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# Frictional Ignition With Coal Mining Bits

By Welby G. Courtney

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# **Frictional Ignition With Coal Mining Bits**

**By Welby G. Courtney**

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#### UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mm	millimeter
cal/cm <sup>2</sup> ·s	calorie per square centimeter per second	mm <sup>2</sup>	square millimeter
cm	centimeter	μm	micrometer
cm <sup>2</sup>	square centimeter	ms	millisecond
cm/min	centimeter per minute	pct	percent
cm/r	centimeter per revolution	psig	pound per square inch gauge
cm/s	centimeter per second	rpm	revolution per minute
deg	degree	rps	revolution per second
gpm	gallon per minute	s	second
gpm/cm <sup>2</sup>	gallon per minute per square centimeter		

# FRictional IGNITION WITH COAL MINING BITS

By Welby G. Courtney<sup>1</sup>

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## ABSTRACT

This publication reviews recent U.S. Bureau of Mines studies of frictional ignition of a methane-air environment by coal mining bits cutting into sandstone and the effectiveness of remedial techniques to reduce the likelihood of frictional ignition. Frictional ignition with a mining bit always involves a worn bit having a wear flat on the tip of the bit. The worn bit forms hot spots on the surface of the sandstone because of frictional abrasion. The hot spots then can ignite the methane-air environment. A small wear flat forms a small hot spot, which does not give ignition, while a large wear flat forms a large hot spot, which gives ignition.

The likelihood of frictional ignition can be somewhat reduced by using a mushroom-shaped tungsten-carbide bit tip on the mining bit and by increasing the bit clearance angle; it can be significantly reduced by using a water spray nozzle in back of each bit, which is carefully oriented to direct the water spray onto the sandstone surface directly behind the bit and thereby cool the hot spots formed by the worn bit. A bit replacement schedule must be used to avoid the formation of a dangerously worn bit.

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## INTRODUCTION

The frictional use of quartzitic and pyritic materials to make fire was known to Neanderthals (1),<sup>2</sup> and frictional ignition has been called "about the second oldest profession" (2). Frictional ignition of a violent coal mine explosion such as shown in figure 1 was reported in 1675 (1).

Field reports by the Mine Safety and Health Administration (MSHA) have indicated a general increase in the frequency of frictional ignitions in U.S. coal mines during the past years (fig. 2). While no miners have been killed in the United States because of frictional ignition since the early 1970's, injuries have occurred. The coal mine explosion in Nova Scotia in 1979 that led to 14 fatalities was caused by a frictional ignition with the shearer drum shown in figure 3 (3). The increase in frictional ignitions in the United States thus is alarming.

The MSHA field reports indicate that frictional ignitions in the United States almost always involve a metal bit cutting into sandstone.<sup>3</sup> Field samples of sandstone involved in frictional ignitions in Great Britain indicated that the sandstone must contain at least 20 pct quartz and usually contains 40 pct or more quartz (5). Early studies of frictional ignition reviewed in 1969 by Powell (6) indicated that frictional ignition with a metal bit cutting sandstone (1) involved a luminous hot streak that formed on the surface of the sandstone because of abrasion by the

bit and did not involve hot, airborne, moving sparks,<sup>4</sup> (2) always involved a worn bit that had formed a wear flat on the tip of the bit and was never obtained with a new, sharp bit, (3) could be obtained with almost any abrading material but was, e.g., much easier to obtain with steel than with a tungsten-carbide cermet (9), and (4) was apparently less likely to occur with a lower bit velocity (5, 9-10). Figure 4 shows the hot streak formed on the

<sup>4</sup>Ignition by sparks can occur when the sparks adhere to a surface. However, references 7 and 8, e.g., conclude that ignition can be obtained with airborne, moving sparks.



Figure 1.—Coal mine explosion.

<sup>2</sup>Italic numbers in parentheses refer to items in the list of references at the end of this report.

<sup>3</sup>Very occasionally frictional ignitions have appeared to involve a bit cutting into pyritic material. Also, a few incidents have involved sandstone-sandstone abrasion during the fall of a sandstone roof, a hand pick striking sandstone, and a drill bit striking sandstone or steel. One possible exception involved the cutting of "hard coal" (4).

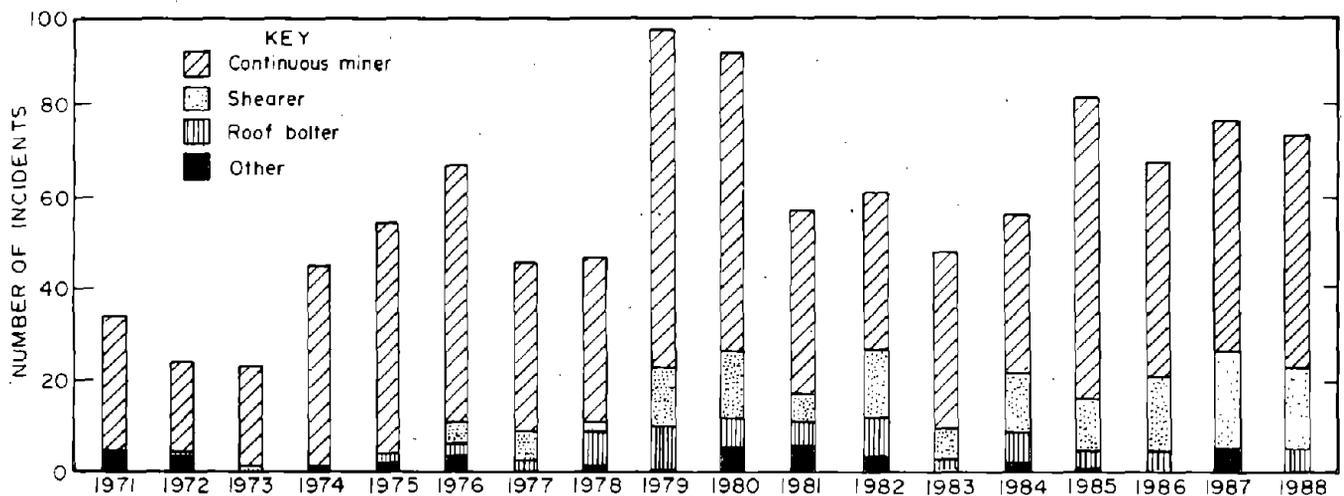


Figure 2.—Frequency of frictional ignitions in U.S. coal mines.



Figure 3.-Shearer drum that caused frictional ignition of coal mine explosion in Nova Scotia (3).

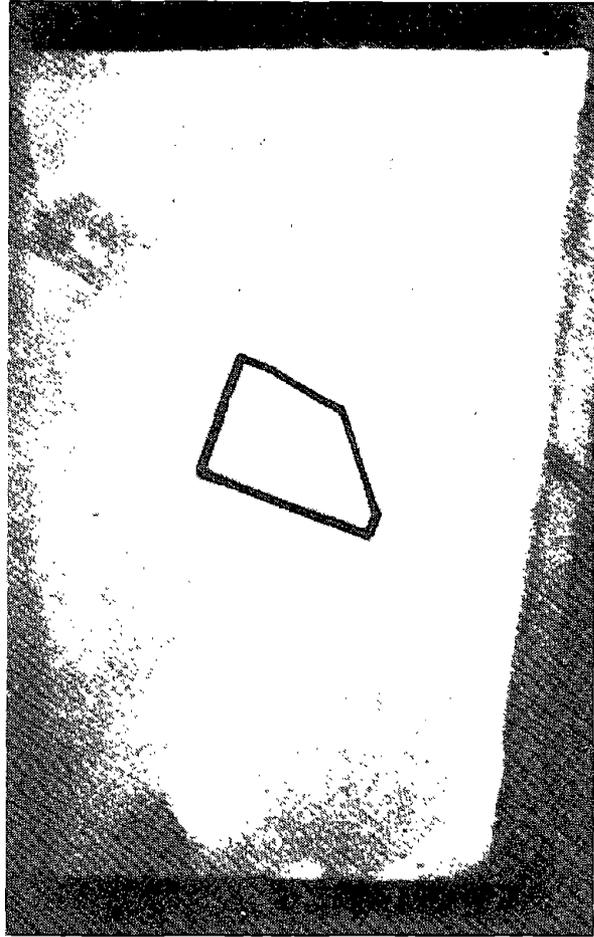
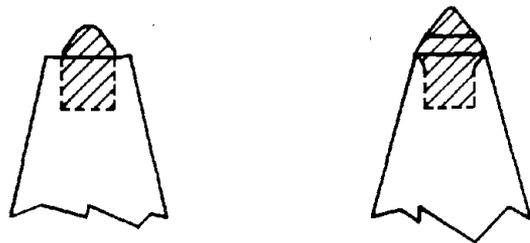


Figure 4.-Hot streak formed on surface of sandstone with worn bit.

surface of a sandstone block by a downward-moving, worn rectangular bit having a wear flat.

All mining bits presently use tungsten-carbide tips to reduce bit wear, but the carbide tips usually are small. The U.S. Bureau of Mines (11) designed large mushroom-shaped carbide tips for conical bits and dovetail-shaped carbide tips for rectangular (radial) bits to physically protect the steel shank and thereby reduce the likelihood of frictional ignition due to abrasion by the incendive steel shank. Figure 5 shows conventional- and mushroom-tipped conical bits. Figure 6 shows conventional plug- and peak-tipped rectangular bits and a mushroom-type dovetail-tipped bit. Laboratory tests indicated that the mushroom- and dovetail-tipped bits had longer wear lives than the conventional-tipped bits before the incendive steel shank became exposed (12). An in-mine test with conical bits supported these laboratory conclusions (13).

Bureau tests have indicated, however, that frictional ignition can eventually be obtained with the wear flat formed on the tungsten-carbide tip of a nonrotating (frozen) conical bit without exposure of the steel shank. The likelihood of frictional ignition was significantly reduced with an increased initial bit clearance angle  $\theta_C$ ,



Conventional tip

Mushroom tip

Figure 5.-Conventional- and mushroom-tipped conical bits.

e.g., with conical bits, with an increased initial bit attack angle  $\theta_A$  and/or a decreased internal bit tip angle  $\theta_T$  as shown in figure 7, where  $\theta_A$  is the angle between the bit axis and the sandstone surface and  $\theta_C = \theta_A - \theta_T/2$  (14). Figure 8 shows that the number of cuts to give ignition with a new, tungsten-carbide-tipped, frozen conical bit cutting into a sandstone block increased by a factor of

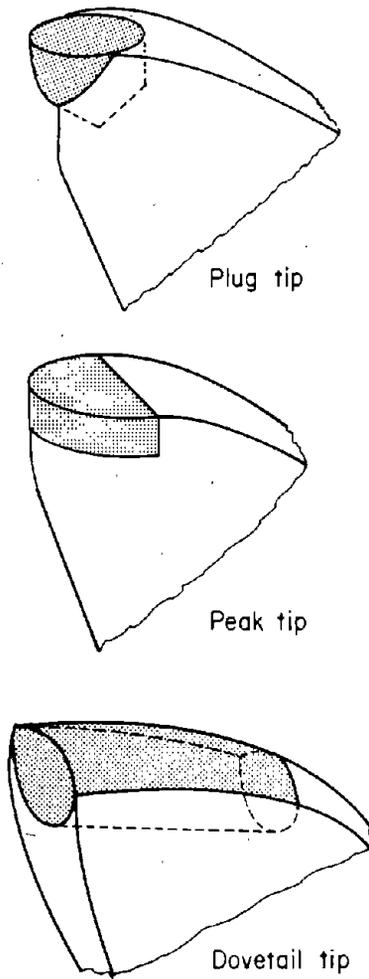


Figure 6.—Conventional- and dovetail-tipped rectangular bits.

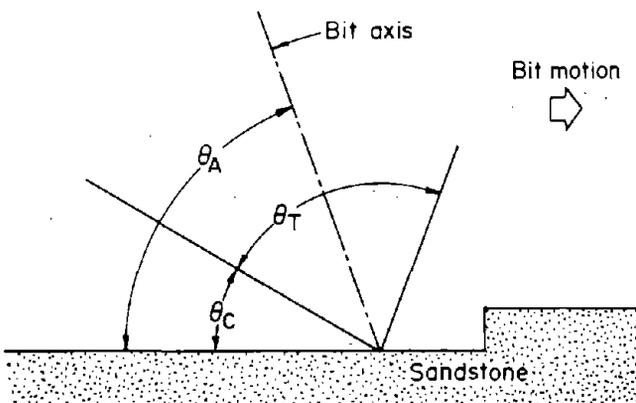


Figure 7.—Geometry of conical bit tip. ( $\theta_A$  = attack angle;  $\theta_C$  = initial clearance angle;  $\theta_T$  = initial tip angle.)

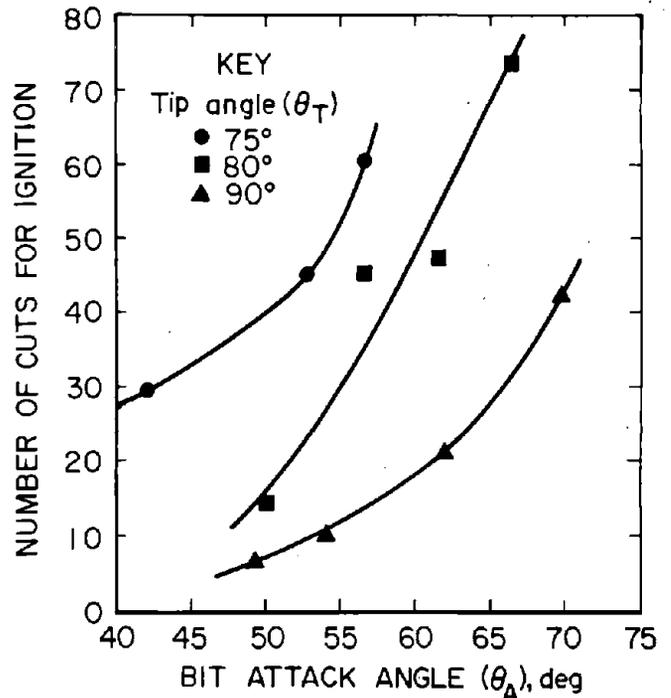


Figure 8.—Effect of bit attack angle and initial tip angle on frictional ignition with conical bits.

about 3 if  $\theta_A$  increased by  $10^\circ$  or  $\theta_T$  decreased by  $10^\circ$ . An in-mine test by Jim Walter Resources (JWR) (15) supported these laboratory conclusions. In a section prone to frictional ignitions because of a sandstone parting, no ignitions occurred in mining 50,000 tons of coal with mushroom bits having a Bureau-recommended bit attack angle of  $57^\circ$ , while two ignitions then occurred in mining 10,000 tons using conventional-tipped bits having the normal mine attack angle of  $50^\circ$ .

While both of these features (mushroom tip and increased bit clearance angle) are valuable in reducing the early ignition hazard associated with conical bits, both features merely postpone the time when the bits have been worn to a dangerous condition likely to cause frictional ignition. A replacement schedule for worn bits is therefore required. E.g., the bits in the JWR field test (15) were replaced after every shuttle car was loaded if the mining machine was cutting into a sandstone parting.

Other laboratory studies (16-17) have indicated that a solid-cone water spray impacting onto the surface of the freshly cut sandstone directly in back of the cutter bit very significantly reduced the likelihood of frictional ignition, even with very worn bits, by promptly cooling the hot streak formed by the worn bit cutting the sandstone. The water requirement to reduce ignition was about 0.5 gpm for each bit and thus was somewhat high but not excessive.

the use of water that impinges onto the front of the bit to reduce airborne respirable dust has become a standard mining practice in Great Britain. However, laboratory tests indicate that it had negligible effect in reducing frictional ignition (18).

As part of its program to enhance the safety of workers in the mining industry, the Bureau has studied the problem of frictional ignition and especially the use of water sprays in back of the cutter bits to reduce the likelihood of frictional ignition. This report reviews several Bureau-funded studies conducted from 1979 to 1988. A detailed laboratory study with a rectangular bit and several types of water sprays was conducted by Bituminous Coal Research (now, Bituminous Coal Research National Laboratory (BCRNL)) from 1979 to 1981 under Bureau contract (18).

## EXPERIMENTAL TECHNIQUE

Previous laboratory techniques to investigate frictional ignition have involved (1) a worn field bit making a single centimeter-deep spiral cut into new locations on a rotating block of sandstone (5), (2) a metal tool (9) or a worn rectangular field bit (10) making multiple shallow cuts at the same location on a stationary sandstone block, and (3) miscellaneous techniques such as a metal tool held against a grinding wheel, drill bit, falling weight, hand pick, and high-speed projectile (6).

The miscellaneous techniques were used mainly to indicate qualitatively whether frictional ignition could occur. Techniques 1 and 2 were used mainly to indicate the effectiveness of a remedial technique in reducing the likelihood of frictional ignition. E.g., in investigating the effect of bit velocity, a worn bit making a deep spiral cut in a sandstone block (5) gave ignition in 3 s with a bit velocity of 150 cm/s and 0.3 s with a bit velocity of 450 cm/s. The metal tool making multiple shallow cuts at the same location in a sandstone block (9) gave ignition with about 175 cuts with a tool velocity of 150 cm/s and 75 cuts with a tool velocity of 450 cm/s. The worn bit making multiple shallow cuts at the same location (10) gave ignition with about 350 and 240 cuts with bit velocities of 100 and 280 cm/s, respectively. The investigators recommended that a lower bit velocity be used to reduce the likelihood of frictional ignition.

However, the relationship between these cutting techniques and field cutting is not clear. It was thought advisable to simulate field cutting insofar as reasonably possible. A new laboratory frictional ignition apparatus was developed by BCRNL (18). A single field bit was mounted onto a field cutter drum rotating downward in the vertical plane at a typical field drum rotation speed. A 51-cm-high block of sandstone containing 78 pct quartz (from Cleveland Quarries, Berea, OH) was positioned on a cart, with the bedding plane horizontal, and was moved horizontally across the rotating drum. A series of slanted downward cuts thus were made in new parts of the sandstone block. The block was precut to excavate the circular arc in the block and was positioned so that a 0.6-cm-deep

In-house Bureau studies of a second back spray and rectangular bit system and a back spray and conical bit system were conducted in 1983, and a study of a front spray and conical bit system was conducted in 1987. Brief Bureau studies of several commercial back-spray systems with rectangular and conical bits were conducted in 1983 and 1987. Results of these studies have not been previously published. A field test with back sprays and conical bits on a wet-head-modified cutter drum on a Simmons Rand 265<sup>5</sup> continuous mining machine was completed in late 1988. These studies generally had a practical orientation. Recent Bureau work having a more fundamental orientation is briefly presented in the "Discussion" section.

cut was made by the bit along the entire length of the arc. The block and drum were enclosed in a plywood chamber containing a 7-pct methane-air environment. The chamber included plastic blowout panels to relieve the chamber pressure when ignition occurred. Figure 9 shows the ignition chamber.

The number of cuts made by the bit to ignite the methane-air environment was counted. The number of cuts during 1 pass of the block depended upon the cart speed and drum rotation speed and usually was about 20. If no ignition occurred during passage of the block, the block usually was redressed, repositioned, and again passed across the rotating drum. The total number of cuts to obtain ignition was taken as a measure of the ease of

<sup>5</sup>Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

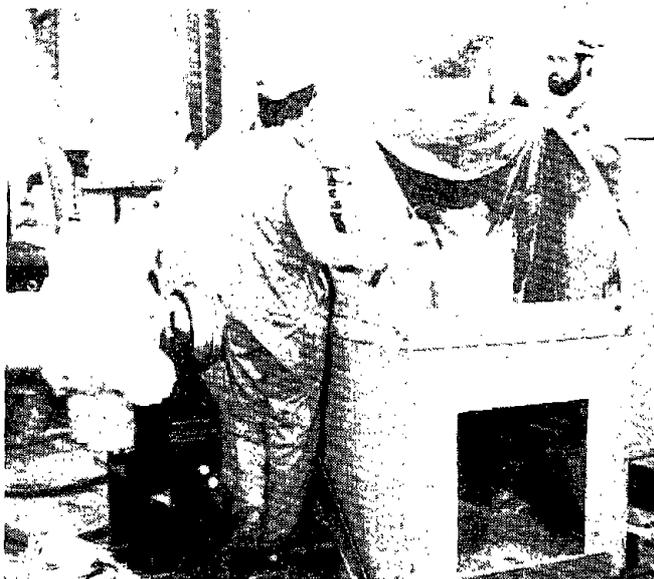


Figure 9.—Frictional ignition chamber.

ignition. The number of cuts to obtain ignition when a remedial technique was used, such as a lesser drum rotation speed or a water spray, then was measured. The increase in the number of cuts required to obtain ignition with the remedial technique was taken as a measure of the effectiveness of the remedial technique.

The present cutting technique is similar to the technique reported later in reference 19, in which multiple deep cuts with a worn field bit mounted on a field shearer drum rotating at a field speed were made in a sandstone block being moved horizontally below the drum.

The initial laboratory study described below used a wet-head shearer drum fabricated for a Joy Technologies, Inc., ILS shearer. Subsequent laboratory studies used a segment of the cutter drum from a used Joy 12 ripper-type continuous mining machine, which was modified here to be a wet head by using a small-diameter water seal attached to the end of the drum shaft. The field study used a wet-head cutter drum on a Simmons Rand 265 ripper machine that was designed and fabricated by Simmons Rand and used large-diameter water seals from Cannings Seals in Great Britain.

## RESULTS

Six laboratory studies with water sprays were conducted, four with different rectangular bits and two with different conical bits. A third study with conical bits and back sprays mounted on the wet-head Simmons Rand 265 continuous mining machine was conducted in the field.

### RECTANGULAR BITS

#### Kennametal K-100

In 1979, the Bureau initiated a contract with BCRNL (18) (1) to conduct a laboratory study of frictional ignition and especially the effectiveness of water sprays in reducing the likelihood of frictional ignition with rectangular cutting bits on a shearer drum and (2) to initiate and monitor a subsequent field study. A 76-cm-wide wet-head cutter drum for a Joy ILS shearer expected to be available for laboratory tests at the Bureau's Bruceton facility was designed by BCRNL and AMS Technology and fabricated by AMS. The drum used 43 bits and a tight lacing pattern (fig. 10) designed for difficult cutting conditions. Scheduling difficulties prevented use of the Joy ILS shearer at Bruceton, so the test chamber described earlier was used with the ILS drum.

Kennametal, Inc., K-100 bits having a 2.5-cm-wide tip were used here. Figure 11 shows the side view of the K-100 bit. The bit had the conventional, peak-shaped, tungsten-carbide and cobalt cermet tip and a shank made of AISI Type 4140 steel. New bits and bits that had been shortened by 0.04 to 0.56 cm and ground flat to simulate a worn field bit were used. Bit wear during a test was negligible. The tip-to-tip diameter was 137 cm. A drum speed of 47 rpm was used in most of this study, giving a tip velocity of 337 cm/s. A cart speed of 41 cm/min was usually used, giving about 60 cuts during 1 pass of the 51 cm-wide sandstone block, with one-third of the 2.5-cm-wide bit tip cutting into fresh sandstone and two-thirds of the tip abrading the previously cut portion of the sandstone.

Initial work used a single bit. The hot streak formed on the surface of the sandstone by a worn K-100 bit cutting

into the sandstone block was shown in figure 4. Airborne hot sparks were also formed, but motion picture and video

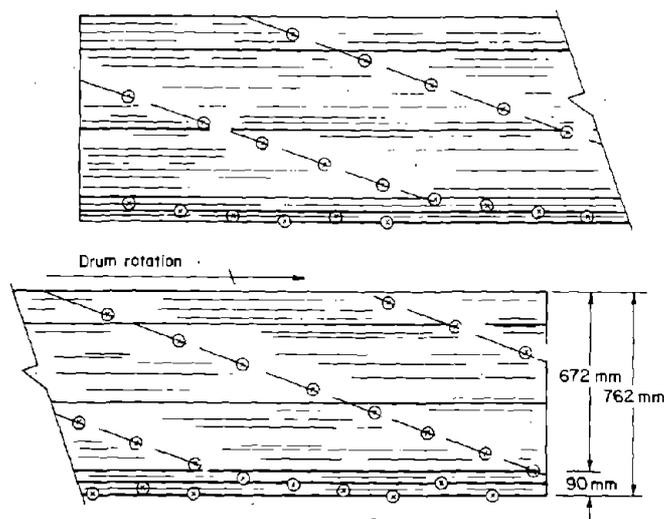


Figure 10.—Bit lacing of Joy ILS shearer drum. Circled x's denote mining bits.

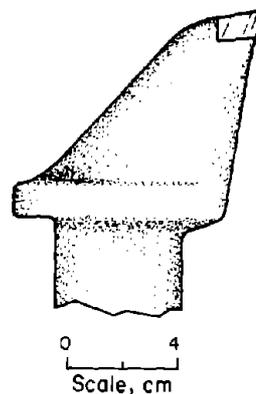


Figure 11.—Kennametal K-100 bit.

photography indicated that ignition, with one exception,<sup>6</sup> occurred at the bottom part of the hot streak.

The number of cuts to give frictional ignition depended upon the amount of wear of the bit tip. The average number of cuts to obtain ignition with worn bits is given in table 1 and shown in figure 12. Raw data are given in the footnotes in table 1. Results were rather scattered. Data considered to be probable "outliers" due to cutting into damp sandstone (see section on GTE bits) are enclosed in brackets in table 1 and were ignored in calculating the average number of strikes. Excluding outliers, the results still had considerable scatter; i.e., the coefficients of variation of the sets of data in the footnotes of table 1 and also other sets of data presented later in this report ranged from 25 to 80 pct.

Table 1.—Effect of bit wear on frictional ignition with Kennametal K-100 bit during dry cutting

Bit shortening, cm	Av number of cuts for ignition
0	<sup>1</sup> >217
0.08	<sup>2</sup> >293
0.16	<sup>3</sup> 45
0.27	<sup>4</sup> 5.8
0.32	<sup>5</sup> 7.0
0.40	<sup>6</sup> 3.3
0.45	<sup>7</sup> 5.5
0.48	<sup>8</sup> 3.6
0.54	<sup>9</sup> 2.2

<sup>1</sup>No ignition with 150, 180, 230, 230, 250, 260.

<sup>2</sup>No ignition with 205, 255, 304, 306, 310, 312, 312, 318.

<sup>3</sup>2, 3, 9, 14, 17, 28, 40, 50, 69, 79, 82, 91, 100,

[143]; no ignition with [207, 328].

<sup>4</sup>4, 4, 7, 8, [22, 120].

<sup>5</sup>2, 3, 3, 3, 3, 4, 4, 5, 5, 6, 6, 6, 9, 9, 11, 12, 12, 12, 13, 16,

[34, 38, 39, 50, 58, 60, 61].

<sup>6</sup>2, 2, 4, 5, [14, 42, 57].

<sup>7</sup>4, 4, 6, 8, [13].

<sup>8</sup>2, 2, 2, 4, 4, 4, 5, 6, [14, 91].

<sup>9</sup>1, 1, 1, 3, 3, 4, [17, 22].

No ignition was obtained with 217 dry cuts with a new bit or 293 cuts with a 0.08-cm-worn bit. Ignition was obtained with a slightly more worn bit, e.g., with an average of 45 dry cuts with a 0.16-cm-worn bit and 5.8 dry cuts with a 0.27-cm-worn bit. The steel shank, which became exposed when the bit was worn 0.14 cm, presumably was the major contributor to ignition. The physical difference between a "safe" 0.08-cm-worn bit and a "dangerous" 0.27-cm-worn bit was only barely discernible in the laboratory, and a bit replacement schedule in the field probably could not be based on visual observation of the extent of bit wear or exposure of the steel shank.

The likelihood of frictional ignition with a worn bit was not decreased with a lower drum rotation speed in the

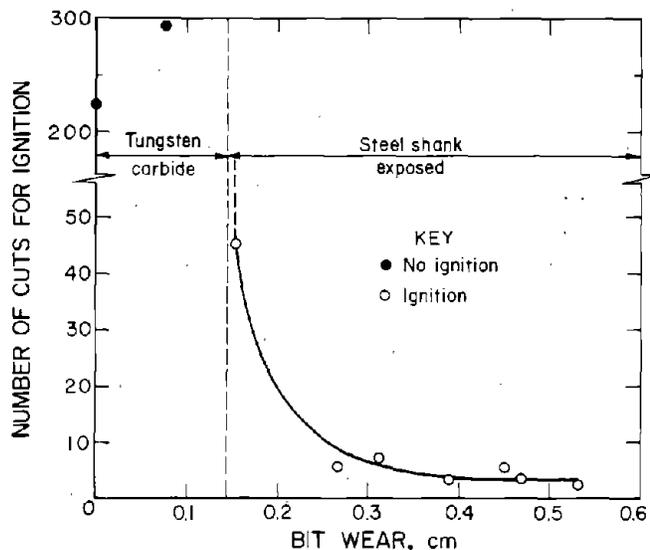


Figure 12.—Effect of bit wear on frictional ignition with Kennametal K-100 bit.

range considered to be of practical interest. Results obtained with a 0.45-cm-worn bit during dry cutting are given in table 2 and plotted in figure 13. Ignition was obtained with about the same number of cuts when the drum was operated with a bit velocity of 108 or 337 cm/s (15 or 47 rpm). The likelihood of frictional ignition did rapidly decrease (the number of cuts for ignition rapidly increased) with a still lower drum speed, but such a low drum speed may be impractical for underground mining.

Table 2.—Effect of bit speed on frictional ignition with 0.45-cm-worn Kennametal K-100 bit during dry cutting

Drum speed, rpm	Bit speed, cm/s	Number of cuts for ignition
47	337	<sup>1</sup> 5.5
38	272	12
27	194	4, 6
21	150	14
17	122	8
15	108	7
13	93	>117
9	65	>32

<sup>1</sup>See table 1.

The effect of water sprays from various water spray nozzles mounted in front or in back of a worn bit was investigated. With a water jet impinging onto the front of a 0.32-cm-worn bit, a 0.2-gpm jet was ineffective in preventing ignition; i.e., ignition occurred with nine cuts during wet operation versus seven dry cuts (table 1). A 1.1-gpm front jet was more effective, in that ignition occurred with 69 wet cuts versus seven dry cuts.

A back-mounted spray nozzle whose spray impacted the back of a 0.48-cm-worn bit was not very effective. With

<sup>6</sup>In one test, ignition occurred below the block and presumably was due to the hot sparks adhering to the floor of the chamber.

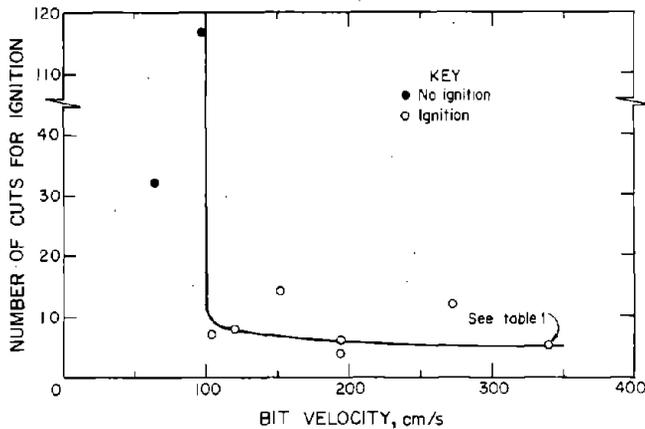


Figure 13.—Effect of bit velocity on frictional ignition with 0.45-cm-worn Kennametal K-100 bit.

a water jet, ignition was obtained with 10 wet cuts, while ignition was obtained with an average of 3.6 dry cuts (table 1). A fan-type spray (Spraying Systems Co. VV1502) was effective when the fan spray nozzle was operated at 100 psig because the spray splashed off the back of the bit and impacted the sandstone surface within about 5 cm behind the leading edge of the tip of the bit. However, the fan spray was ineffective if the nozzle was operated at 140 psig because the splash impact zone then was further behind the bit; i.e., impacting the hot streak with the water spray within about 5 cm behind the bit tip appeared to be required to avoid ignition. A solid-cone spray that impinged onto the back of the bit similarly gave only a modest anti-ignition benefit; i.e., ignition occurred with 13 wet cuts compared with 3.6 dry cuts.

A fan spray impinging the freshly cut sandstone surface directly behind the bit, with the fan oriented parallel to and directed onto the bit path, was somewhat effective. E.g., a 0.3-gpm fan spray did not permit ignition with a 0.48-cm-worn bit with 120 wet cuts, while ignition was obtained with 3.6 dry cuts. However, ignition was obtained with 90 wet cuts with a 0.80-cm-worn bit. Also, the fan spray was ineffective when oriented perpendicular to the bit path. Since the fan spray appeared to be of only modest benefit with a very worn bit and especially since maintenance of a parallel orientation in the field was expected to be difficult because of nozzle misorientation, no additional work was done with fan sprays.

A cone spray was selected for further work to avoid the nozzle orientation problem. A solid-cone spray was preferred to a hollow-cone spray in order to give better cooling of the hot streak; i.e., the solid circle of drops at the impaction plane obtained with a solid-cone spray was expected to give better cooling than the annular ring of drops obtained with a hollow-cone spray. Spray nozzles giving a mean number drop size of about 200  $\mu\text{m}$ , considered to be optimum for impaction coverage of a target surface (20), were chosen. Only Spraying Systems nozzles

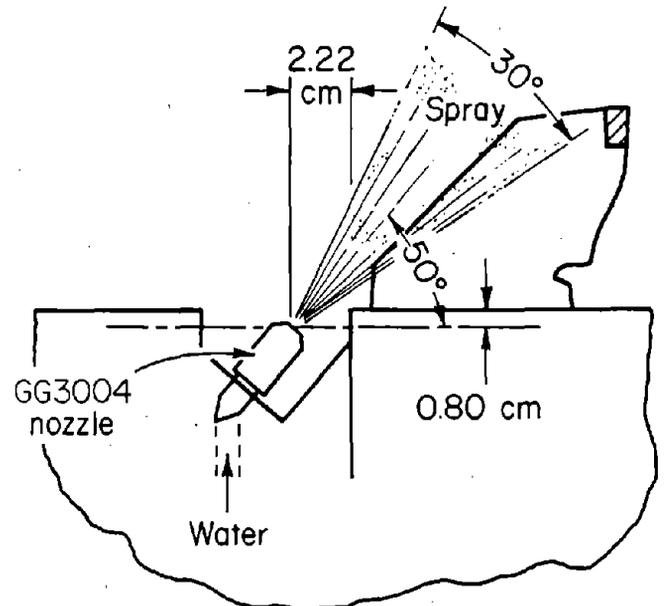


Figure 14.—Anti-ignition back-spray and bit geometry with Kennametal K-100 bit.

were considered in this study since the manufacturer provided information on mean drop size. The Spraying Systems nozzles considered included the GG3 nozzle, with an internal spray angle of 60° (0.9 gpm at 100 psig) and the GG3004 nozzle, with an internal spray angle of 30° (0.5 gpm at 100 psig).

The GG3 spray at 70 psig did not give ignition with 115 wet cuts with a very worn bit, while ignition occurred with an average of 3.6 dry cuts. Water consumption was 0.7 gpm and thus somewhat high. The GG3004 nozzle was selected for detailed work since it involved a lesser water-flow rate and was considered to be more practical for field mining operations. Also, a spray with a 30° internal angle gives a greater water density (e.g., gallon per minute per square centimeter) at the impaction plane on the sandstone surface than a 60° spray with a similar flow rate and thus should give better cooling of the hot streak.

The likelihood of frictional ignition with a very worn bit was significantly reduced when the spray from the GG3004 nozzle located 13 cm behind the bit tip impinged onto the freshly cut sandstone surface directly in back of the bit. Figure 14 shows the spray-bit geometry used here, with the spray nozzle oriented 50° to the surface of the drum. At the impaction plane, the spray had a diameter of about 6.4 cm and an area of 33 cm<sup>2</sup>. Impingement of about 10 pct of the spray water onto the back of the bit was purposely selected here in the event that a smaller bit may be used in the field. The spray nozzle was recessed in a steel housing to protect the nozzle from damage by broken coal.

Laboratory results with a GG3004 nozzle, showing the effect of waterflow rate and pressure on the number of

cuts to give ignition with worn bits, are given in table 3. Ignition did not occur with 100+ wet cuts using 0.4 to 0.6 gpm (70 to 110 psig). Figure 15 shows the effect of the back spray on cooling the hot streak and is to be compared with figure 4. The hot streak extended about 2 cm behind the bit and thus existed for about 7 ms before being cooled by the back spray. Ignition did occur in four out of six tests (table 3, footnote 4) when the nozzle pressure was 40 psig (0.3 gpm), but this low-pressure spray was poorly formed and gave a poor impingement pattern on the sandstone surface.

**Table 3.-Effect of Spraying Systems GG3004 back spray on frictional ignition with worn Kennametal K-100 bit**

Bit wear, cm	Spray		Av number of cuts for ignition
	Flow rate, gpm	Pressure, psig	
0.40 . . . .	Dry	Dry	<sup>1</sup> 3.3
	0.44	70	<sup>2</sup> > 114
0.45 . . . .	.50	90	<sup>3</sup> > 130
	Dry	Dry	<sup>4</sup> 5.5
	.34	40	<sup>4</sup> > 65
	.47	80	<sup>5</sup> > 98
0.54 . . . .	.56	110	<sup>6</sup> > 119
	Dry	Dry	<sup>7</sup> 2.2
	.44	70	<sup>7</sup> > 120

<sup>1</sup>See table 1.

<sup>2</sup>No ignition with 102, 109, 131.

<sup>3</sup>No ignition with 97, 114, 178.

<sup>4</sup>15, 15, 43, 76; no ignition with 119, 122.

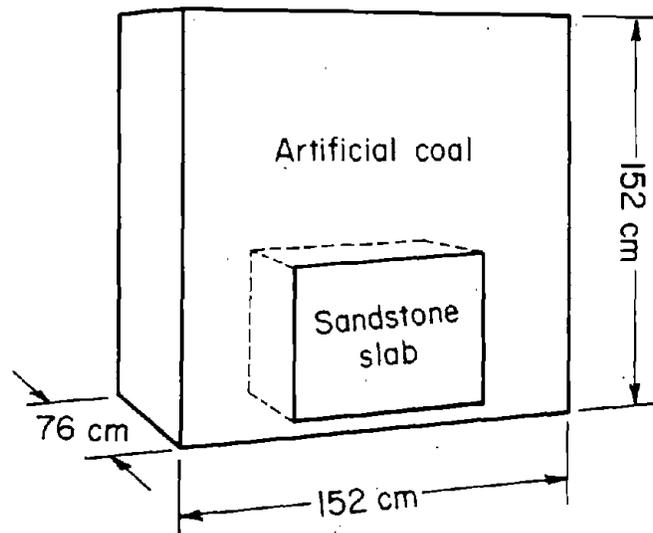
<sup>5</sup>30; no ignition with 119, 121, 121.

<sup>6</sup>No ignition with 115, 117, 120, 120, 124.

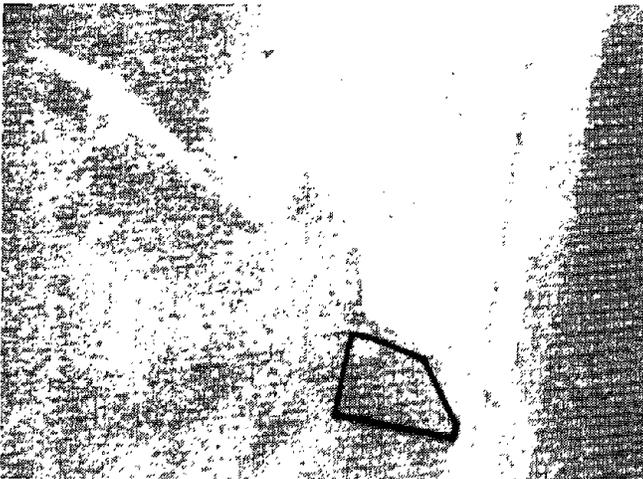
<sup>7</sup>No ignition with 108, 119, 121, 121, 121, 121, 121, 121, 123, 126.

The above tests used a single bit. With a fully laced drum, broken coal from nearby bits may interfere with the spray pattern and reduce the anti-ignition effectiveness of the back spray. This aspect was investigated using the drum fully laced with 43 bits making a sump-type cut into a 152-cm-high, 152-cm-long, 76-cm-wide block of artificial

coal containing a 51-cm-high, 76-cm-long, 76-cm-wide sandstone slab in the bottom part of the block (fig. 16). A GG3004 spray nozzle was located behind each of the 43 bits as shown in figure 14. Figure 17 shows several of the bits with their back sprays. Total water consumption was 22 gpm when the 43 sprays were operated at 100 psig. Bits worn 0.54 cm were used to subject the anti-ignition back sprays to a severe test. The drum and block were again enclosed in a wooden box containing a 7-pct methane-air mixture. The drum was operated at 47 rpm. Depth of cut usually was 0.079 cm/r. The time to give ignition was taken as a measure of the ease of ignition.



**Figure 16.-Artificial coal block containing sandstone slab.**



**Figure 15.-Hot streak cooled by back spray.**



**Figure 17.-Back sprays with fully laced Joy ILS shearer drum.**

No ignition occurred during 50 s of dry cutting into the artificial coal part of the block. Results obtained with the drum cutting into the sandstone part of the block are given in table 4. Raw data are again given in the footnotes, with tests considered to be outliers given in brackets. The 17 "dry" tests in brackets in footnote 1 were conducted shortly after a wet test and thus involved cutting into damp sandstone. The bracketed test in footnote 3 involved bits that were severely worn on their sides because of abrasion of the bit on the side of the sandstone slab; this test was considered to be an outlier since the back spray would not impact and cool the hot streak formed on the side of the sandstone slab.

**Table 4.—Effect of Spraying Systems GG3004 back spray on frictional ignition with fully laced drum using 0.54-cm-worn Kennametal K-100 bit**

Depth of cut, cm/r	Spray		Av time for ignition, s	Nozzles plugged
	Flow rate, gpm	Pressure, psig		
0.079 . .	Dry	Dry	<sup>1</sup> 13	0
	0.37	40	<sup>2</sup> 53	0
	.41	60	<sup>3</sup> >75	9
	.47	80	<sup>4</sup> >73	0
	.47	80	<sup>5</sup> >65	4
	.53	100	<sup>6</sup> >63	0
	.53	100	<sup>7</sup> >69	9
	.67	170	<sup>8</sup> >68	0
	.82	240	<sup>9</sup> >92	9
	0.19 . . .	Dry	Dry	<sup>10</sup> 13
.53		100	<sup>9</sup> >54	0
0.58 . . .	.53	100	<sup>9</sup> >74	0

<sup>1</sup>3, 6, 8, 9, 10, 12, 22, 30, [6, 10, 10, 11, 12, 14, 14, 16, 19, 24, 32, 34, 34, 38, 42, 42, 48].

<sup>2</sup>38, 68.

<sup>3</sup>[22]; no ignition with 72, 78.

<sup>4</sup>No ignition with 72, 74.

<sup>5</sup>No ignition with 50, 80.

<sup>6</sup>No ignition with 48, 52, 60, 60, 66, 70, 70, 78.

<sup>7</sup>48; no ignition with 75, 83.

<sup>8</sup>No ignition with 61, 74.

<sup>9</sup>1 test.

<sup>10</sup>12, 14.

Ignition occurred with an average of 13 s during dry cutting into the sandstone slab. Ignition was not observed in 54+ s during wet cutting if the water pressure was 60 psig or higher. Ignition was observed in 53 s when the water pressure was reduced to 40 psig.

No ignition occurred (>65 s) when four adjacent spray nozzles were plugged, indicating that a back spray provided considerable anti-ignition protection in cooling the hot streaks formed by nearby bits whose spray nozzles became clogged. When nine adjacent spray nozzles were plugged, no ignition occurred in five of six tests (averaging >75 s), again indicating the considerable protection provided by a back spray to nearby bits.

The depth of cut did not appear to be significant, in that ignition was also obtained in 13 s of dry cutting when the depth of cut was 0.19 cm/r.

Since 47 rpm corresponds to 0.8 rps, a 13-s test corresponds to 10 cuts by a bit. These multibit results may be compared with the earlier single-bit results, which gave ignition with 2.2 dry cuts, and suggest that frictional

ignition is less likely with a multibit system. However, the anti-ignition protection provided by back sprays with both systems appears to be very significant. Briefly summarized, the BCRNL results were—

1. In dry cutting,
  - a. No frictional ignition occurred using new or slightly worn bits but ignition readily occurred with a few cuts using slightly more worn bits;
  - b. Decreased bit velocity (in the range considered to be of practical interest) had negligible effect on reducing the likelihood of frictional ignition using very worn bits.
2. In wet cutting with very worn bits,
  - a. Frictional ignition readily occurred when the water spray impinged onto the bit;
  - b. The likelihood of ignition was significantly reduced if the spray from a Spraying Systems GG3004 nozzle impinged onto the freshly cut sandstone surface directly behind the bit when the nozzle was operated at 80 to 240 psig (0.47 to 0.82 gpm), but ignition occurred when the nozzle was operated at 40 psig;
  - c. The broken coal did not significantly interfere with the anti-ignition effectiveness of the back spray;
  - d. No ignition occurred when four adjacent nozzles were plugged, and the likelihood of ignition was significantly reduced when nine adjacent nozzles were plugged.

BCRNL recommended that a Spraying System GG3004 spray nozzle giving a solid-cone spray be located behind each cutter bit, be carefully oriented so that the spray water impinged onto the freshly cut mineral surface *directly* behind the bit, and be operated at 80 to 100 psig (0.5 gpm) at the nozzle.

An early field test with an anti-ignition-modified Joy ILS drum using back sprays that extended 0.3 cm beyond their steel protective housings failed because of breakage of the spray nozzles. Field tests with the anti-ignition-modified Joy ILS drum using the recessed spray nozzle shown in figure 14 were cancelled because of the unavailability of a field shearer.

### Carmet TC3

A mining company purchased anti-ignition shearer drums with Carmet (Allegheny Ludlum Industries Co.) TC3 rectangular bits and specified back-mounted Senior Conflow, Inc., 280INC spray nozzles instead of the Spraying Systems GG3004 nozzles because of easier nozzle replacement. The 280INC nozzle gives a solid-cone spray having about the same spray geometry and waterflow rate (0.4 gpm at 100 psig) as the GG3004 nozzle and was expected to provide similar anti-ignition protection.

However, several frictional ignitions occurred in the field with the anti-ignition-modified drums. The mine operator had experienced nozzle clogging and had attempted to avoid clogging by (1) modifying half of the 280INC nozzles so that they delivered a hollow-cone spray instead of the solid-cone spray and (2) increasing the water pressure to 300 psig instead of using the 80- to 100-psig

range recommended by BCRNL. Furthermore, the operator planned to use Senior Conflow 777NC nozzles operated at 500 psig in the future. While the general spray characteristics of the 777NC nozzle are similar to those of the 280INC and GG3004 nozzles and should provide similar anti-ignition protection at 100 psig, the anti-ignition performance of these nozzles at 300 and 500 psig was unknown.

Numerous in-mine tests have indicated that nozzle clogging due to dirty water entering the mining machine can be easily avoided with a Bureau-designed nonclogging system (21), which involves a Y-type strainer, a hydrocyclone, and a polishing filter. Rust and scale particles that form in the water channels inside the machine can be eliminated with screens installed in each spray nozzle. Otherwise, regarding modification 1, the anti-ignition performance of a hollow-cone spray had not been investigated but was expected to be less than that provided by a solid-cone spray because of lesser cooling of the hot streak by the annular drop-impaction pattern instead of the solid-circle pattern. Regarding modification 2, a nozzle operated at high pressure tends to give a fine mist instead of the coarse spray obtained when the nozzle is operated at lower pressure. Misting is undesirable from an anti-ignition viewpoint since the small mist drops rapidly lose their momentum and would be less likely to impact the sandstone surface and cool the hot streak.

Laboratory tests with the Carmet TC3 bit were conducted by the Bureau to investigate the anti-ignition performance of the 280INC and 777NC nozzles, especially when operated at high pressure. Figure 18 shows the 1.3-cm-wide Carmet TC3 bit. TC3 bits were shortened by 0.32 and 0.43 cm and flattened to simulate field bits that had become worn in order to expose the incendiary steel

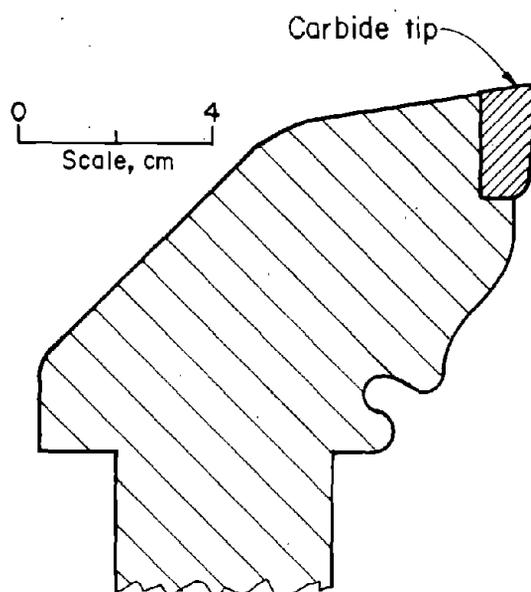


Figure 18.—Carmet TC3 bit.

shank and subject the back sprays to a severe test. Previous work (with the GTE bit described later) had indicated that ignition with sandstone that had been dampened by a previous wet test was more difficult, i.e., required more cuts for ignition. Therefore, a sequence of only two ignition tests were made per day. The first test was conducted dry to confirm that the sandstone was suitably dry. The second test was conducted wet. Tests were then stopped, and a space heater was installed in the chamber to dry the sandstone block overnight. A new dry-wet sequence of two tests was conducted the next day.

Results are given in table 5. Frictional ignition with the 0.32-cm-worn TC3 bit was obtained with an average of 4.0 dry cuts but was not obtained with about 65 wet cuts using either the 280INC nozzle operated at 100, 300, and 500 psig (0.4, 1.1, and 1.1 gpm) or the 777NC nozzle operated at 100 and 300 psig (0.4 and 0.8 gpm). However, with the 0.43-cm-worn bit, ignition was obtained with 19 and 9 wet cuts when the 777NC nozzle was operated at 100 and 300 psig and in 1 of 2 tests performed at 500 psig versus the average of 2.4 dry cuts for ignition.

Table 5.—Ignition results with Carmet TC3 bit and Senior Conflow back spray

Bit wear, cm	Nozzle	Spray		Av number of cuts for Ignition
		Flow rate, gpm	Pressure, psig	
0.32 ..	Dry	Dry	Dry	<sup>1</sup> 4.0
	280INC	0.4	100	<sup>2</sup> >66
	280INC	1.1	300	<sup>3</sup> >65
	280INC	1.1	500	<sup>4</sup> >63
	777NC	.4	100	<sup>5</sup> >68
	777NC	.8	300	<sup>6</sup> >69
0.43 ..	Dry	Dry	Dry	<sup>7</sup> 2.4
	777NC	.4	100	<sup>8</sup> 19
	777NC	.8	300	<sup>9</sup> 9.0
	777NC	1.3	500	<sup>10</sup> >36

<sup>1</sup>2, 2, 2, 3, 3, 3, 4, 4, 5, 7, 8.

<sup>2</sup>No ignition with 65, 68.

<sup>3</sup>No ignition with 62, 64, 68.

<sup>4</sup>No ignition with 62, 64.

<sup>5</sup>No ignition with 68, 68, 68.

<sup>6</sup>No ignition with 68, 70.

<sup>7</sup>2, 2, 2, 2, 2, 3, 3, 3.

<sup>8</sup>1 test.

<sup>9</sup>5, 9, 12.

<sup>10</sup>4; no ignition with 68.

As with the Kennametal K-100 bit, the physical difference between the "safe" 0.32-cm-worn bit and the "dangerous" 0.43-cm-worn bit when using back sprays was barely discernible in the laboratory; e.g., the lengths of the exposed steel shanks were 1.7 and 2.2 cm, respectively.

Since the areas of the exposed steel shanks of the worn Carmet TC3 and the Kennametal K-100 bits are comparable and the worn K-100 bit was easily protected with the Spraying Systems GG3004 nozzle operated at 0.5 gpm and 100 psig, the Senior Conflow 280INC and 777NC sprays as used here appear to be somewhat less protective than the Spraying Systems GG3004 nozzle.

Operation of either the 280INC or 777NC nozzle at 300 psig and especially at 500 psig would appear to offer

no anti-ignition advantage and would definitely be disadvantageous in terms of high waterflow rate and the usual expense and inconvenience of operating at high water pressure.

It may be that the several field ignitions with the anti-ignition drums involved nozzle clogging.

### AMS THRU-FLUSH

Sometimes there may be insufficient physical space on the cutter drum to locate a spray nozzle on the drum directly behind each bit as shown in figure 14. The back-mounted anti-ignition spray nozzles then must be located to one side of the bit, or some other physical change in the nozzle-bit geometry must be considered.

One approach is to install the spray nozzle directly in the back part of the bit shank. Such a bit is commercially available from AMS Technology and is called a THRU-FLUSH bit. AMS offers either a slot-type spray nozzle, which gives a fan spray whose orientation is fixed and directed onto the bit path, or a solid-cone spray. AMS reported that field tests indicate that the fan spray gives a significant reduction in respirable dust compared with both the AMS cone spray and a conventional boom-mounted water spray system.

The anti-ignition performance of the fan-spray version of the THRU-FLUSH bit was investigated in the laboratory. In initial work, the THRU-FLUSH bit was cut down 1.3 cm and flattened to expose the steel shank behind the carbide section in the front part of the bit tip but still protect the recessed spray nozzle, thereby simulating a worn field bit. However, reproducibility was poor because the trailing steel section of the flattened tip became worn in an irregular manner. The front carbide section of the tip was cut down another 0.6 cm so that only the flattened steel shank was abrading the sandstone surface. Figure 19 shows the 2.5-cm-wide THRU-FLUSH bit on the left and the modified bit used in the present ignition tests on the right. Figure 20 shows the THRU-FLUSH bit with the fan back spray operated at 100 psig. The water density in the spray shown in figure 20 was less near the bit tip than farther behind the tip. This spray inhomogeneity may have been due to a faulty spray nozzle, but this aspect was not examined.

A 38-cm-wide, 51-cm-high sandstone block was used in these tests. The block was moved at 23 cm/min across the drum being rotated at 39 rpm, giving about 65 cuts during 1 pass of the block. About one-fourth of the bit tip cut into a fresh part of the sandstone block and three-fourths of the tip abraded the previously cut part of the block.

Results are given in table 6. The outlier in footnote 2 occurred when the side of the bit abraded the side of the sandstone block. Frictional ignition was obtained with an average of 3.7 dry cuts and was not obtained with 63+ wet

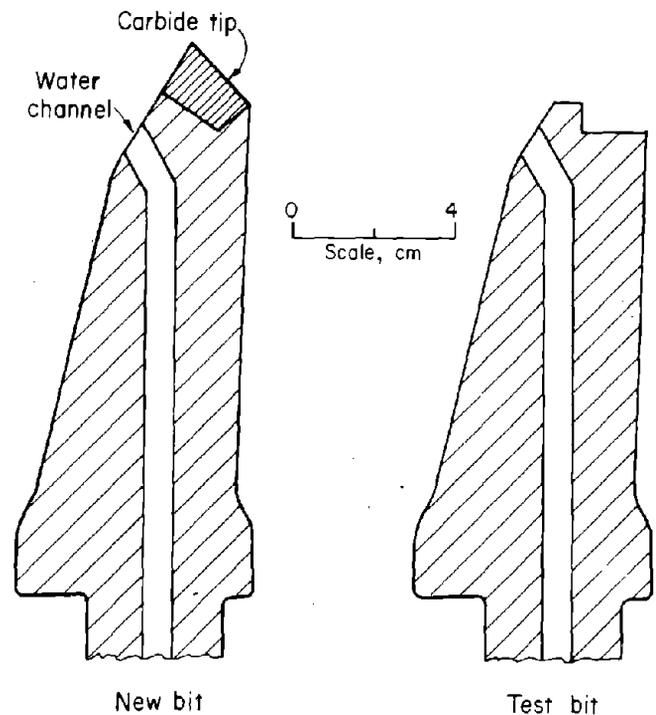


Figure 19.-AMS THRU-FLUSH bit (left) and test bit (right).



Figure 20.-AMS THRU-FLUSH bit with fan back spray at 100 psig.

cuts. The AMS fan spray thus significantly reduced the likelihood of frictional ignition with the THRU-FLUSH bit, although the water consumption of 1 gpm was somewhat high.

**Table 6.-Ignition results with AMS THRU-FLUSH bit using fan-type back spray**

Spray		Av number of cuts for ignition
Flow rate, gpm	Pressure, psig	
Dry	Dry	<sup>1</sup> 3.7
0.9	50	<sup>2</sup> > 64
1.1	100	<sup>3</sup> > 67
1.1	300	<sup>4</sup> > 64
1.1	500	<sup>5</sup> > 63

<sup>1</sup>1, 2, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3, 4, 4, 5, 7, 8, 10.

<sup>2</sup>[64]; no ignition with 64, 64.

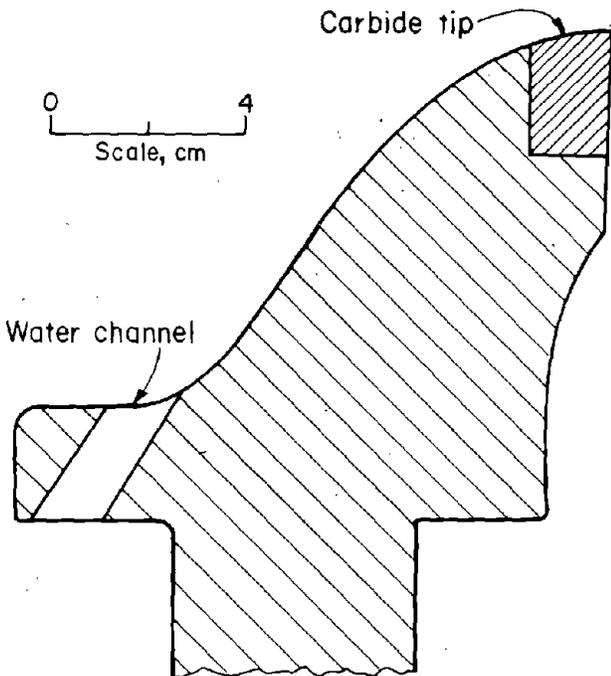
<sup>3</sup>No ignition with 65, 68, 68, 68.

<sup>4</sup>No ignition with 62, 64, 67.

<sup>5</sup>No ignition with 62, 64.

**Hydra Tools HP74ISR**

A rectangular bit that incorporates a water spray nozzle mounted on the cutter drum directly behind the bit, with the spray passing through a channel in the bit block and impinging onto the mineral surface in back of the bit, is commercially available from Hydra Tools International, Inc. (HP74ISR). Spray nozzles giving solid-cone and jet sprays are offered. Figure 21 shows the 2.5-cm-wide bit. Figure 22 shows the cone version of the Hydra Tools back spray, and figure 23 shows the jet version, with both spray nozzles operated at 150 psig.



**Figure 21.-Hydra Tools HP74ISR bit.**

The anti-ignition performances of the Hydra Tools spray systems were investigated. The Hydra Tools tungsten-carbide tip was replaced with a steel tip having the same geometry in order to investigate the effectiveness of the back spray under severe conditions. A new steel tip



**Figure 22.-Hydra Tools HP74ISR bit with cone back spray at 100 psig.**



**Figure 23.-Hydra Tools HP74ISR bit with jet back spray at 100 psig.**

was used in each test. The 51-cm-wide sandstone block was moved at 84 or 127 cm/min across the drum being rotated at 42 rpm, giving 26 or 17 cuts during 1 pass of the block, with 80 and 100 pct of the width of the cuts, respectively, made in fresh sandstone. The total number of cuts to obtain ignition with a new steel tip was counted.

Results (table 7) did not depend upon cart speed. The three bracketed tests in footnote 1 involved cutting into damp sandstone. Ignition was obtained with an average of 5.7 dry cuts. No ignition was obtained with the cone or jet spray with an average of 132 or more cuts. The cone spray perhaps could be considered less protective than the jet spray, in view of the two ignitions in three tests at 100 psig, but additional replicate tests are required. The jet spray definitely involves considerably greater water consumption.

Table 7.—Ignition results with Hydra Tools HP74ISR bit with back spray

Nozzle	Spray		Av number of cuts for ignition
	Flow rate, gpm	Pressure, psig	
Dry . . .	Dry	Dry	<sup>1</sup> 5.7
Cone . .	1.3	100	<sup>2</sup> > 132
Do . . .	1.6	150	<sup>3</sup> > 203
Jet . . .	3	100	<sup>4</sup> > 155
Do . . .	5	150	<sup>4</sup> > 182

<sup>1</sup>1, 2, 2, 2, 2, 2, 2, 3, 3, 5, 5, 5, 5, 6, 6, 6, 7, 8, 9, 11, 12, 13, 14; no ignition with [16, 17, 18].

<sup>2</sup>61, 136; no ignition with 199.

<sup>3</sup>No ignition with 102, 303.

<sup>4</sup>1 test.

The present results indicate that the Hydra Tools back-spray system is effective in reducing the likelihood of frictional ignition with a worn version of their bit. Of course, ignition with only a few dry cuts with the present steel-tipped bit does not indicate the ignition performance of the commercial Hydra Tools bit with its tungsten-carbide tip.

## CONICAL BITS

About 75 pct of the frictional ignition incidents in U.S. coal mines (fig. 2) involved ripper-type continuous mining machines. Application of the back-spray concept to a ripper machine involves (1) the design and fabrication of a wet-head ripper drum using durable large-diameter water seals and (2) careful installation of properly engineered water spray nozzles behind each cutter bit.

In the early 1970's several Bureau-funded field studies (22) investigated the effect of drum-mounted water spray nozzles on respirable dust with wet-head ripper machines, using state-of-the-art water seals. Results indicated that water sprays mounted on the ripper drum in the general vicinity of the cutter bits reduced respirable dust compared with conventional boom-mounted water sprays and did not interfere with visibility or splash onto

the machine operator. However, seal life was severely limited. A durable, large-diameter water seal was recently developed by Cannings Seals in Great Britain and has been successfully used in mining equipment in Europe and elsewhere for several years. A wet-head cutter drum for a Simmons Rand 265 continuous mining machine using Cannings water seals was designed and fabricated by Simmons Rand under Bureau contract J0395040.

However, a ripper drum usually uses conical bits with a small bit attack angle while a shearer drum usually uses rectangular bits with a large attack angle. In addition, the bit and bit block of a conical bit may physically interfere with the back spray impacting the mineral surface immediately behind the bit to a greater extent than occurs with a rectangular bit system such as described previously. Also, there may be insufficient physical space on the ripper drum to locate an anti-ignition spray nozzle directly behind each bit, and the back-mounted spray nozzle for a ripper drum may have to be located to one side of the bit and further away from the mineral surface. The design of an anti-ignition back-spray system for a conical bit on a ripper drum thus may be more difficult than for a rectangular (radial) bit on a shearer drum because of spray-bit geometry.

A laboratory study of the anti-ignition performance of several types of back-spray nozzles with a typical conical bit using the wet-head segment of a Joy 12CM drum is described in the following section. A recent field study of a specific back-located spray nozzle with several types of conical bits using the fully laced Simmons Rand 265 wet-head drum is described later.

## GTE

A commercial "double-carbide" GTE Corp. conical bit being used in a coal mine in which a future field test was expected to be performed was tested with the wet-head segment of the Joy 12CM drum. The commercial bit block gave a bit attack angle of 45°. The bit and bit block involved considerable interference with the back spray impacting the mineral surface immediately behind the bit. This interference was especially severe for a bit mounted on the end of the drum.

The effect of spray parameters for a single conical bit mounted in the middle or at the end of the drum was investigated. Water spray nozzles were located on the cutter drum in back of and, because of space limitations with the Joy 12CM as laced, to one side of the bit. The spray nozzles were about 10 cm from the tips of the bits. It was expected that a field drum would channel water through a scroll mounted on the outer surface of the drum. The spray nozzles were mounted 2 cm above the surface of the drum to simulate a field drum with scroll. A universal joint was used to facilitate nozzle orientation. Figure 24 shows the end bit with its spray nozzle.



Figure 24.—Back spray and conical bit located at end of cutter drum.

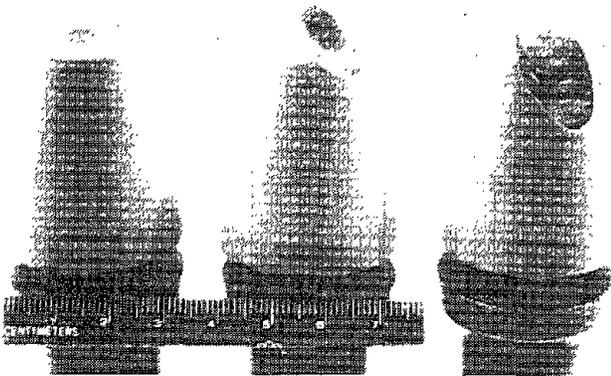


Figure 25.—New and 0.5- and 0.75-cm-worn GTE bits, left to right.

The base of the bit was cut with a slot that fit over a tongue in the bit block to prevent the bit from rotating during cutting. The tip of the bit was shortened by 0.5 or 0.75 cm and then cut to have a flat surface to simulate a field bit that had become frozen and had worn a wear flat. The flattened bit purposely exposed part of the steel shank in order to submit the anti-ignition back spray to a severe test. The wear flat was about 2.5 cm wide and 3 cm long. Figure 25 shows a new bit on the left and 0.5- and 0.75-cm-worn bits for the end location in the middle and on the right. A newly fabricated flattened bit was "worn in" with 100 cuts to match the flat on the bit to the excavated arc in the 51- by 51- by 51-cm block of sandstone. With the typical cart speed of 28 or 71 cm/min and the drum speed of 39 rpm used in the field, about 70 or

29 cuts were respectively made in the block during 1 pass. With the slower cart speed, about 33 pct of the bit cut into sandstone and 67 pct abraded the previously cut surface of the sandstone. With the faster cart speed, about 60 pct of the bit cut into sandstone and 40 pct abraded the previously cut surface.

The sandstone used in these studies readily absorbed water, and frictional ignition with a damp sandstone surface that had been moistened by weather or a previous wet test was more difficult (required more cuts) than with a dry sandstone surface. In four instances involving a sequence of dry-wet-dry tests with a 0.75-cm-worn middle bit, the second "dry" test involved cutting into the dampened sandstone and required an average of 22.5 cuts for ignition instead of the average of 4.7 cuts in the first dry test using sandstone that had been dried overnight. Later tests therefore involved only one wet test per day, with the sandstone block then dried overnight with a space heater.

The present wet results were very sensitive to the precise orientation of the back spray nozzle, in that changing the aim of the nozzle relative to the bit by only a few degrees significantly decreased the anti-ignition effectiveness of the back spray. This decrease appeared to be due to water impacting the bit and bit block; i.e., such water again seemingly was wasted in terms of anti-ignition performance. The spray nozzles were oriented initially by visually observing the spray impaction pattern on a plastic sheet held to simulate the impaction plane on the sandstone and later by using a template.

Results are given in table 8 and reported in reference 23. Bracketed tests in the footnotes were considered to be outliers due to cutting into damp stone or to a poor nozzle orientation. Ignition with worn bits again was readily obtained with only a few dry cuts. There was no drastic difference at the middle and end locations; e.g., with a 0.75-cm-worn bit, ignition was obtained with an average of 4.7 dry cuts with the middle bit and 5.0 dry cuts with the end bit. Results did not depend upon cart speed.

As before, the likelihood of frictional ignition during dry cutting was not appreciably reduced when the drum speed was decreased; i.e., with the 0.75-cm-worn middle bit, ignition was obtained with 5 and 7 dry cuts in 2 tests when the drum was operated at 20 rpm compared with the average of 4.7 cuts when the drum was operated at 39 rpm.

Wet cutting with a carefully oriented back spray again significantly reduced the likelihood of frictional ignition. With 0.5-cm-worn middle and end bits, ignition was obtained with an average of 6.9 and 2.8 dry cuts and was not obtained with 60+ and 40+ wet cuts. Similarly, with 0.75-cm-worn middle bits, ignition was obtained with 4.7 dry cuts and was not obtained with 39+ wet cuts.

The planned field test was canceled by the coal mine operator.

Table 8.—Ignition results with GTE conical bit and Spraying Systems back spray

Nozzle	Spray			Bit wear, cm	Av number of cuts for ignition	
	Flow rate, gpm	Pressure, psig	Internal angle, deg		Middle bit	End bit
Dry	Dry	Dry	Dry	New	-	<sup>1</sup> >47
	Dry	Dry	Dry	0.50	<sup>2</sup> 6.9	<sup>3</sup> 2.8
	Dry	Dry	Dry	.75	<sup>4</sup> 4.7	<sup>5</sup> 5.0
GG3	0.7	60	60	.75	-	<sup>6</sup> 29
	.8	80	60	.75	-	<sup>6</sup> >42
	.9	100	60	.75	-	<sup>6</sup> >24
3002.5	.3	60	35	.75	<sup>7</sup> >69	-
	.3	80	35	.75	<sup>8</sup> 41.7	<sup>6</sup> >59
	.4	110	35	.75	<sup>9</sup> >47	<sup>10</sup> >20.5
3004	.4	60	30	.50	<sup>11</sup> >72	-
	.5	80	30	.50	<sup>12</sup> >60	-
	.5	80	30	.75	<sup>13</sup> >39	-
	.5	110	30	.75	<sup>14</sup> >54	<sup>15</sup> >24
	.5	100	25	.50	-	<sup>16</sup> 14
TTD 3-56	.6	150	25	.50	-	<sup>17</sup> 34
	.4	100	20	.50	<sup>18</sup> >67.2	<sup>19</sup> 39.5
TTD 2-56	.5	150	20	.50	<sup>20</sup> >59.3	<sup>21</sup> >69.5

<sup>1</sup>24; no ignition with 70.

<sup>2</sup>3, 4, 5, 5, 6, 7, 10, 11, 11, [17, 23, 23, 27, 44, 59, 72]; no ignition with [50, 72, 76].

<sup>3</sup>1, 1, 2, 7.

<sup>4</sup>1, 1, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3, 4, 4, 4, 4, 4, 4, 5, 5, 5, 5, 5, 5, 6, 6, 6, 6, 6, 7, 7, 7, 7, 8, 8, 8, 8, 9, [14, 14, 16, 16, 26, 32, 35]; no ignition with [36].

<sup>5</sup>1, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 3, 4, 4, 4, 5, 5, 6, 6, 7, 7, 7, 8, 8, 9, 9, 9, 10, 10, 14, [14, 14, 26, 28]; no ignition with [61].

<sup>6</sup>1 test.

<sup>7</sup>66; no ignition with 69, 72.

<sup>8</sup>28, 35, 62.

<sup>9</sup>[7], 29; no ignition with 65.

<sup>10</sup>15; no ignition with 26.

<sup>11</sup>No ignition with 70, 72, 72, 73, 73.

<sup>12</sup>27; no ignition with 74, 80.

<sup>13</sup>23, 26, 26; no ignition with 81.

<sup>14</sup>14, no ignition with 24, 33, 58, 74, 75, 75.

<sup>15</sup>[3, 4, 6]; no ignition with 24.

<sup>16</sup>[3], 14.

<sup>17</sup>[6], 34.

<sup>18</sup>No ignition with 62, 67, 67, 73.

<sup>19</sup>[5], 24, 27, 47, 60.

<sup>20</sup>No ignition with 33, 67, 67, 70.

<sup>21</sup>No ignition with 69, 70.

NOTE.—Dashes indicate no tests were performed under these conditions.

### Anti-Ignition-Modified Cutter Drum for Simmons Rand 265 Continuous Mining Machine

The bit lacing for the wet-head Simmons Rand 265 ripper machine was designed by AMS for moderate cutting conditions occurring in a specific mine that had a history of frictional ignitions and was expected to provide a field test site. The drum was laced with a total of 76 AMS conical bits, 72 bits in the center part of the drum and 2 bits in the middle part of each end of the drum. The bit blocks gave a bit attack angle of 52°. Sufficient space was available to install water spray nozzles about 18 cm behind the tip of each of the 72 center bits. Figure 26 shows several of the center bits and their spray nozzles. No spray nozzles were used behind the four end bits because of engineering difficulties in channeling water to the end locations. While a channeling technique could undoubtedly be devised, the present effort was limited by financial restrictions, and conveyance of the water to the end locations was postponed to a future effort if seal durability in the field could be demonstrated.

The AMS solid-cone spray nozzle (06-900870-000) had a 20° internal angle and delivered a well-formed spray at 0.3 gpm and 50 psig. Each nozzle was carefully oriented using a template so that about 75 pct of the spray water impacted the mineral surface directly behind the bit and 25 pct of the water impacted the bit and bit block. This spray orientation led to wastage of the water impacted on the bit and block but was selected in view of the sensitivity of the anti-ignition performance to the spray-bit orientation and the possibility that other bits might be used in the field. No laboratory ignition tests were done with this spray-bit system.

The wet-head-modified Simmons Rand 265 machine was installed in the ignition-prone mine in mid-1987 in a section having a 30-cm-high sandstone parting. Figure 27 shows the modified drum in operation in the mine. Results indicated no water leakage with the Cannings water seals during the mining of 150,000 tons, despite several early shifts of dry operation with no water being passed into the seals. Miscellaneous conical bits were used. No frictional ignitions have occurred, airborne respirable dust was dramatically reduced according to visual observation,

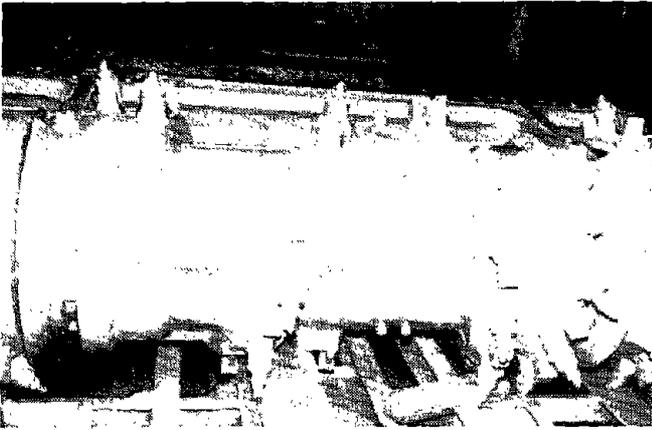


Figure 26.-Anti-ignition-modified Simmons Rand 265 drum.



Figure 27.-Modified Simmons Rand 265 drum in operation.

bit life increased 50 pct, and the wet-head drum was well received by face personnel because of increased visibility (24). The test was completed in mid-1988 when the mining machine was removed for routine maintenance overhaul. Inspection of the seals indicated that they were still in good condition.

### Kennametal K-178DC

A conical bit that incorporates water spray nozzles directly in the bit block behind and/or in front of the bit is commercially available from Kennametal (K-178DC) (fig. 28). The bit attack angle is 55°. Kennametal offers either solid- or hollow-cone or jet spray nozzles. Figure 29 shows the bit with the Kennametal solid-cone back spray (Senior Conflow 2801) operated at 150 psig. Figure 30 shows the Kennametal jet front spray, also operated at 150 psig.

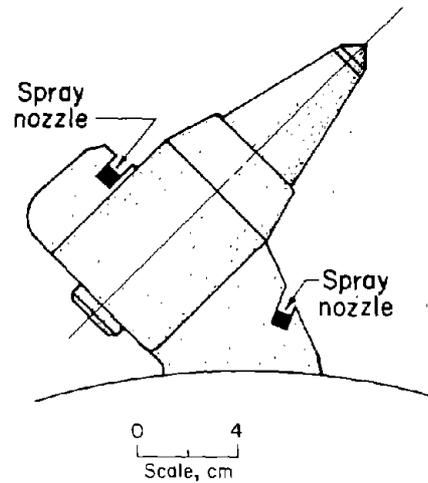


Figure 28.-Kennametal K-178DC bit.

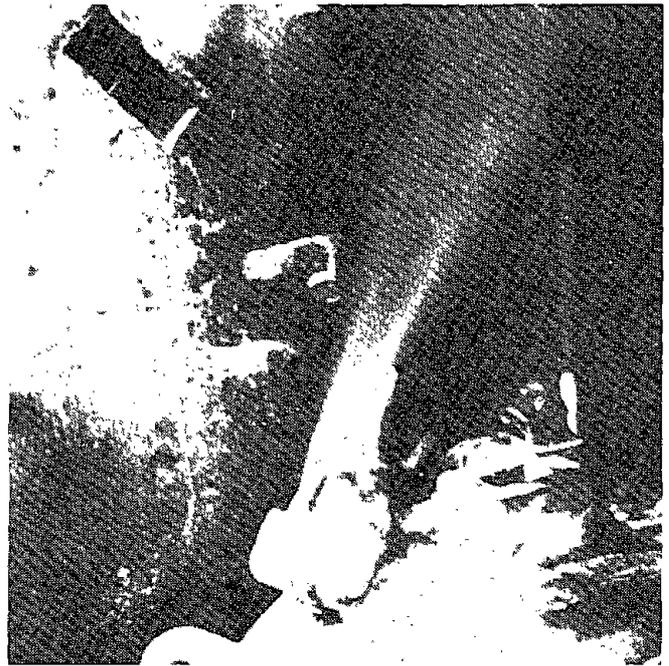


Figure 29.-Kennametal K-178DC bit with solid-cone back spray at 150 psig.

The anti-ignition performance of the Kennametal back- and front-located spray systems was investigated. The anti-ignition benefit of a front-located high-pressure jet using a Bureau-designed 0.06-cm-diam nozzle orifice also was tested during other work investigating the enhancement of cutting (25). The Kennametal tungsten-carbide tip was replaced with a steel tip having the same geometry in order to subject the Kennametal sprays to severe test conditions. A new steel-tipped bit was used in each test.



Figure 30.—Kennametal K-178DC bit with jet front spray at 150 psig.

Results are given in table 9. Ignition was obtained with an average of 4.2 dry cuts and was not obtained with 97+ wet cuts with the hollow- or solid-cone spray mounted in back of the bit. With the front-mounted Kennametal and Bureau jet sprays, ignition was obtained in about half of the tests at each of the cited pressures.

The Kennametal back spray thus significantly reduced the likelihood of frictional ignition. Again, the present results giving ignition with only a few dry cuts with the steel-tipped bit do not indicate the ignition performance of the commercial Kennametal bit with its tungsten-carbide tip.

Table 9.—Ignition results with Kennametal K-178DC bit

Location	Nozzle		Spray		Av number of cuts for ignition
	Type	Flow rate, gpm	Pressure, psig	Dry	
Dry ...	Dry .....	Dry	Dry		<sup>1</sup> 4.2
Back ..	Hollow cone	1	150		<sup>2</sup> > 97
Do ...	Solid cone..	1	100		<sup>3</sup> > 138
Front ..	Jet .....	.9	150		<sup>4</sup> > 18
Do ...	Bureau jet..	.75	2,000		<sup>5</sup> > 65
Do ...	.. do .....	.90	3,000		<sup>6</sup> > 26
Do ...	.. do .....	1.15	5,000		<sup>7</sup> > 65

<sup>1</sup>1, 1, 3, 3, 3, 4, 6, 8, 9.

<sup>2</sup>No ignition with 28, 107, 117, 137.

<sup>3</sup>1 test.

<sup>4</sup>9; no ignition with 28.

<sup>5</sup>10; no ignition with 121.

<sup>6</sup>17, 21, 39.

<sup>7</sup>10, 13, 24, 35, 37; no ignition with 103, 122, 179.

## DISCUSSION

Frictional ignition with the cutter bits on a mining machine can occur when the mining machine is cutting into sandstone (or pyrite). Conversely, if the mining machine is cutting into sandstone, the mine operator probably should *expect* frictional ignitions.

Remedial techniques to reduce the likelihood of frictional ignition include

1. Mushroom-shaped tungsten-carbide bit tips;
2. Increased bit clearance angle, e.g., with conical bits, increased bit attack angle and/or decreased internal tip angle; and
3. A carefully oriented water spray nozzle in back of each cutter bit.

With a shearer drum, the preferred remedial technique is to use drum-mounted back sprays. Fabrication of an anti-ignition shearer drum involves moving the variously located antidust water spray nozzles on the commercially available wet-head shearer drum so that they are located directly behind each of the bits and are carefully oriented so their sprays impact the mineral surface directly behind the bits. Several anti-ignition back spray and bit systems are commercially available (e.g., AMS, Hydra Tools, Kennametal) and have been used in the field. An antidust benefit has been reported with the anti-ignition back spray.

A wet-head cutter drum for the Simmons Rand 265 continuous mining machine that incorporates anti-ignition drum-mounted back-located spray nozzles was developed by Simmons Rand and AMS. However, wet-head cutter drums for other continuous mining machines are not commercially available at present. In the interim, the operator can use the mushroom tip and increased clearance angle features for conical bits presently being used by JWR (15). Mushroom-shaped tips for conical bits are commercially available.

The mine operator is cautioned that no anti-ignition remedial technique will be a panacea and that a systematic schedule must be used to replace bits before they have worn to a dangerous condition. The JWR schedule of replacing bits after every shuttle car is loaded when sandstone is being cut is inconvenient and expensive but is probably as important in avoiding frictional ignition as the use of mushroom tips and increased bit clearance angle (15).

Ignition seemingly can be obtained with almost any tip material but appears less likely to occur (requires more cuts) with a harder, more durable material. With conical bits, ignition was typically obtained here with 5 cuts using a medium-hard steel tip and 50 cuts using a hard tungsten-carbide tip. Similar results were obtained with the more massive rectangular bits. Ignition with the Carmet TC3 bit

required about 10 cuts with a steel tip but was not obtained here with 200 cuts with a tungsten-carbide tip. A small, 1-mm<sup>2</sup> wear flat did form on the carbide tip, and ignition presumably would eventually have been obtained with the larger wear flat formed with additional cuts. The formation of a similar small wear flat on a synthetic diamond tip was observed here and also reported by Roepke (26). The wear rates of diamond-tipped and tungsten-carbide-tipped rectangular bits were not measured here because of the low wear rates of the massive tips. However, field tests (27) indicated that diamond-tipped rectangular bits were significantly more durable than comparable tungsten-carbide-tipped bits and thus may be less likely to cause frictional ignition.

The present observation that a lower bit velocity did not appreciably decrease the likelihood of frictional ignition with a worn bit until a very low velocity was used does not agree with previous studies (5, 9-10). This disparity perhaps is due to differences in bits or test procedures. The present procedure involved a moving bit that intermittently made deep cuts into new locations of a sandstone block, while the study reported in reference 5 used a stationary bit making a continuous deep cut into a new location on the moving sandstone block and the studies in references 9 and 10 used moving bits making shallow cuts into the same location on a stationary sandstone block. However, the present results indicate that a lower bit velocity probably is not a reasonable alternative to avoiding frictional ignition with worn bits in a practical mining operation.

Improved ventilation is often proposed as a remedial technique to reduce the likelihood of frictional ignition. While improved ventilation reduces the severity of the methane explosion that results from a frictional ignition, it probably increases the likelihood of a frictional ignition. Methane is discharged from the face into the entry and mixes with the ventilation airstream in the entry. A boundary layer automatically forms at the face, wherein the local methane concentration is high at the face and decreases away from the face. A combustible methane-air zone therefore must be formed near the face. If the ventilation is increased, the total amount of methane in the boundary layer is decreased but the combustible methane-air zone is moved closer to the ignition source, the hot streak at the face. The net result is that the likelihood of a frictional ignition should increase as the ventilation increases, but the severity of the resulting methane explosion should decrease; i.e., small pops occur instead of a big bang.

The anti-ignition effectiveness of a back spray depends upon the severity of the hot streak, the spray density at the impaction plane on the sandstone, the cooling effectiveness of the spray drops, and the spray-bit geometry. A minimum water density at the spray impaction plane of about 0.015 gpm/cm<sup>2</sup> appears to be required to cool the hot streak formed by the rectangular Kennametal K-100 bit during severe test conditions. With the spray and conical bit system used with the GTE bits, a minimum water density of about 0.007 gpm/cm<sup>2</sup> was required for the

middle bit but 0.015 gpm/cm<sup>2</sup> was required for the end bit. With the AMS spray used on the Simmons Rand 265 drum, the water density also was 0.007 gpm/cm<sup>2</sup>. Such water densities can be readily achieved with commercial water spray nozzles using modest flow rates and pressures, e.g., with the GG3004 nozzle operated at 0.5 gpm and 100 psig or with the AMS nozzle operated at 0.3 gpm and 50 psig. The use of a high waterflow rate of 1 or 2 gpm is commercially popular but does not appear to be required from an anti-ignition viewpoint. Powell and Billinge (17) recently reported that 90- $\mu$ m drops were twice as effective as 200- $\mu$ m drops in cooling the hot streak, and a future study of improved water sprays will include spray nozzles selected to give 90- $\mu$ m drops.

However, continued bit wear may give a hot streak that is not adequately cooled by this water density; therefore, a bit replacement schedule still should be used with a back-spray technique, but a less frequent bit replacement would probably be required. Also, although all back spray systems tested here successfully reduced the likelihood of frictional ignition by all bits tested here by a very significant degree, other bit geometries might prevent the hot streaks from being promptly cooled by back sprays and thereby allow frictional ignitions. These aspects have not yet been examined.

The present observation that frictional ignition is less likely when the sandstone contains water is not surprising and was reported by Titman (28). However, the natural water in the sandstone does not appear significant; i.e., the ignition frequency in the field in the wet summer months was comparable to the frequency in the dry winter months. Infusion of the coal seam with water in order to reduce respirable dust should have an anti-ignition benefit, but the degree of benefit remains to be determined.

From a more fundamental viewpoint, the ignition of a methane-air mixture by a hot surface depends upon the temperature and area of the hot surface and the exposure time. With an electrically heated surface and a 1-s exposure time, Rae (29) reported that a surface temperature of about 1,400° C was required for ignition with a 10-mm<sup>2</sup> surface while 1,250° and 1,200° C were required with 50- and 100-mm<sup>2</sup> surfaces. Similar results were reported by other investigators (30-33), but the required surface temperature increased as exposure time decreased; e.g., with a 10-ms exposure time, 1,900° and 1,850° C were required with 50- and 100-mm<sup>2</sup> surfaces.

When a metal bit cuts into a material such as sandstone, frictional abrasion leads to the formation of a wear flat on the tip of the bit and the generation of heat by the wear flat. Following Osburn (34), cutting involves a sequence of chipping-crushing-abrading processes such as shown in figure 31, where the tip of the wear flat cuts off a chip of the sandstone, and the wear flat, which has a wear angle, then crushes the remaining layer of the sandstone and also abrades the newly formed sandstone particles against the sandstone substrate. It is generally thought that the surfaces of the wear flat and the sandstone become heated by abrasion between asperities until the melting temperature of the lower melting material is

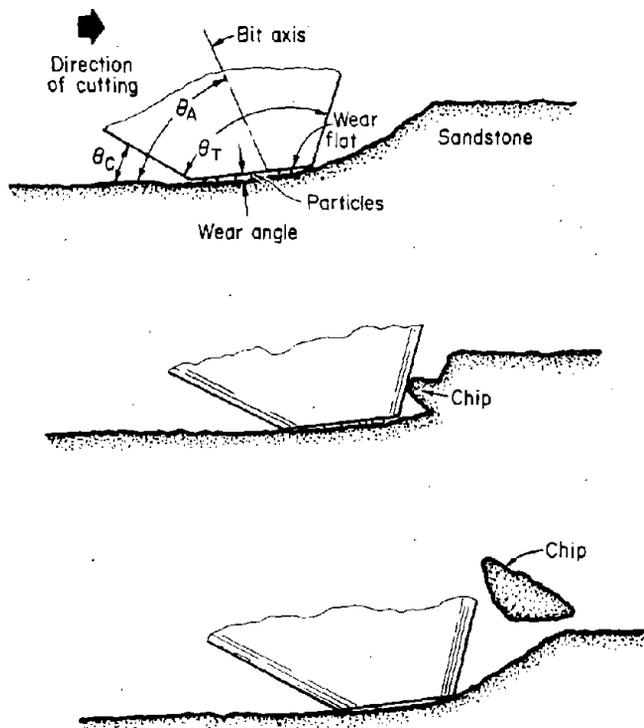


Figure 31.—Cutting processes with worn conical bit. ( $\theta_A$  = attack angle;  $\theta_c$  = initial clearance angle;  $\theta_T$  = initial tip angle.)

reached. A hot smear of the molten material then forms on the surface of the sandstone. Further heat generation due to abrasion is considered to be minor since the contact area is lubricated by the molten material. With a steel tip, the smear is considered to be molten steel at  $1,450^\circ\text{C}$ . With a high-melting tip material such as tungsten carbide, the smear is usually considered to involve molten silica ( $\text{SiO}_2$ ) at  $1,710^\circ\text{C}$ . Such temperatures are sufficiently high to ignite a methane-air mixture if the area and exposure time of the hot smear are adequate.

Blickensderfer (9) investigated the frictional ignition of a methane-air mixture using a rectangular, 1-cm-wide tool to make a series of 0.005-cm-deep cuts at the same location in a 10-cm-long sandstone block. Ignition with a steel tool typically required about 75 cuts with a tool velocity of 450 cm/s and 175 cuts with a tool velocity of 150 cm/s. A steel smear was left on the sandstone. A temperature of about  $1,400^\circ\text{C}$  was measured directly behind the tool for about 2 ms after passage of the tool, which then decreased to  $1,200^\circ\text{C}$  in an additional 2 ms. The steel smear was about 20  $\mu\text{m}$  thick, and the top 0.5- $\mu\text{m}$  layer of the smear was oxidized.

Blickensderfer (35) developed a theoretical model of frictional ignition with a steel tool cutting into sandstone. He assumed that (1) abrasion between the wear flat on the tool and the sandstone rapidly heated the surface of the wear flat on the steel tool to its melting point of  $1,450^\circ\text{C}$ , (2) a smear of molten steel was deposited on the sandstone and was maintained at its

melting point until the tool passed on and exposed the molten smear, and (3) the exposed molten steel smear then cooled by heat conduction into the sandstone substrate. The steel smear theoretically was at  $1,450^\circ\text{C}$  for 1.7 ms after exposure because of the heat released during solidification of the molten steel smear and 2.7 ms if the heat of oxidation of the 0.5- $\mu\text{m}$  oxide layer on the steel smear was included. With a tool velocity of 450 cm/s, the length of the molten smear was 12 mm and the area thus was  $120\text{ mm}^2$ . Blickensderfer concluded that such a hot surface ( $1,450^\circ\text{C}$  for 2.7 ms with a  $120\text{-mm}^2$  area) reasonably agreed with the requirements noted earlier for ignition of a methane-air mixture with electrically heated surfaces.

Blickensderfer considered that the likelihood of frictional ignition decreased as the area of the molten smear decreased. When the tool velocity decreased to 150 cm/s, the theoretical area of the exposed molten smear decreased to  $40\text{ mm}^2$ . He concluded that this decrease in molten area explained the increase in the number of cuts experimentally required to get ignition with the lower tool velocity.

Cutler (31) similarly measured a streak temperature of about  $1,400^\circ\text{C}$  behind a tungsten-carbide-tipped mining bit cutting into sandstone.

In the present study, the nature of the hot streak formed by a mining bit appears to be complex. Figure 4 shows that the streak directly behind the bit initially is very hot: i.e., the film was overexposed for about 20 ms (5 cm) after passage of the bit because of the high local temperature.<sup>7</sup> The streak then cooled to show a series of discrete luminous hot spots about 1 cm or so apart on the surface of the sandstone, although luminous strips about 5 cm long occasionally formed. The hot spots usually were about  $100\text{ mm}^2$  in area. Figure 32 gives another example of the series of hot spots formed by the bit, which in this case had passed downward out of the field of view. The hot spots at the bottom and top of figure 32 were about 20 and 100 ms old, respectively, and were still hot enough to be luminous but did not give ignitions.

The BCRNL study (18) indicated that water that impacted the sandstone surface further than 5 cm (20 ms) behind the bit was ineffective in preventing frictional ignition. Ignition therefore presumably involves the very hot spots in the hot streak within about 5 cm behind the bit, because the spots further than 5 cm behind the bit seemingly had cooled to a safe temperature.

The hot spots formed here during an early nonigniting dry cut visually were similar to the hot spots formed during the next cut that gave ignition. Also, ignition always occurred during the bottom part of the igniting cut. Thus, a worn bit readily generates a nonigniting hot spot but then undergoes a small change and generates an igniting hot spot.

<sup>7</sup>Photometric measurement here of streak temperature was unsuccessful in that a streak temperature of about  $1,100^\circ \pm 300^\circ\text{C}$  was measured behind the bit with both steel and tungsten-carbide tips.



Figure 32.—Spotty hot streak formed on surface of sandstone.

The heat-generation process (or processes) taking place when a metal bit cuts into sandstone therefore must (1) be intermittent (to generate hot spots) and (2) be sensitive to small changes in the bit (to generate the igniting hot spot). A spotty type of hot streak and the qualitative similarity between nonigniting and igniting hot spots do not appear to have been reported by other investigators.

Intermittent metal smears were left on the sandstone surface. X-ray analysis of the smears indicated that a tip made of Type 4140 steel left a steel smear while a cobalt-bonded tungsten-carbide tip left a cobalt smear. The metal smear was intermittent and did not appear to match the more regular sequence of luminous hot spots such as shown in figure 32. The formation of a metal smear implies melting of the metal tip.

The luminous spotty hot streak formed on sandstone by a steel or carbide tip in a nitrogen environment visually was similar to the luminous streak formed in an air environment, and any exothermic oxidation of the molten metal smear appears to be of secondary importance.<sup>8</sup>

<sup>8</sup>Frictional ignition due to sandstone-sandstone abrasion (35-38) is not addressed here.

Heat generation during the cutting of sandstone with a metal bit presumably involves mechanical friction and depends upon the normal (perpendicular) force exerted by the wear flat of the bit on the sandstone substrate during the cutting process. With the present cutting technique, a tangential force is being applied to the bit by the rotating cutter drum in order to cut the sandstone, but no external normal force is being applied to push the bit against the sandstone target, as in rubbing-friction or drill-bit tests. A local normal force during the cutting operation does occur if a wear angle forms on the tip of the bit as shown in figure 31.

An intermittent heat-generation process might be the formation of chips, where the partly formed chip (fig. 31) presses the wear flat against the sandstone substrate and thereby momentarily generates a high local normal force on the bit. Screen analysis of the particles formed during a 1-cm-deep cut indicated that 30 pct of the mass of the particles were large flakes with a nominal flake diameter greater than about 0.1 cm, indicating that chipping does occur. The normal force exerted by the bit during the present cutting operation has not yet been measured.

While melting of the steel tip implies that the temperature of the wear flat on the bit during cutting is about 1,450° C, the temperature of the surface of the wear flat does not appear to have been directly measured. A temperature of about 400° C was measured with a thermocouple 0.5 mm below the surface of the wear flat on a rectangular bit continuously cutting into sandstone (39). A similar low temperature of about 300° C was measured here with a thermocouple 1.2 mm below the wear flat on a conical bit intermittently cutting sandstone and also was measured with a thermocouple inside a drill bit (40). However, extrapolation of single values to the surface of the wear flat is of course impossible.

A theoretical model of the temperature-time history of a conical steel bit having a wear flat and intermittently cutting into a sandstone block was developed by Edwards at the Bureau's Pittsburgh Research Center. The model involved (1) a constant rate of heating of the interface between the wear flat on the bit and the sandstone surface during the cutting part of the drum rotation due to frictional abrasion combined with cooling by heat conduction into the bit and the sandstone and (2) heat conduction into the bit and convective cooling of the bit during the remainder of the rotation cycle. A sawtoothed temperature-time curve resulted. The model used the bit geometry and drum rotation speed corresponding to the temperature-measurement test noted above and a constant-area wear flat of 0.7 cm<sup>2</sup> obtained in a separate ignition test that gave ignition in the seventh cut with this wear-flat area. The theoretical temperatures 1.2 mm inside the bit and at the surface of the wear flat on the bit depended linearly upon the heating rate. The heating rate at the surface of the wear flat was varied until the theoretical temperature 1.2 mm inside the bit matched the experimental temperature. When a heating rate of 90 cal/cm<sup>2</sup>·s was used, the theoretical internal

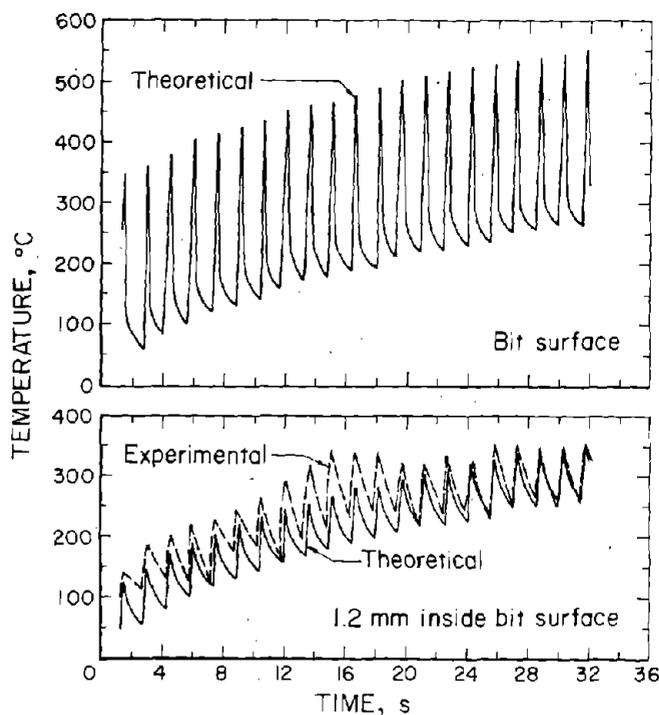


Figure 33.—Theoretical temperatures inside conical bit and on wear-flat surface on conical bit.

temperature matched the experimental temperatures of 200° C at the end of the 7th cut and 300° C after the 20th cut (fig. 33).

The corresponding theoretical temperatures of the surface of the wear flat were only 400° and 500° C after the 7th and 20th cuts, while the observed melting of the steel wear flat implies that the temperature of the surface of the wear flat was about 1,450° C. However, Ueda (41) recently reported that the temperature inside a grinding wheel abrading a steel target measured with a thermocouple was considerably lower than the temperature measured with a pyrometric technique, and the validity of thermocouple measurements thus is uncertain.

The formation of the wear flat would seem to be a critical feature of the ignition process. With a conical bit, when the bit attack angle decreased, ignition required fewer cuts with a new bit (fig. 8) and involved a larger area wear flat on the used bit.

The wear rate of a steel-tipped conical bit was investigated by measuring the area of the wear flat formed on a new bit in an air environment versus the number of cuts in the sandstone block. The area of the wear flat formed after a few cuts was measured by inking the wear flat, pressing the inked flat against graph paper, and counting the number of inked squares. A few additional cuts were then made, and the area of the wear flat was

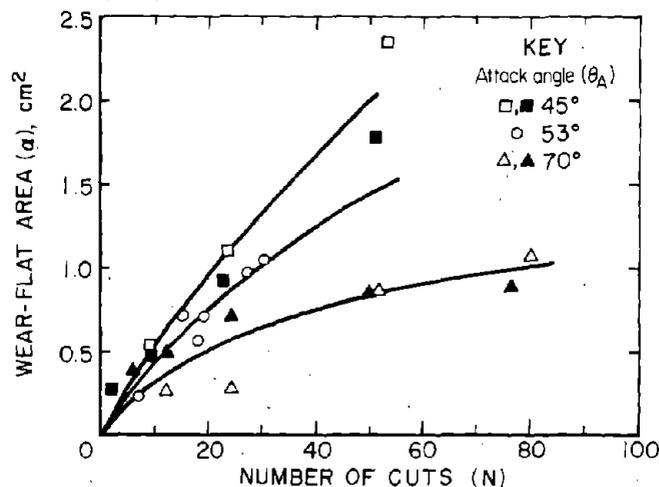


Figure 34.—Area of wear flat formed on steel-tipped conical bit versus number of cuts. (Solid and hollow symbols for the same  $\theta_A$  indicate repeat tests.)

remeasured, and so forth. The effect of bit attack angle  $\theta_A$  was investigated. A constant internal bit tip angle  $\theta_T$  of 80° was used.

Figure 34 plots the area of the wear flat  $\alpha$  versus the number of cuts  $N$  for three attack angles ( $\theta_A = 45^\circ$ ,  $53^\circ$ , and  $70^\circ$ ). The area increased approximately parabolically with  $N$ . The area also increased as  $\theta_A$  decreased; e.g., after 20 cuts, the area was 0.5 cm<sup>2</sup> if  $\theta_A = 70^\circ$  and 1 cm<sup>2</sup> if  $\theta_A = 45^\circ$ . Similar results were observed with brass and tungsten-carbide tips.

The linear wear length  $\ell$ , perpendicular to the sandstone surface, is related to the wear flat and the bit geometry  $\theta_A$  and  $\theta_T$  for a conical bit as shown in figure 35. The wear flat is oval in shape because of the slanted wear of the conical tip. Approximating the oval wear flat with a circle and assuming the wear flat is parallel to the sandstone surface,  $\ell$  is related to the wear-flat area  $\alpha$  by simple geometry, with  $\ell = \sqrt{\alpha} \cdot \{\sin(\theta_A) / [\tan(\theta_T/2) \cdot \sqrt{\pi}]\}$ . The parabolic  $\alpha - N$  relations for various  $\theta_A$ 's in figure 34 convert to a single parabolic-type  $\ell - N$  relation for the tip material, which is independent of  $\theta_A$ . The large wear flat obtained with a small  $\theta_A$  compared with the small wear flat obtained with a large  $\theta_A$  thus appears to be a simple geometric effect and does not involve a variation of  $\ell$  with  $\theta_A$ . The value of  $\ell$  does depend upon the nature of the tip material and the total length of cut  $L$ . Since the 109-cm-diam drum is cutting into a 51-cm-high sandstone block, each cut is 54 cm long and  $L = 54 \cdot N$  (in centimeters). Figure 36 plots  $\ell$  versus  $L$  for brass, steel, and carbide tips. The wear rate of a tip is the tangent of an  $\ell - L$  curve. Initial wear rates were high and depended upon the bit material. The wear rates then slowed and were similar for these various materials.

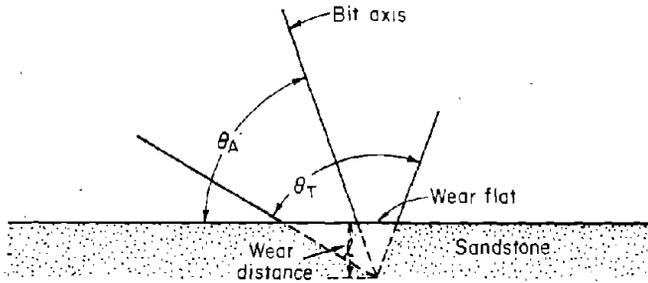


Figure 35.—Geometry of linear wear distance with conical bit. ( $\theta_A$  = attack angle;  $\theta_T$  = Initial tip angle.)

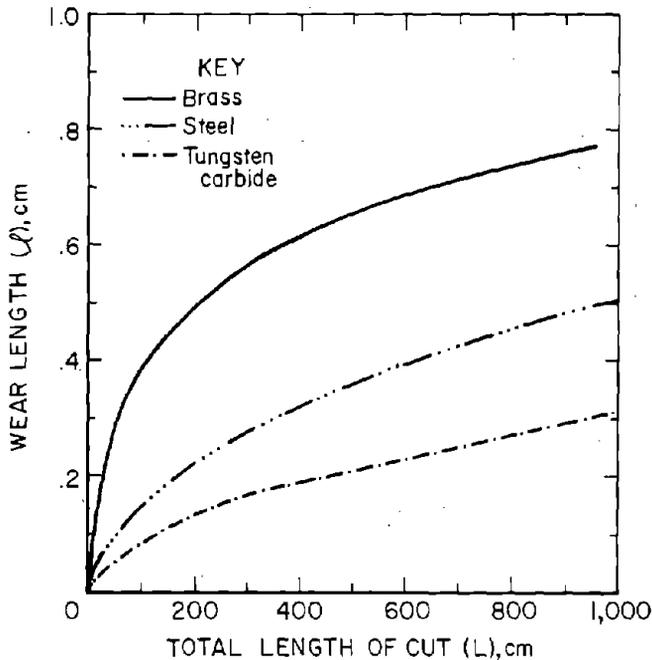


Figure 36.—Linear wear distance versus cutting distance with conical bits.

The rapid early wear of a drag-type drill bit was previously reported (42-43). Neville and Crone (43) similarly observed that the area of the wear flat formed on a drill bit increased if the bit attack angle  $\theta_A$  decreased and that the linear wear rate of the bit tip was independent of  $\theta_A$ . They concluded that (1) wear was independent of the external normal force (thrust) exerted on the drill bit because the bit is mainly crushing and not rubbing the rock and (2) any temperature effect due to heating of the drill bit was minor.

The variation in the early wear rates of the present three materials and the similarity of the later wear rates suggest that different aspects of the wear process are important in the early and the later stages of bit wear, which remain to be explained.

However, the area of a wear flat formed in a methane-air environment during an ignition test was about three times larger than the wear-flat area formed in an air environment with the same number of cuts; i.e., the wear length  $\ell$  in a combustible methane-air environment was about two times the wear length in an air environment (fig. 36). The simplest explanation for this increase in wear rate in a methane-air environment perhaps is that a hot spot ignites the methane-air mixture to form a micro flame kernel that heats the surface of the bit (and also the sandstone) but is quenched by the bit and sandstone surfaces and does not ignite the bulk methane-air environment. The hot surface of the wear flat then wears faster than the warm surface of the wear flat because of heat generated only by friction; this process forms a large-area wear flat, which then forms a macro flame kernel that ignites the bulk environment.

A working hypothesis for the mechanism of frictional ignition with a new frozen conical bit cutting sandstone thus might be as follows:

1. The bit tip initially abrades very rapidly to form a small wear flat. The initial linear wear rate of the tip is slower with a harder (more durable) tip material.
2. The tip of the wear flat forms chips of the sandstone target, and the wear flat abrades the remaining layer of the sandstone and the resulting sandstone particles. During chip formation, the normal force exerted by the bit on the sandstone target is momentarily very high, leading to the intermittent formation of a small hot spot on the surface of the sandstone.
3. The small hot spot on the sandstone is about  $1,450^\circ\text{C}$  and ignites a small flame kernel. The small flame kernel heats the wear flat and increases its wear rate but is quenched by the bit and the sandstone and does not propagate into and ignite the bulk combustible environment.
4. The area of the wear flat on the bit tip increases because of frictional abrasion. The rate of increase of the wear-flat area depends upon the linear wear rate of the bit tip and the tip geometry. The linear wear rate is increased in a combustible environment because of heating of the tip by the flame kernel. Eventually, a large flame kernel ignited by a large hot spot formed by a large-area wear flat propagates into and ignites the bulk combustible environment.

A similar mechanism should apply to frictional ignition with a rectangular-shaped bit except that the geometrical relation between the area of the wear flat and the linear

wear of the tip of the rectangular bit will be different from that shown in figure 35.

Major features requiring clarification include hot-spot formation by chipping, quenching of the flame kernel, and cooling of the hot spots by the back spray. E.g., the bit geometry presumably should have a significant effect on kernel quenching and in "protecting" the hot spot from being cooled by the spray water drops. Detailed investigation of these features is planned.

It should also be noted that an anti-ignition back spray may also achieve an antidust benefit. The dust cloud formed when a conical bit cuts into sandstone is shown in figure 37. With an antidust wet-head cutter drum such as discussed in reference 22, the drum-mounted water spray nozzles usually were located in the general vicinity of the bits and the water drops merely filled the cavity between the surface of the drum and the face. With an anti-ignition wet-head drum, the spray nozzles must be located behind the bit and must be carefully aimed to impact the mineral surface immediately behind the bit. The anti-ignition sprays thus are pointed directly into the dust cloud and should be more likely to capture the dust particles.



Figure 37.—Dust cloud formed by bit cutting sandstone.

## CONCLUSIONS

1. In the United States, frictional ignition usually involves a metal bit cutting into sandstone to form a hot streak on the surface of the sandstone.

2. Frictional ignition always involves a worn bit having a wear flat on the tip of the bit; it seemingly can be obtained with almost any bit material but is much more likely to occur with a steel tip than with a tungsten-carbide tip.

3. The likelihood of frictional ignition decreases with (1) a mushroom-shaped tungsten-carbide bit tip and (2) an increased bit clearance angle. A field test with conical-shaped bits in a coal mine supports these laboratory conclusions. Commercial versions of mushroom-shaped tungsten-carbide-tipped conical bits are available.

4. The likelihood of ignition is not significantly decreased with a lower bit velocity in the range considered to be of practical interest.

5. The likelihood of ignition with very worn bits significantly decreases if water spray nozzles are located in back of each bit and are carefully oriented so that the water spray impacts and cools the hot streak on the sandstone surface immediately behind the bit. A minimum water density at the impaction plane of about 0.007 gpm/cm<sup>2</sup> is apparently required and can readily be achieved with commercial spray nozzles operated at

moderate conditions (0.5 gpm, 50 to 100 psig). The likelihood of ignition with all bits tested here was reduced by using a carefully designed back spray. Commercial versions of back spray and bit systems that use a high waterflow rate (1 gpm) are available.

6. Replacement of worn bits must be scheduled. The frequency of bit replacement will depend upon the remedial technique but may range from every shuttle car load (if a mushroom bit and increased bit clearance angle are used) to every week (if a back spray is used).

7. Formation of the hot streak appears to involve complex cutting-abrasion phenomena. Formation of local hot spots may be due to a momentary high normal force on the bit because of chip formation during the cutting process. The hot spot perhaps forms a micro flame kernel at the wear flat and sandstone interface, which heats the bit but does not propagate into the bulk environment. The heated bit would then wear more rapidly to form a large wear flat, which forms a macro flame kernel that ignites the bulk environment.

8. An anti-ignition back spray may also achieve an antidust benefit because the back spray is aimed directly into the dust cloud formed by the cutter bit.

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