were operating at one-half the thrust and rotational speed required by the WC-Co bits.

In the majority of cases, the WC-Co bits had to be replaced after drilling two holes. In the eastern mines, the WC-Co bits were changed frequently in the middle of drilling a single hole. Time lost in bit changing was excessive and it was impossible to compare the penetration rate. When the PDC and WC-Co bits are new, no difference in performance or penetration rate is detected. In most mines, the miners were quick to accept PDC bits, since they reduced by more than fifty times the necessity of replacing worn-out bits.

During the testing period, brazing, roll pins, and drill steels failed. Because PDC bits are a new technology, no brazing alloys, drill steels, or roll pins compatible with PDC bit life are available on the market. In roof rock containing less than 25 pct quartz, all bits failed because of brazing fatigue during prolonged drilling. Other researchers have also made this observation (9).

Field experience also shows that the optimum parameters may be different for various groups of rock or different geological conditions. Many roof rocks contain a very small percentage of quartz or no quartz at all, and their compressive strength is two-fold higher than the average

strength of sandstone. Since these rock types are not abrasive, it may be possible to increase rpm and obtain higher penetration rates. For example, siliceous dolomite roof rock in Mine No. 3 has a compressive strength of 32,500 psi. This mine was unable to obtain satisfactory penetration rates, so they replaced the roof-bolt motors to increase the rotational speed and thrust, which solved the problem.

The test results in Table 3 show that during field testing only three of these mines were able to obtain maximum bit life. To achieve best results from PDC bits, mines have to determine rpm, thrust, and water pressure by a trial and error method for their individual cutting conditions.

At the conclusion of the first series of tests, it was decided to monitor the performance of the PDC bits in cooperation with the test mines over a period of four months. An informal understanding was reached with these mines to record bit life, collect used bits, and gather other useful information pertaining to performance of PDC bits. Each bit received by the Bureau was analyzed to determine the type of failure.

Discussion

For the purpose of this discussion of the test results, the roof rocks from the test mines have been divided into three groups. The first group consists of roof rock containing only shale and siliceous dolomite, with less than 12 to 35 pct quartz. The second group contains 2 to 3 ft of sandstone on top of shale and mudstone. The third group consists of massive sandstone roof rock containing 75 pct or higher quartz--this group contains no shale, limestone, or dolomite rock formations.

Based on this multi-mine study monitored over four months, it is possible to state that PDC bits have 200 to 600 times greater bit life over WC-Co bits. The following performance was obtained from PDC bits under field conditions:

- * PDC bits are capable of drilling up to 6,000 ft in roof rock that contains from 15 to 20 pct quartz, while a single WC-Co bit can drill only 15 to 20 ft, with a possibility of drilling an additional one or two holes after resharpener. In softer rock formations, it will be possible to increase thrust, rotational speed, and water pressure to remove cuttings, and obtain much higher penetration rates and bit life greater than 6,000 ft.
- * In softer rock formations like shale, limestone, and dolomite, and in medium-hard sandy shale overlaid by 1 to 2 ft of softer grade sandstone, PDC bits can drill 2,000 to 2,400 ft, while WC-Co bits can drill only 10 to 15 ft before resharpener.
- * In sandstones having compressive strengths in excess of 28,000 psi and quartz content greater than 85 pct, PDC bits can drill 80 to 100 ft or more, while WC-Co bits can drill only 4 to 6 in.

Figure 7 shows that there is a definite relationship between the quartz content of roof rock and PDC bit life. Bit life, measured in ft, decreases with increasing quartz content of rock, and the relationship can be described by the following equation:

$$Y = A_1X + A_2X^2 + C$$

where $A_1 = -92.55$ pct quartz
and $A_2 = -0.35$ pct quartz
 $C = 5,764$ ft

Some investigators have suggested that bit life can be related to either strength or hardness (16,17). Many investigators in the field of rock mechanics believe that the strength and hardness of rocks are related to each other (16-18), but, in reality, they are only occasionally associated with each other. Siliceous dolomite found in the roof rock of Mine No. 3 has a compressive strength of 32,500 psi, which is much higher than the compressive strength of sandstones found in Mines No. 6-9. However, despite its lower compressive or tensile strength, sandstone is very abrasive and the bit life in Mines No 6 and 9 was much less than in Mine No. 1.

Naively coal field in South India and the Canadian tar sands in Alberta, Canada, contain consolidated sands with virtually no cohesive, compressive, or tensile strength; but bit life in these mines is the lowest of any sedimentary rocks found anywhere in the world (19). Therefore, it is safe to state that higher quartz content in rock is what reduces bit life, and quartz content should be used to predict bit life. Another researcher has suggested that tool wear may be expected to increase with an increase in abrasiveness and quartz content of coal measure rocks (20).

Since 1970, on the average, two incidents per year of frictional ignition of methane during roof bolting have been reported by MSHA (21). Considering the reduction in friction in the PDC bit-rock contact area, the superior thermal conductivity of PDC bits, and the absence of temperature rise because water flows around the bit tip, it can be stated that the PDC bits have the potential to eliminate methane ignition caused by roof bolt drilling.

Conclusions

Based on this multi-mine study over a period of four months, it is possible to state that the PDC bit has a 200 to 600 times greater bit life than the WC-Co bit, with the following performance being obtained from PDC bits under numerous field conditions:

- * In almost all tests, bit cost per ft was reduced by at least 60 pct.
- * PDC bits are capable of drilling up to 6,000 ft in roof rocks containing up to 25 pct quartz, while a single WC-Co bit can drill only 15 to 20 ft.
- * In soft to medium-hard sandy shale overlaid by 1 to 2 ft of softer grade sandstone, PDC bits can drill 2,000 to 2,400 ft, while the WC-Co bits can drill only 10 to 15 ft.

- * In sandstones having compressive strengths of 28,000 to 32,000 psi and quartz contents greater than 85 pct, PDC bits can drill more than 100 ft, while WC-Co inserts can drill only 4 to 6 in.
- * In softer rock formations, it will be possible to increase thrust, rotational speed, and water pressure to remove cuttings and obtain a much higher penetration rate and bit life greater than 6,000 ft.
- * In mine roof rock containing less than 40 pct quartz, the PDC bit failure primarily occurs because of brazing fatigue, while in roof rock containing greater than 75 pct quartz, bit failure is commonly caused by abrasion.

When the PDC and WC-Co inserts are new, there is no difference in the penetration rate. The sharp edge of a WC-Co bit becomes dull after drilling one to three holes, and after this, it is unable to cut rock. The PDC bit edge remains sharp throughout its life, however, and the bit shows no reduction in penetration rate. The increase in bit life reduces the bending back, stooping, and twisting motions needed to change the bits. A 200 to 600 times increase in bit life should reduce injuries occurring during bit replacement and other activities related to roof-bolting operations, but the test period was too short to verify this assumption.

Bit failure can be divided into four categories. The first category consists of catastrophic failure of drill steels or bits caused by excessive thrust and shearing of bit bodies or steel. The second type of failure is thermal fatigue caused by loss of water pressure or excessive thrust. Both of these failures are common to PDC and WC-Co bits. The third category of bit failure is associated with brazing failure of PDC insert mounting. The fourth category of failure is microscopic abrasion because of the presence of quartz. This is the least destructive type of PDC bit failure.

Recommendations for Future Research

Under field testing conditions, it was impossible to devise a perfect combination of thrust, rotational speed, and water pressure; therefore, to obtain the highest penetration rate and the greatest bit longevity, laboratory tests should be undertaken to find an optimum combination of these parameters.

The PDC bit design itself appears to be superior, and it should be tested with a WC-Co disk alone. In all likelihood, this attempt will lead to a starter bit without the diamond coating.

At present, only a fraction of the diamond coated surface is consumed in roof-bolt drilling. So, to reduce bit cost in the future, the PDC coating should be applied only to the surface areas subjected to the cutting action.

An increase in the thickness of WC-Co backing may enhance bit life.

Drill steels need to be improved because the existing drill steel or rods are unable to withstand extended cyclic loading demanded by PDC bits. In many cases, the premature bit failure is caused by the cracking, bending, and splitting of the drill steel.

Brazing used to mount the PDC needs to be improved because the brazing failed when the bits were used for more than one week. This problem may be alleviated by sandwiching the PDC bit tips at the bottom or by some other mechanism yet to be devised.

Since the roll pins currently used to attach the bits fail under fatigue, a suitable, long-lasting roll pin needs to be developed so that bits are not damaged when roll pins fail.

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Table 1-Physical properties of diamond, PDC, WC + 6% Co, and 4340 steel*

Material Properties	Unit	Natural Diamond	PDC	WC + 6% Co	4340 steel
Density	g/cm ³	3.52	3.0-3.25	14.95	7.8
Hardness-Knoop	kg/mm ²	6,000-9,000	5,000-8,000	1,475	558
Young's modulus	10 ⁶ psi	105-152	132	92	29
Poisson's ratio	NA	0.1-0.29	0.2	0.22	0.3
Tensile strength	10 ³ psi	NA	NA	160	238
Transverse rupture strength	10 ³ psi	NA	125-225	275	NA
Compression strength	10 ³ psi	1,260	890	780	238
Fracture toughness K _{IC}	Ksifin	3.1	6.3	10.8	45.8
Coefficient of thermal expansion					
25-100° C	10 ⁻⁶ /°C	1.34	1.5-3.8	4.3	11.2
25-200° C	NA	NA	NA	4.7	12.4
25-400° C	NA	2.29	NA	5.0	13.6
25-600° C	NA	NA	NA	5.4	14.3
25-800° C	NA	3.14	NA	5.6	NA
Thermal conductivity					
25° C	W/cm-°C	5-20	5.43	1.0	0.48

NA Not applicable

* Data provided by Smith International, Inc., Provo, Utah.

Table 2—Chemical analysis of coal roof rocks

Oxide	Mine	Mine	Mine	Mine	Mine	Mine
	No. 1	No. 2	No. 4	No. 7	No. 8	No. 9
SiO ₂	32.8	15.2	49.1	91.6	73.6	94.8
Al ₂ O ₃	4.0	3.8	12.3	4.2	12.9	1.68
TiO ₂ . . . . .	.17	.17	.65	.3	1.0	.07
FeO	2.4	1.8	.75	.75	1.7	.24
Fe ₂ O ₃ . . . . .	.3	.00	.47	.13	.6	.00
MnO . . . . .	.04	.03	.03	.01	.03	.01
MgO	8.6	14.3	6.63	.23	.9	< .16
CaO	22.0	21.5	8.39	.11	.08	< .14
Na ₂ O	< .07	< .07	< .07	< .07	.15	< .07
K ₂ O . . . . .	.58	.94	2.29	.48	2.05	.20
P ₂ O ₅ . . . . .	.12	.14	.20	1.41	4.93	.09
LOI + 110	29.0	40.23	17.3	.34	.27	.68
LOI - 110	3.32	.06	.64	.34	.27	.06
Total	105.40	100.24	100.82	101.97	100.48	100.20

Table 3—Performance and cost effectiveness of WC-Co and PDC bits in nine coal mines

Mine No.	Roof rock type	Properties of roof rock		Bit life, ft (bit cost, per ft)	
		Compressive strength, psi	Silica content, pct	WC-Co	PDC
1 . .	SL, silty SS, SS	25,772	16	10 (\$0.20)	4,500-6,000 (\$0.03-\$0.02)
2 . .	Siltstone, SS, MS	6,369	NA	5-10 (\$0.41-\$0.20)	1,560-4,940 (\$0.09-\$0.03)
3 . .	SL	32,540	12	16-31 (\$0.13-\$0.07)	2,492-4,604 (\$0.05-\$0.03)
4 . .	MS, SS	NA	NA	18 (\$0.11)	3,900 (\$0.04)
5 . .	Dolomitic shale	8,000-10,000	35	96-244 (\$0.02-\$0.01)	816-3,192 (\$0.17-\$0.04)
6 . .	Interbedded mudstone, SS	NA	NA	10 (\$0.20)	1,400 (\$0.10)
7 . .	Dark grey SS	NA	85	2-3 (\$1.02-\$0.68)	500-1,080 (\$0.28-\$0.12)
8 . .	SL, SS	28,412	85	0.5 (\$2.00)	98 (\$1.14)
9 . .	SL, SS	27,320	70	0.5 (\$2.10)	72-88 (\$1.94-\$1.59)

NA Not available

MS Mudstone

SS Sandstone

SL Shale

WC Tungsten carbide

PDC Polycrystalline diamond compact

LIST OF ILLUSTRATIONS

Figure 1.--Test bits.

Figure 2.--Macroscopic chipping of cutting edge of WC-Co bit after drilling a single, 4-ft hole in sandstone.

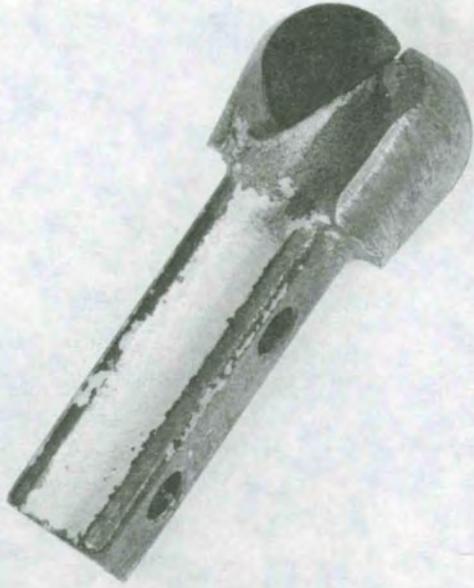
Figure 3.--Microscopic abrasion of the cutting edge of PDC bit after drilling 401 holes in siliceous dolomite.

Figure 4.--Example of heterogeneity of roof rocks.

Figure 5.--Roof rock core sample from mine No. 8. Variation in shade indicates variation of quartz content.

Figure 6.--Comparison of bit life of WC-Co and PDC bits in nine coal mines.

Figure 7.--Relationship between PDC bit life and quartz content of roof rock.



PDC Roof drill bit



WC Roof drill bit

Figure 1.--Test bits.

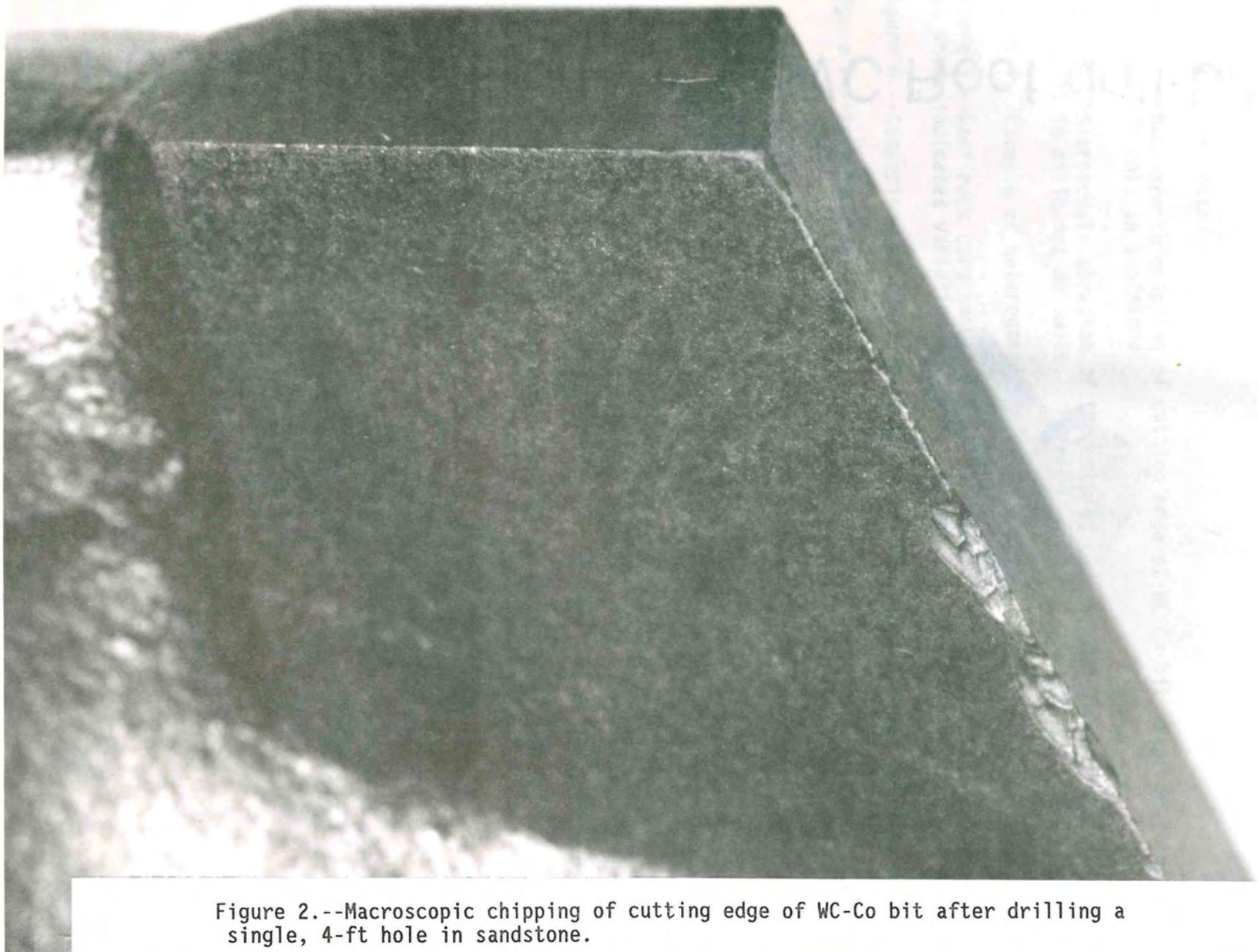


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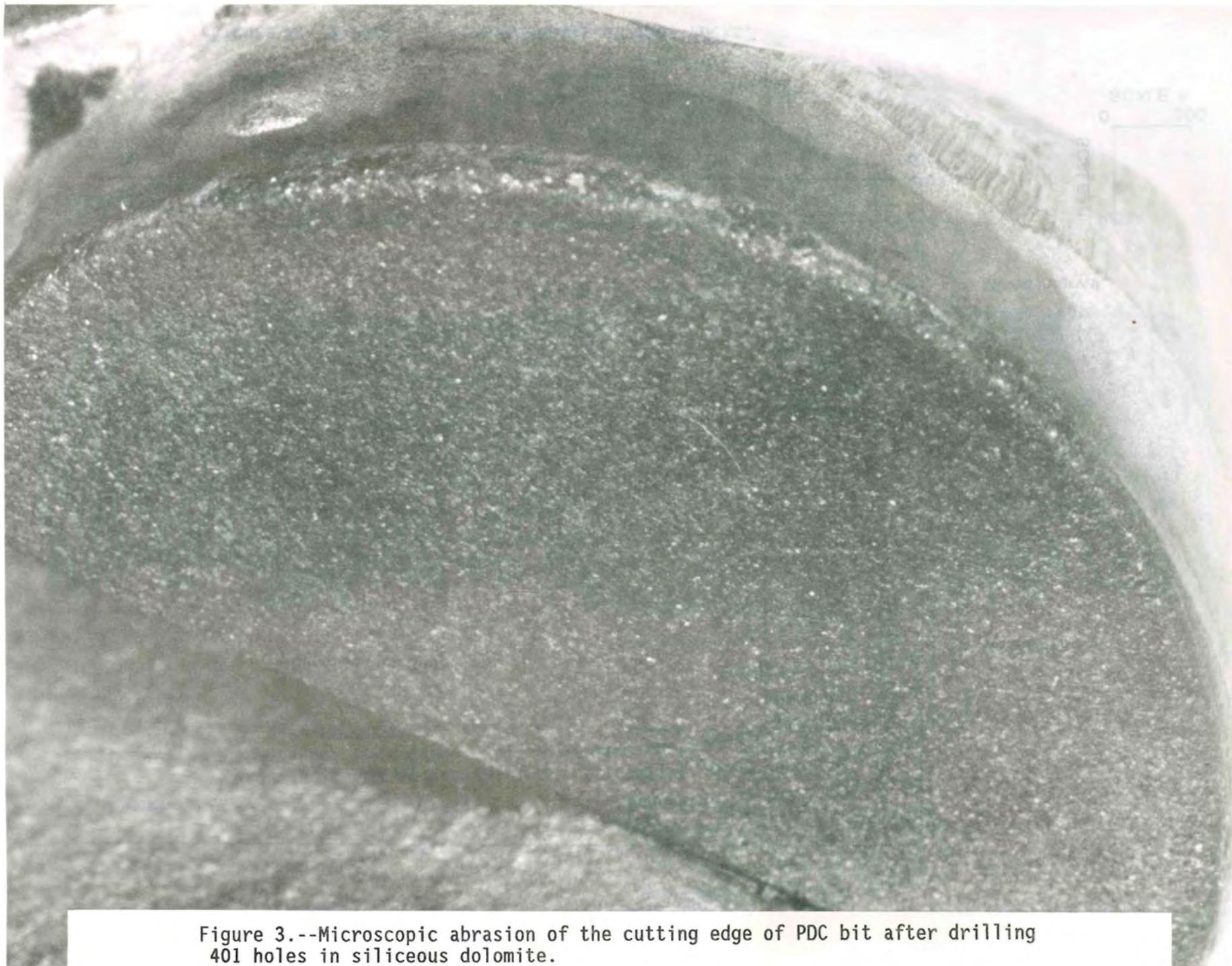


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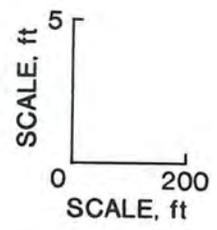
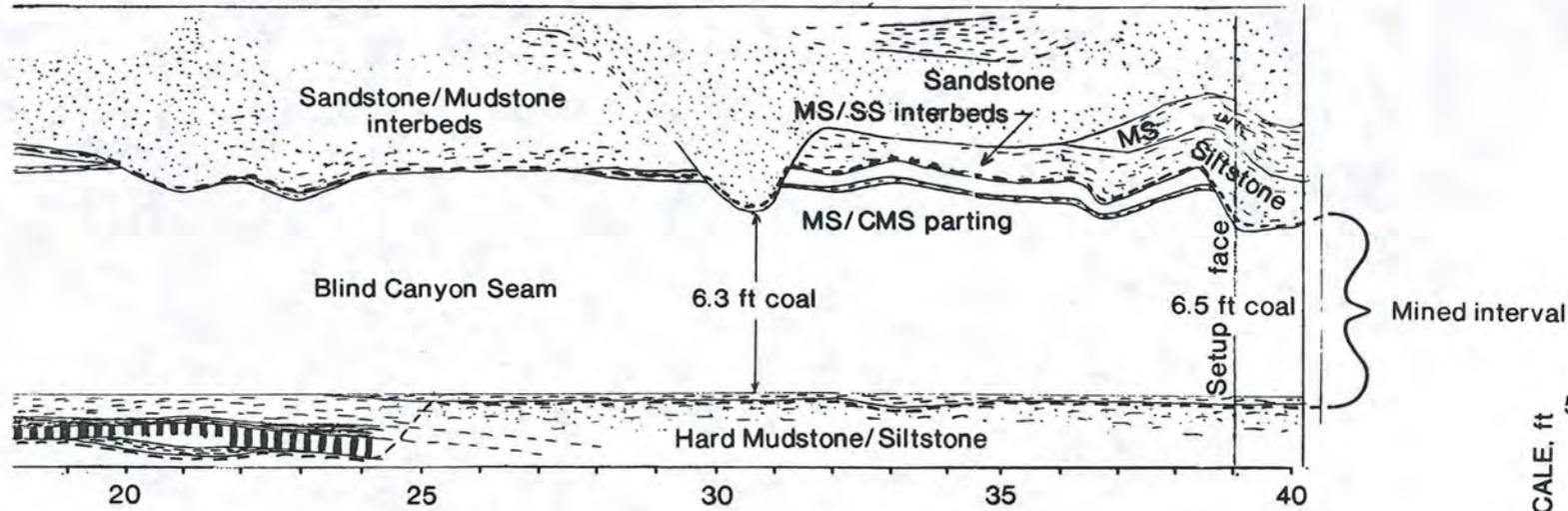
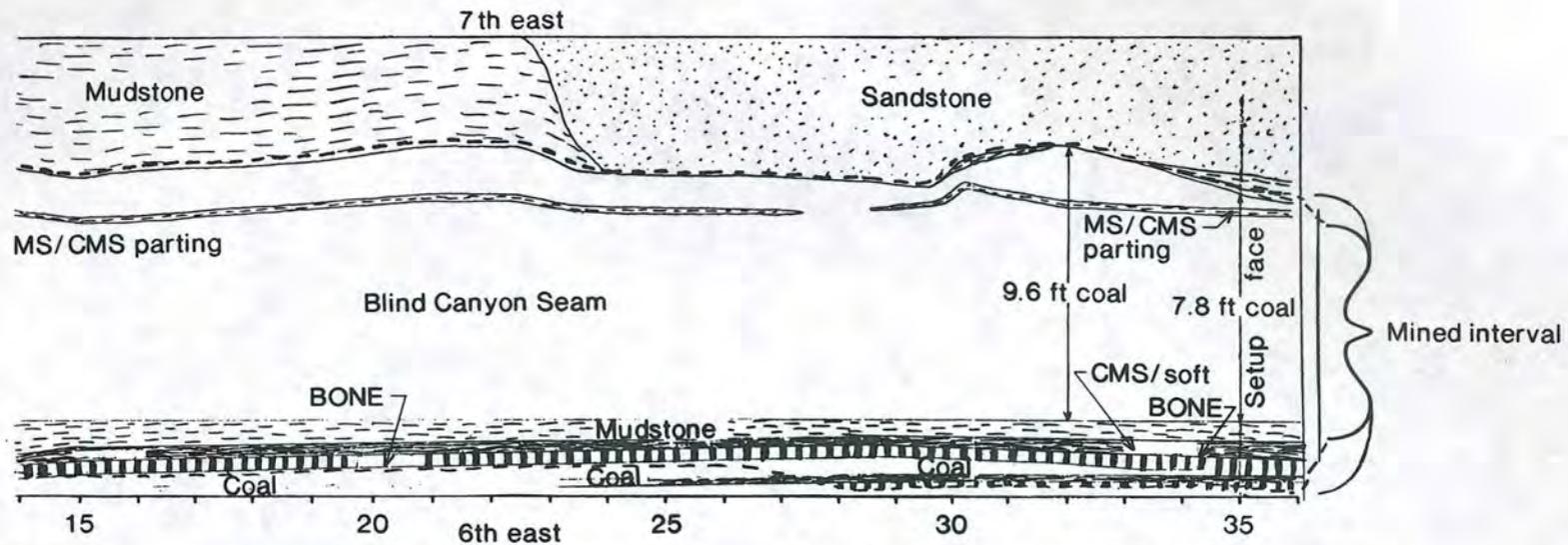


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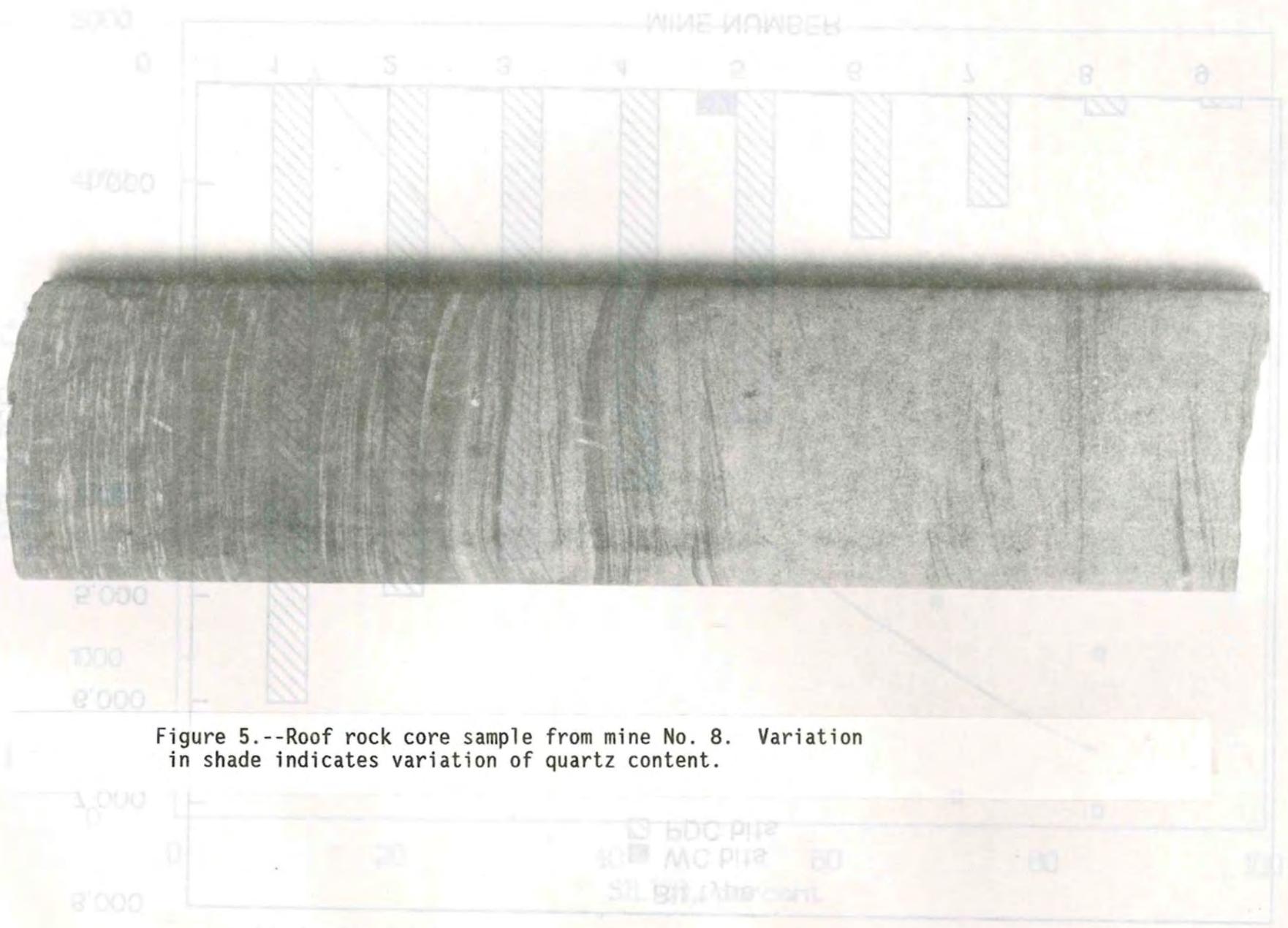


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Figure 7.--Relationship between PDC bit life and quartz content of roof rock

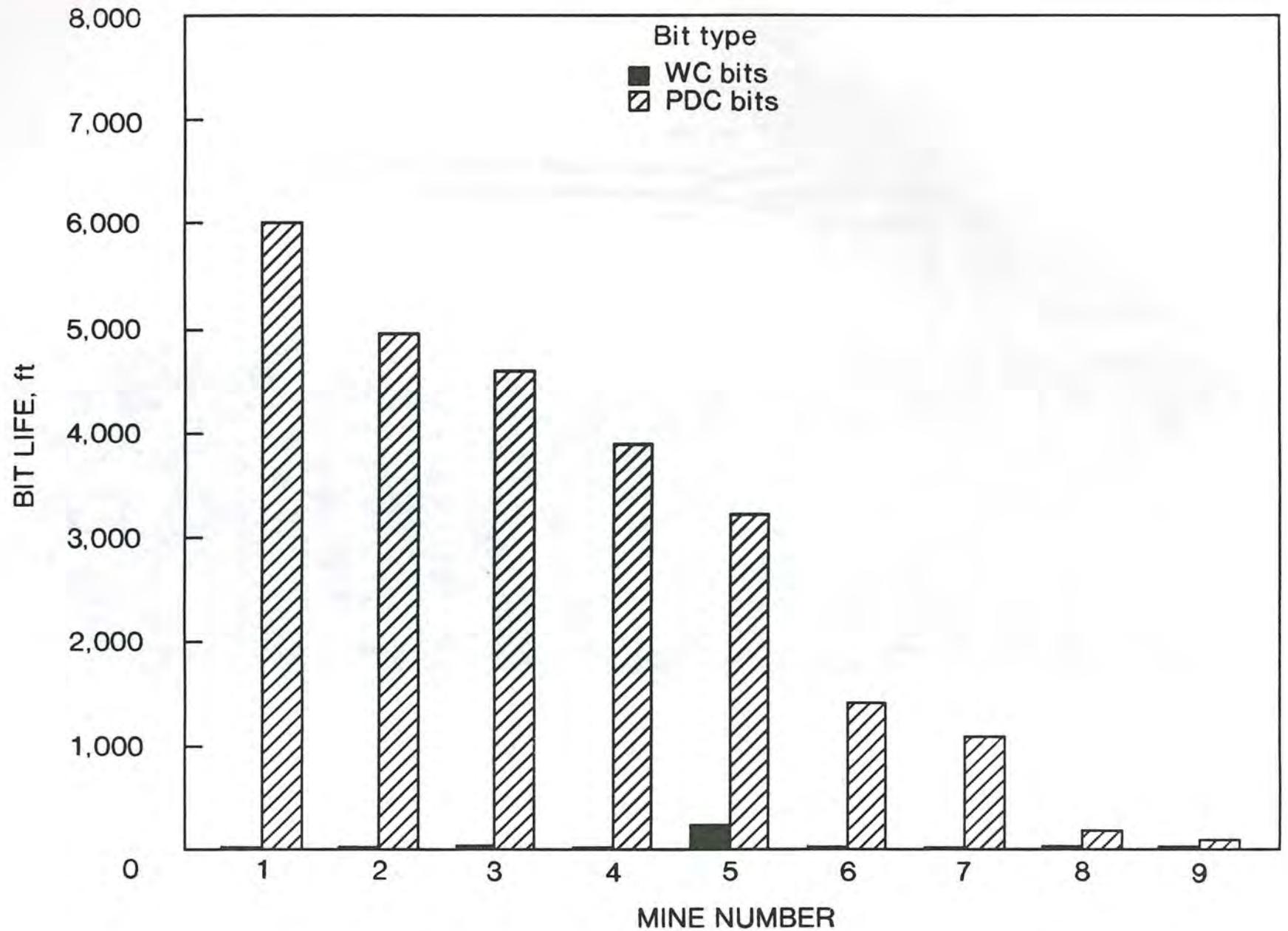


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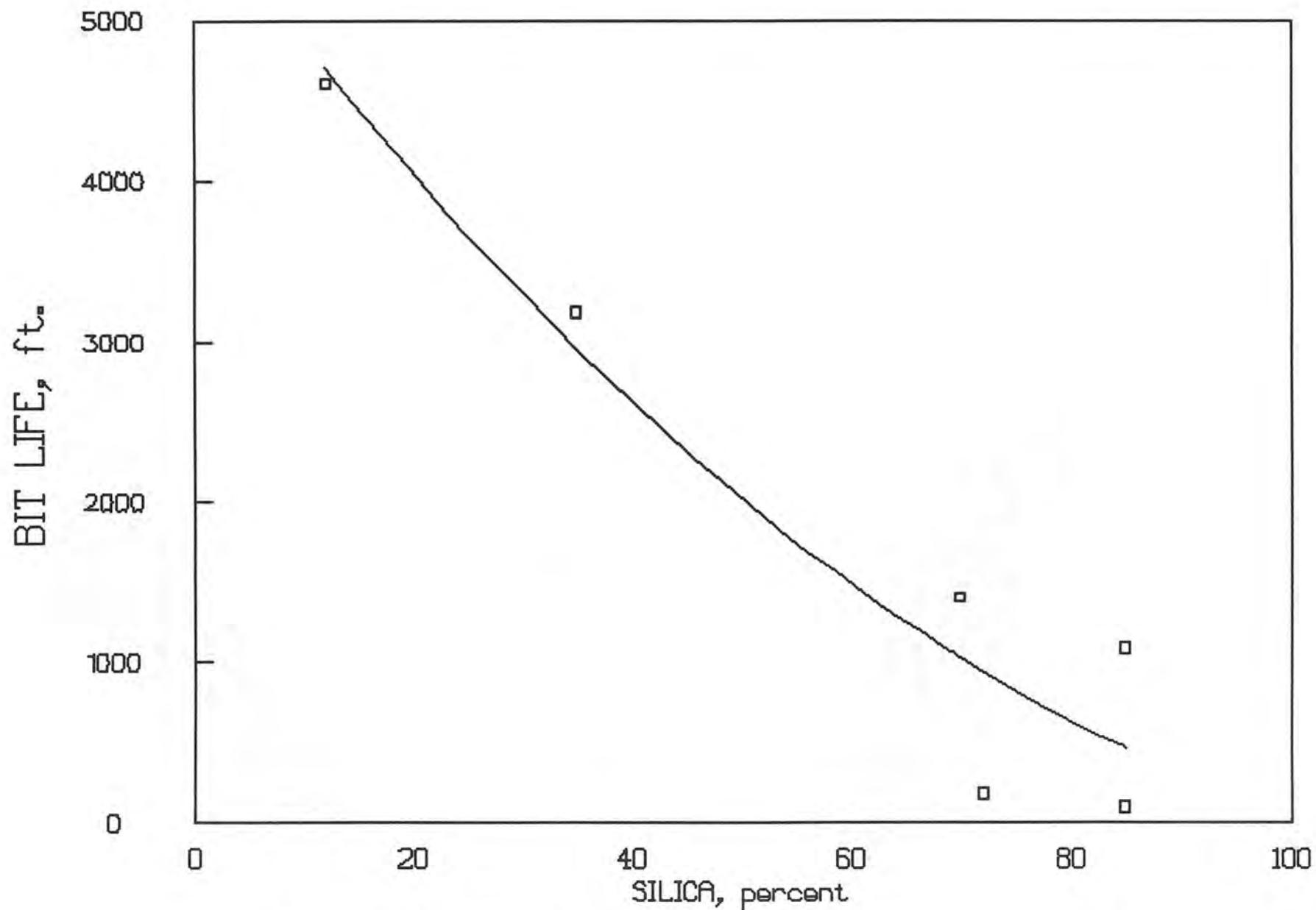


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Proceedings Fourth Conference on Ground Control For Midwestern U.S. Coal Mines

held at

**Ramada Hotel
Mt. Vernon, Illinois**

November 2-4, 1992

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November, 1992