RI 9237

REPORT OF INVESTIGATIONS/1989

Evaluation of High-Pressure Front-Mounted Water Jets for Frictional-Ignition Suppression

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel J. Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

Taylor, Charles D. (Charles Darrell), 1946-
Evaluation of high-pressure front-mounted water jets for frictional-ignition suppression.

(Report of investigations; 9237)

Bibliography: p. 8

Supt. of Docs. no.: I 28.23:9237.

1. Mine explosions—Prevention. 2. Bits (Drilling and boring)—Safety measures. 3. Water-jet. 4. Coal mines and mining—Safety measures. I. Furno, A. L. (Aldo L.). II. Title. III. Series: Report of investigations (United States. Bureau of Mines); 9237.

TN23.U43 [TN313] 622 s [622'.8] 88-600410

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	hp	horsepower
fpm	foot per minute	in	inch
ft	foot	pct	percent
ft^3	cubic foot	psig	pound (force) per square inch, gauge
gpm	gallon per minute	rpm	revolution per minute

EVALUATION OF HIGH-PRESSURE FRONT-MOUNTED WATER JETS FOR FRICTIONAL-IGNITION SUPPRESSION

By C. D. Taylor[1] and A. L. Furno[2]

ABSTRACT

The U.S. Bureau of Mines conducted a laboratory study to determine what effect use of water-jet-assisted cutting has on frictional-ignition suppression. A single bit with a steel tip, installed on a rotating drum, repeatedly made 22-in-long cuts in a block of Berea sandstone. The drum was operated in an enclosure that contained an explosive methane-air mixture. High-pressure front-mounted water jets operating at 2,000 to 5,000 psig and low-pressure rear-mounted sprays operating at 80 psig were used; the number of ignitions that occurred with each type of spray was compared. The rear-mounted spray was more effective for preventing frictional ignitions than the front-mounted water jet.

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INTRODUCTION

BACKGROUND

There are numerous ways in which ignitions of flammable methane-air mixtures can occur in underground mines. The most frequent cause is frictional heating, which occurs when a metal cutting bit strikes rock, such as sandstone, that contains quartz. Data compiled by the U.S. Mine Safety and Health Administration (MSHA) indicate that there was an increase in the number of frictional ignitions occurring in underground coal mines between 1978 and 1986 (fig. 1). Numerous investigations (*1-8*)[3] have studied factors that affect the probability of such ignitions.

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

During mining, methane released at the working face mixes with the ventilation airflow to form a combustible mixture. Although small, hot pieces of metal and rock are formed during mining, they usually are not large enough to ignite the mixture. Most ignitions occur after the metal cutting bits strike the sandstone, and hot streaks of metal, usually several inches long, are deposited on the rock surface. The temperature of the hot streaks is high enough and the area of the deposited material is large enough to ignite the combustible methane-air mixture.

Most attempts to prevent frictional ignitions emphasize use of ventilation airflow to maintain methane levels below 1 pct, as required by MSHA regulations (*9*). The explosive range for a methane-air mixture is 5 to 15 pct. As the airflow increases, potentially explosive concentrations of methane tend to localize in small pockets near the face

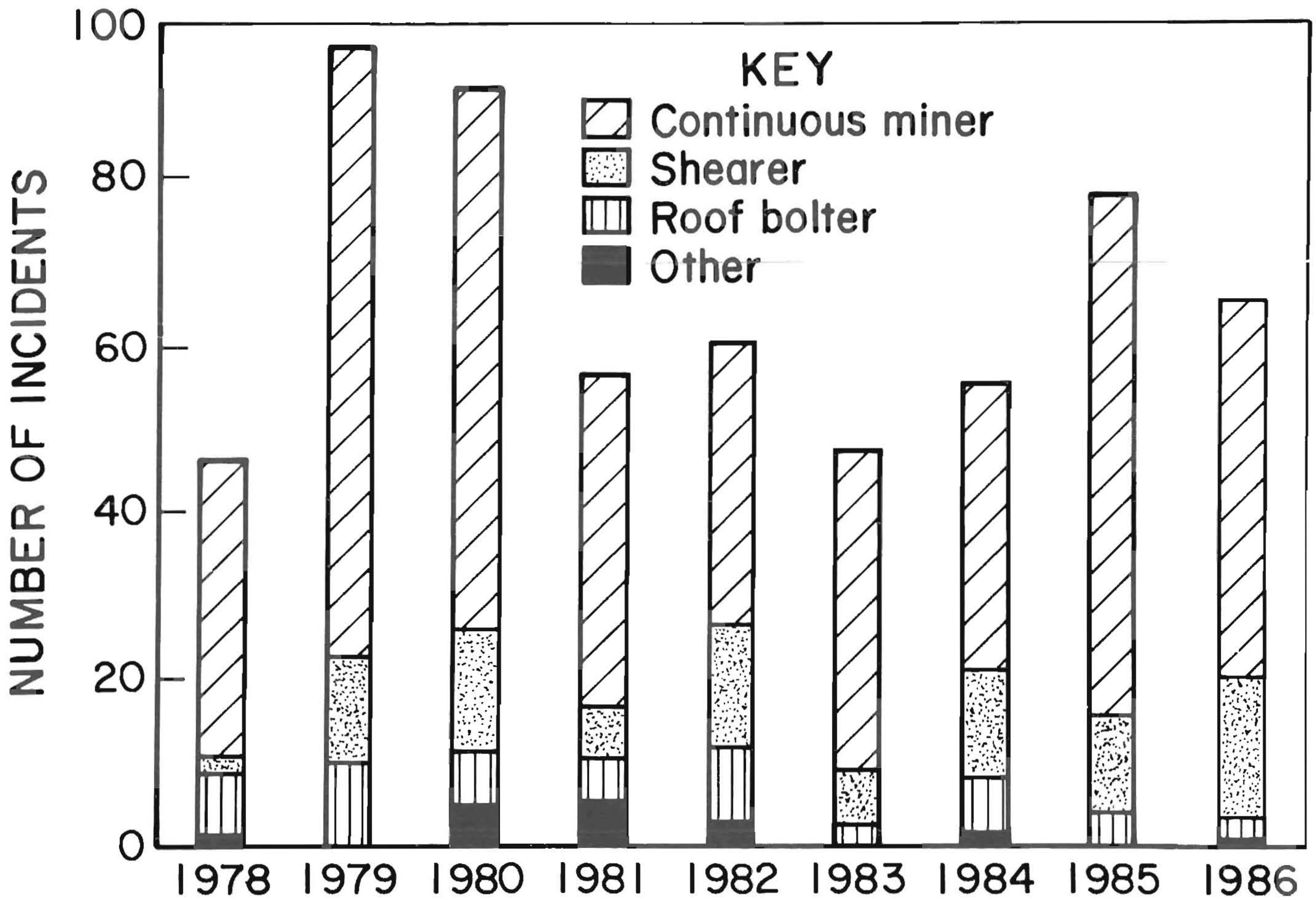

Figure 1.—Frequency of frictional ignitions in underground coal mines. (Based on data from MSHA.)

and roof. In some cases, it is not possible to eliminate all such pockets by ventilation, and even small pockets can be ignited by frictional heating. However, an ignition usually will not occur if the hot streak, formed by frictional heating, is cooled below the methane ignition temperature. The most efficient way to cool the hot streak is to use water directed from a nozzle located near the bit tip.

WATER-JET-ASSISTED CUTTING

Several studies (*7, 10-12*) have shown that to provide effective cooling, the water must be delivered from sprays located near the bit. During laboratory tests, the Bureau of Mines compared the number of frictional ignitions that occurred when water spray was directed from nozzles in front of or behind the bit (*13*). At pressures from 70 to 110 psig, front-mounted nozzles were not effective in preventing frictional ignitions. However, use of rear-mounted full-cone nozzles, operating at 80 psig, prevented the ignition of methane.

No data were available to determine if use of high-pressure front-mounted water jets would be more effective for ignition suppression than low-pressure front-mounted sprays. Water-jet-assisted cutting is a mining technique that uses high-pressure (3,000- to 10,000-psig) solid streams or jets of water that impact the rock surface directly in front of the cutting bit. Bureau research has focused on determining if use of water-jet-assisted cutting would improve the cutting efficiency and reliability of continuous mining machines that employ drag bits (*14*). Tests with a longwall shearer have demonstrated that respirable dust levels were reduced 79 pct when the water pressure was raised from 190 to 3,000 psig (*15*).

In water-jet-assisted cutting, there must be an efficient transfer of energy between the nozzle orifice and the rock surface. This requires that the water-jet nozzle, which delivers a solid stream of water, be located in front of the bit block.

The objective of this study was to determine what effect the high-pressure jets of water used for water-jet-assisted cutting would have on frictional-ignition suppression. The performance of the high-pressure front-mounted water-jet nozzle was compared with performance of a low-pressure rear-mounted spray configuration, known from prior studies to be effective for ignition suppression (*13*).

ACKNOWLEDGMENTS

The authors acknowledge the assistance provided by Kenneth E. Mura and C. Kevin Luster, physical science technicians, of the Bureau's Pittsburgh Research Center for conducting the frictional-ignition tests.

EXPERIMENTAL PROCEDURES

TEST APPARATUS

The original test apparatus was built by Bituminous Coal Research, Inc., as part of a Bureau contract (*13*). The apparatus was modified to accommodate a 3-ft-long, 28-in-diameter segment from a continuous miner cutting drum (fig. 2). A 75-hp hydraulic pump powered the motor that rotated the drum. The drum speed was 40 rpm (440-fpm bit peripheral velocity).

Water for the nozzles passed first through the cutting drum. Earlier frictional-ignition testing, with a similar test apparatus, had not used pressures above 125 psig, because a satisfactory rotating-drum seal was not available. Subsequently, a high-pressure rotating seal, rated at 15,000 psig, was obtained for these tests. Water at pressures from 2,000 to 5,000 psig was supplied by a plunger pump.

The nozzle used for water-jet-assisted cutting was positioned in front of the bit block, about 3 in from the bit tip, and directed so that the solid stream of water impacted the rock surface within 0.25 in of the bit tip (fig. 3). The nozzle had a modified Leach and Walker design (*16*) with a 0.024-in orifice. Water flow rates at 2,000, 3,000, and 5,000 psig were 0.75, 0.90, and 1.15 gpm, respectively.

Line pressure of 80 psig was adequate for the rear-mounted spray tests. The rear-mounted spray nozzle provided a full-cone spray pattern that wetted the back of the bit and the stone immediately behind the bit (fig. 4). At 80 psig, the water flow rate through the 0.034-in orifice was 0.20 gpm.

The cutting drum and sandstone block were enclosed in a 185-ft^3 chamber (approximately 9- by 9-ft base dimensions) constructed of 3/4-in plywood (fig. 5). After an ignition, pressure in the test apparatus was released when the 2-mil-thick polyethylene sheeting, used to seal two large openings, ruptured.

The rock sample was a 20- by 22- by 22-in block of Berea sandstone.[4] The sandstone was positioned on a cart

[4]A typical Berea sandstone contains, by volume, approximately 93.71 pct silica, 3.86 pct ferric oxide, 0.54 pct ferrous oxide, 0.25 pct magnesium oxide, and 0.10 pct calcium oxide. The compression strength of the Berea sandstone is as follows, in pounds (force) per square inch:

	Wet saturated	*Dry*
With grain	7,148	9,402
Against grain	8,067	10,230

Figure 2.—Cutting drum.

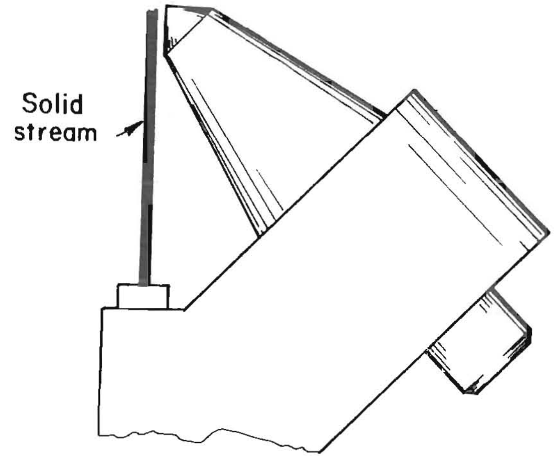

Figure 3.—Solid-stream water jet from front-mounted nozzle.

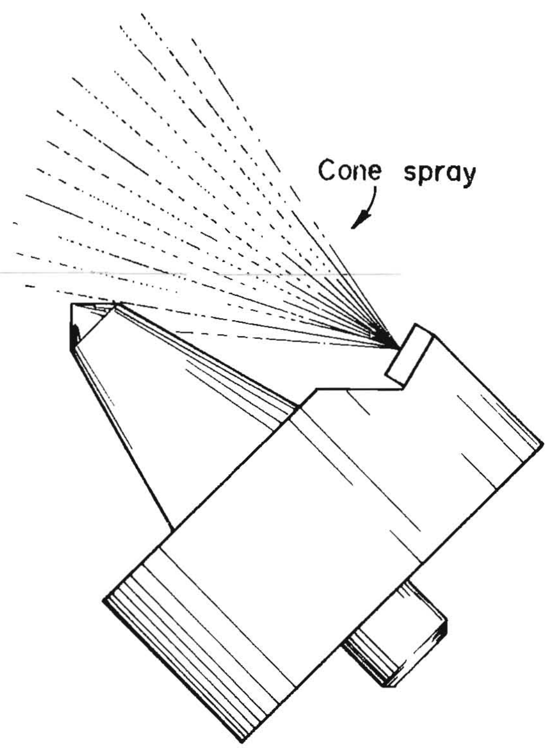

Figure 4.—Full-cone spray from rear-mounted nozzle.

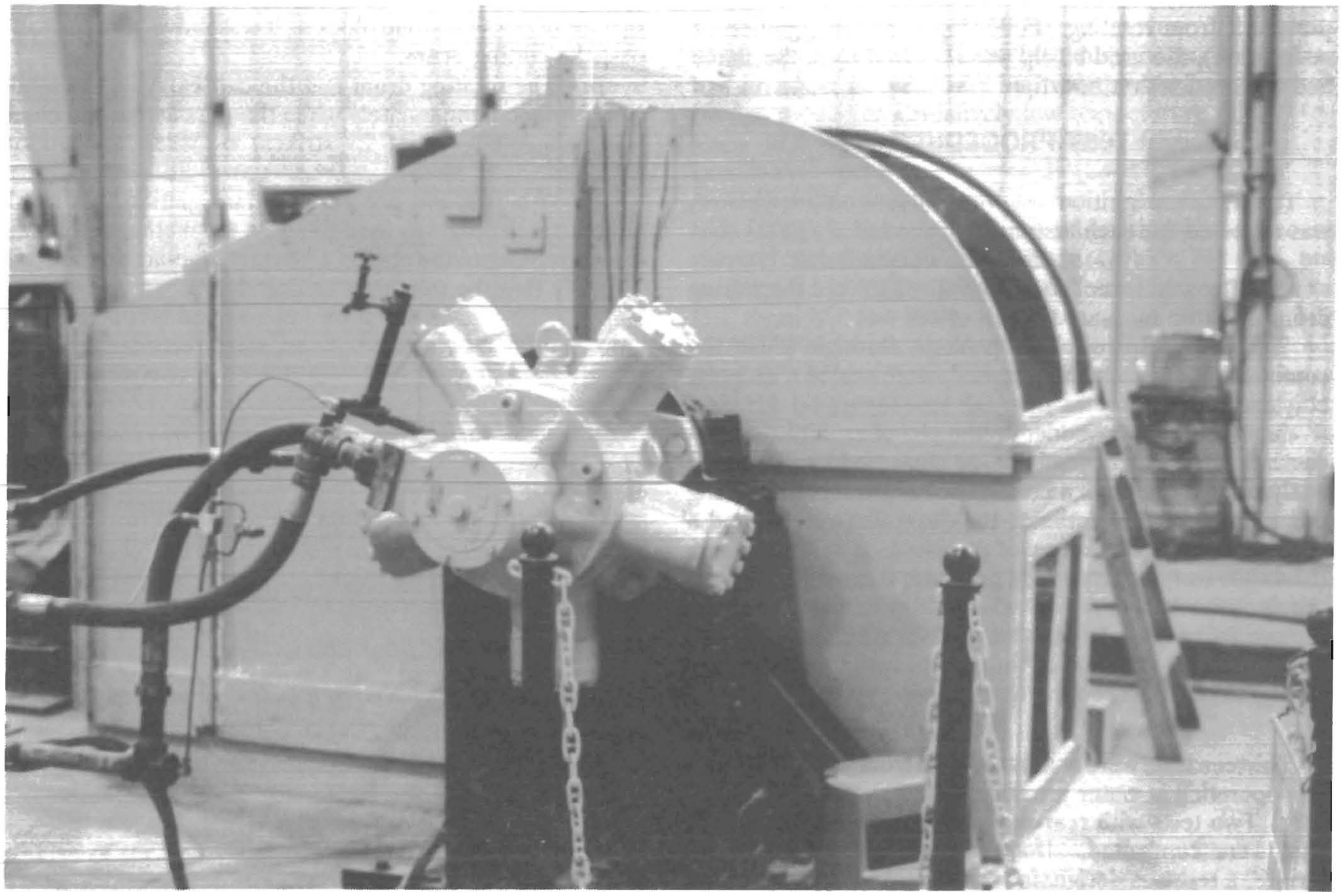

Figure 5.—Frictional-ignition test chamber.

that moved the rock, parallel to the cutting drum shaft, at a predetermined speed. Cart speed was adjusted so that for each complete pass of the stone there were approximately 25 bit strikes, spaced 3/4 in from each other. After each test, the rock surface was smoothed and shaped with a carbide-tipped flat bit. The sandstone block was positioned to give a constant 3/8-in depth of cut per strike. All tests used conical-shaped bits. Two different bit blocks were designed to provide water to either the front-mounted or the rear-mounted nozzle. The bit attack angles for the bit blocks with the front- and rear-mounted sprays were 57° and 52° C, respectively. Tungsten carbide, which is used for most bit tips, is very strong and is resistant to wear in medium-strength rocks such as Berea sandstone. Many strikes with a tungsten carbide bit are necessary before sufficient heat is generated to melt the bit tip and to deposit molten metal on the rock surface. To reduce the number of strikes required, and thus reduce the time required for testing, the tungsten carbide tip was replaced with a tip made of shank steel. Experience has shown that the frictional-ignition hazard is reduced by a factor of 7 to 10 with carbide-tipped bits compared with steel-tipped bits having identical geometries (17). The tip

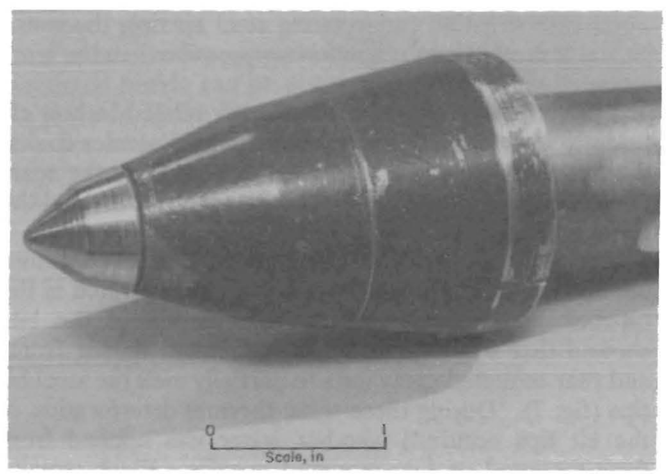

Figure 6.—Steel tip mounted on bit body.

was machined to approximately the same size and shape as the tungsten carbide tip that is normally used in the bit shank (fig. 6). To further accelerate bit wear and increase the probability of frictional ignition, a setscrew, placed in the bit holder, was used to lock the bit in place and to prevent it from rotating. Following each test (ignition or no ignition), the used bit tip was removed from the shank and replaced with a new tip.

TEST PROCEDURE

The frictional-ignition test procedure, as outlined below, was repeated for each test:

1. The sandstone block was moved toward the cutting drum until the measured depth of cut was 3/8 in.
2. The pressure-relief openings, through which the combustible products were vented, were sealed with polyethylene sheets.
3. Methane was added to the chamber until the concentration was 7 pct by volume, as measured by a methane analyzer. To maintain a homogeneous gas mixture during the addition of the methane, the drum was rotated and a small fan in the chamber was operated.
4. Water, at the desired pressure, was supplied to the nozzle.
5. The rotating bit cut a series of slanted cuts on the surface of the sandstone block as it was moved horizontally past the cutting drum.
6. The rotating drum and the cart carrying the sandstone stopped immediately when the pass across the block was completed (about 25 strikes) or when an ignition occurred.
7. If a pass did not result in an ignition, the spark from a spark plug was used to ignite the methane; this was done to consume the combustible methane-air mixture and to verify that the mixture was flammable.
8. The sounds of the bit impacts and methane explosion, amplified by a microphone, were recorded to determine the number of strikes during each complete or partial pass.
9. Prior to the next test, the test bit was removed and replaced with a facing bit that was used to smooth the surface of the sandstone.
10. To allow evaporation of excess moisture from the rock surface, a heater was placed in the test chamber and the rock was dried overnight.

DISCUSSION OF RESULTS

Thirteen tests were conducted with front-mounted water jets operating at water pressures of 2,000, 3,000, and 5,000 psig. Two tests with rear-mounted sprays operating at 80 psig were conducted. If no ignition occurred after 50 strikes, a test was designated "no ignition." A summary of the test results is given in table 1.

Ignitions occurred in 9 of the 13 high-pressure front-mounted spray nozzle tests. There were no ignitions in the low-pressure rear-mounted spray nozzle tests. For the worst case situation (nonrotating steel bit tip), the water jet was less effective for ignition suppression than the rear-mounted spray.

The frequency of ignition is directly related to how efficiently water from front- or rear-mounted nozzles cooled the hot metal deposited behind the bit. Only the rear-mounted spray effectively cooled the hot streak behind the bit to prevent frictional ignition.

The number of frictional ignitions that occurred cannot be directly related to the amount of heat generated at the bit-rock interface. However, examination of the bits showed that sufficient heat was generated during front- and rear-mounted spray tests to partially melt the steel bit tips (fig. 7). During these tests, thermal deterioration of the bit tips occurred whether water was applied from front-mounted or rear-mounted nozzles. Black streaks, which could been seen on the rock following cutting, were evidence that the heat generated at the bit-rock interface was sufficient to oxidize part of the steel tip.

The frequency of ignition has also been shown to be related to the rate of bit wear (*18*). A worn bit operating dry has been shown to cause frictional ignitions more often than a new bit operating dry. This is probably due to the increased surface area of the worn bit that comes in contact with the rock. Increased contact surface increases the rate of frictional heating. During cutting, the wear rate was accelerated by frictional heating, which caused thermal deterioration of the bit tip (fig. 7). With thermal deterioration, the bit tip readily deformed, allowing the hot metal to be deposited on the rock surface. As a result, the frequency of frictional ignitions increased.

Table 1.—Frictional-ignition suppression using water sprays

Test	Water pressure, psig	Total strikes	Results
HIGH-PRESSURE FRONT-MOUNTED NOZZLE			
1	2,000	10	Ignition.
2	2,000	121	No ignition.
3	3,000	17	Ignition.
4	3,000	39	Do.
5	3,000	21	Do.
6	5,000	122	No ignition.
7	5,000	13	Ignition.
8	5,000	24	Do.
9	5,000	10	Do.
10	5,000	37	Do.
11	5,000	103	No ignition.
12	5,000	35	Ignition.
13	5,000	179	No ignition.
LOW-PRESSURE REAR-MOUNTED NOZZLE			
14	80	130	No ignition.
15	80	300	Do.

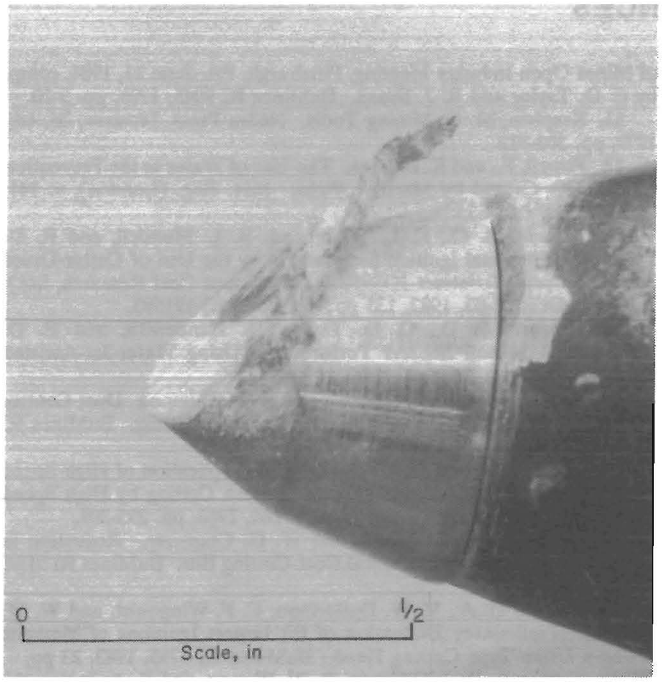

Figure 7.—Steel bit tip showing the results of frictional heating.

Applying water is one of the most effective ways to cool the bit (*10*) and to reduce the rate of bit wear. The results of this study did not indicate, however, whether bit cooling had an effect on wear rate because the steel used for the bit tips melted at a relatively low temperature (1,500° C). Even with the application of water, frictional heating caused the steel to melt.

The effect of water on the wear rate for tungsten carbide bit tips is unknown. Frictional heating can also cause thermal deterioration of tungsten carbide bit tips, but tungsten carbide is relatively unaffected by temperatures less than 600° C. If the temperature can be kept below 600° C, deterioration and, thus, wear rate can be reduced. Further studies are needed to determine if applying water near the bit tip reduces the wear rate of tungsten carbide.

The ability of low-pressure front-mounted sprays to prevent ignitions was not evaluated during this study. Prior testing conducted with the frictional ignition test apparatus (*13*) showed that the low-pressure sprays were ineffective for preventing ignitions. There are insufficient data to determine whether more strikes are required to cause an ignition with high- or low-pressure front-mounted sprays. Data from the current study did show that increasing the water pressure of front-mounted sprays from 2,000 to 5,000 psig does not prevent frictional ignitions.

CONCLUSIONS

Use of sprayed water can suppress frictional ignitions. To be effective, the water must reach and cool the rock surface immediately behind the bit. The position of the nozzle is a more important factor than water pressure. A solid stream of water at 5,000 psig directed from a front-mounted nozzle did not prevent frictional ignitions; rear-mounted spray operating at 80 psig prevented ignitions.

For water-jet-assisted cutting, the cutting drum must be equipped with a water-jet nozzle located in front of each cutting bit. A cutting drum designed for frictional-ignition suppression using low-pressure water should also have a water nozzle located behind each cutting bit. If water-jet-assisted cutting is used and there is the probability of mining in areas of high methane concentration, it would be advantageous to also incorporate a low-pressure rear-mounted spray system into the drum design (*19*). In water-jet-assisted cutting, some high-pressure water from front-mounted nozzles may penetrate beneath the cutting bit, but the results of this study show that the hot area behind the bit was not adequately cooled by the front-mounted nozzles.

Further studies are needed to determine if the front-mounted nozzle can be positioned closer to the bit tip or to the side of the bit so that part of the water will reach the hot streak to provide frictional-ignition suppression. One possible solution, a through-the-bit water delivery system that directs water to the bit tip, will be investigated by the Bureau.

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* U.S. GOVERNMENT PRINTING OFFICE: 611-012/00,060

INT.-BU.OF MINES,PGH.,PA 28890