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Reduction in Frictional Ignition Due to Conical Coal-Cutting Bits

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	in	inch
ft	foot	pct	percent
ft/min	foot per minute	rpm	revolution per minute

REDUCTION IN FRICTIONAL IGNITION DUE TO CONICAL COAL-CUTTING BITS

By Lung Cheng,[1] Aldo L. Furno,[2] and Welby G. Courtney[3]

ABSTRACT

The Bureau of Mines conducted laboratory tests to investigate the ease of frictional ingition with frozen (nonrotating) conical bits cutting into sandstone. The number of strikes with a new bit to obtain ignition of a combustible methane-air environment was measured. Tests were made with bits tipped with both tungsten carbide and steel at several bit attack angles (angle between bit axis and sandstone surface) and initial tip angles (included angle at the tip of the new bit). Carbide-tipped bits required more strikes for ingition than steel-tipped bits, by a factor of 7 to 10. With a carbide-tipped bit, the number of strikes for ingition increased by a factor of about 3 if the bit attack angle increased by 10° or if the initial tip angle decreased by 10°. During use, abrasive wear of the frozen bit caused a flat surface to form at the tip of the bit, thereby decreasing the tip angle. As the attack angle increased, however, the new bit involved a smaller wear-flat area whereby, abrasive wear was decreased.

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INTRODUCTION

The occurrence of frictional ignitions continues to be a severe problem in U.S. coal mining operations. The Mine Safety and Health Administration has reported about 60 ignitions incidents per year for the past several years. Although the resulting methane-air fireball often is only a few feet in size, the possibility of a frictional ignition leading to a full-scale mine explosion is disturbing.

Frictional ignition usually is caused by a hot streak being formed on the surface of a sandstone inclusion due to frictional abrasion and heating when a bit cuts into the sandstone (1).[4] This hot streak can ignite a nearby combustible methane-air mixutre and thereby lead to the fireball.

The frictional ignition tendency of coal-cutting bits invloves the physical-chemical properties of the bit material, including its wear characteristics. In the 1970's, Bureau laboratory work investigating the relative incendivity of metal chips indicated that steel was about 50 times more hazardous than tungsten carbide in causing frictional ignition (2). However, based on the number of strikes for ignition with metal chips impacting on sandstone, tungsten-carbide required more strikes than steel by a factor of 1.5 to 4.0 (3).

Almost all mining machines presently use tungsten-carbide-tipped bits in order to reduce bit wear. However, examination of used field bits indicates that the incendive steel shank often becomes abraded during the cutting process. In 1979, the Bureau designed mushroom-shaped tungsten-carbide tips for conical bits and dovetail-shaped tungsten-carbide tips for rectangular bits to better protect the steel shank and thereby reduce the ignition hazard (4). Laboratory wear tests with conical bits comparing Bureau-designed mushroom tips to conventional-shaped tips indicated significantly less total bit wear with the mushroom tip because of its protective geometry (5). A field test of mushroom-tipped bits substantiated the laboratory results for total bit wear, but the mushroom tip experienced a relatively high fracture rate (5). To increase the fracture resistance, the Bureau modified the tungsten-carbide insert by increasing the fillet radius at the junction of the cap and stem of the mushroom. A subsequent field test comparing the modified mushroom bit to the conventional bit laced side by side on a continuous miner indicated that the mushroom bit was superior to the conventional bit in terms of reduced bit fracture. The mushroom bit reportedly also gave less face sparking than the conventional bit.

Numerous workers have investigated the effects of the geometry of new, unworn conical bits on dust generation, target fracture, cutting force, incendivity, etc. (6-7). Figure 1 shows the cutting geometry of a new conical bit. This geometry involves the bit attack angle and also the initial tip angle, where the attack angle, θ_A, is the angle between the bit axis and the sandstone surface, and the initial tip angle, θ_T, is the included angle of the tip. The initial clearance angle, θ_C, is the initial angle between the clearance face of the tip and

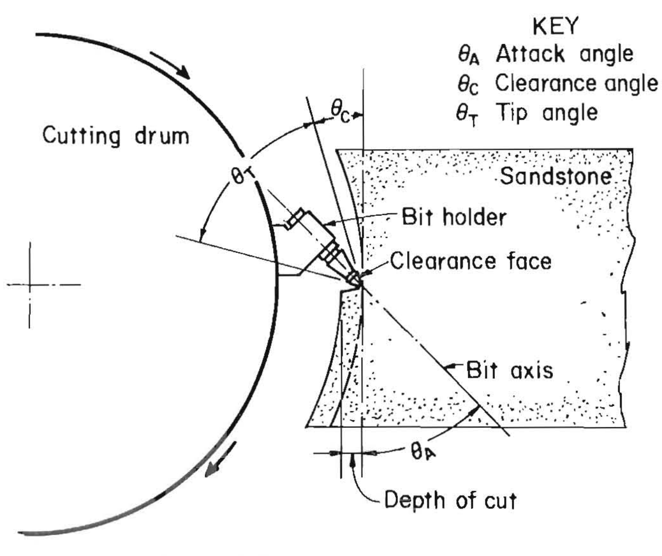

FIGURE 1.—Cutting geometry of conical bit.

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

the sandstone surface and depends upon the attack and initial tip angles ($\theta_C = \theta_A - \theta_T/2$). For example, if the bit attack angle is 57° and the intial tip angle is 80° the intitial clearance angle is 17°.

Bureau laboratory tests have indicated that frictional ignition is only observed with a worn bit, and the wear behavior during use of a conical bit appears to have been largely neglected. A field study indicated that the wear of the shank was appreciable, and a model of the weight loss due to bit wear was developed (8). The bit attack angle is fixed by the bit holder and is constant. The actual tip angle should, however, increase during use because of wear of the tip of the bit, and the actual clearance angle therefore should decrease during use. The cutting geometry shown in figure 1 thus is only a first approximation to the actual cutting geometry of a worn bit. For example, a wear flat should form at the tip of a frozen conical bit, but tip wear of a freely rotating bit will be evenly distributed around the tip. The ignition hazards associated with frozen and rotating bits should be quite different, with the hazard associated with a frozen conical bit probably serving as a worst case.

This report presents the results of an exploratory laboratory study of the importance of cutting geometry (i.e., bit attack angle and initial tip angle), tip material (i.e., tungsten carbide and steel), and bit wear on the frictional ingition hazard of *frozen* conical bits. The present study is part of a large Bureau program investigating the frictional ignition problem.

EXPERIMENTAL METHOD[5]

A single conical bit was mounted on a 3-ft diam segment of a cutter drum from a commercial ripper-type continuous mining machine. A 22- by 20- by 22-in block of Berea sandstone was positioned on a carriage so that a series of slanted downward cuts was made across the horizontal bedding plane of the 22-in-high sandstone block as the carriage was moved horizontally across the rotating drum. The sandstone contained 98 pct silica and had a Shore scale hardness of 25. The drum and carriage were enclosed in a chamber that contained a 7 pct methane-air mixture (fig. 2).

In an ignition test, the block was first dressed with a dressing bit to provide a smooth concave surface. A new bit was then fixed into the bit holder with a setscrew to prevent bit rotation during the test. A 3/8-in depth of cut was used. The drum was operated at 40 rpm and the carriage traversed at 1.5 ft/min, giving a series of about 25 strikes into fresh material for each carriage trip.

[5]Assistance in conduct of the experimental tests was provided by Kenneth E. Mura, C. Kevin Luster, and Thomas Schellinger, physical science technicians, Pittsburgh Research Center.

If ignition did not occur during the first carriage trip, the block was redressed with the dressing bit and ignition during the second carriage trip was attempted with the bit used in the first carriage trip. The total number of strikes required to ignite the combustible methane-air mixture with the new bit was used as a measure of the ease of ignition. The parameters that were varied were the material used in the tip of the bit, the bit attack angle, and the initial tip angle (i.e., initial clearance angle).

Tungsten-carbide-tipped commercial bits used in these tests are listed in table 1. Except for bit E, the tips were all double angle, with θ_{T1} being the inclusion angle of the carbide insert directly at the tip (primary tip angle) and θ_{T2} being the inclusion angle of the carbide insert away from the tip (secondary tip angle). Frictional ignition was usually obtained with a bit worn only in the vicinity of the tip and the initial tip angles were 75°, 80°, and 90°, with the secondary tip angle ignored. The initial tip angle varied by ±1°. The tip type was categorized as *conventional* when the small commercial tip insert covered only part of the top of the shank, *capped* when

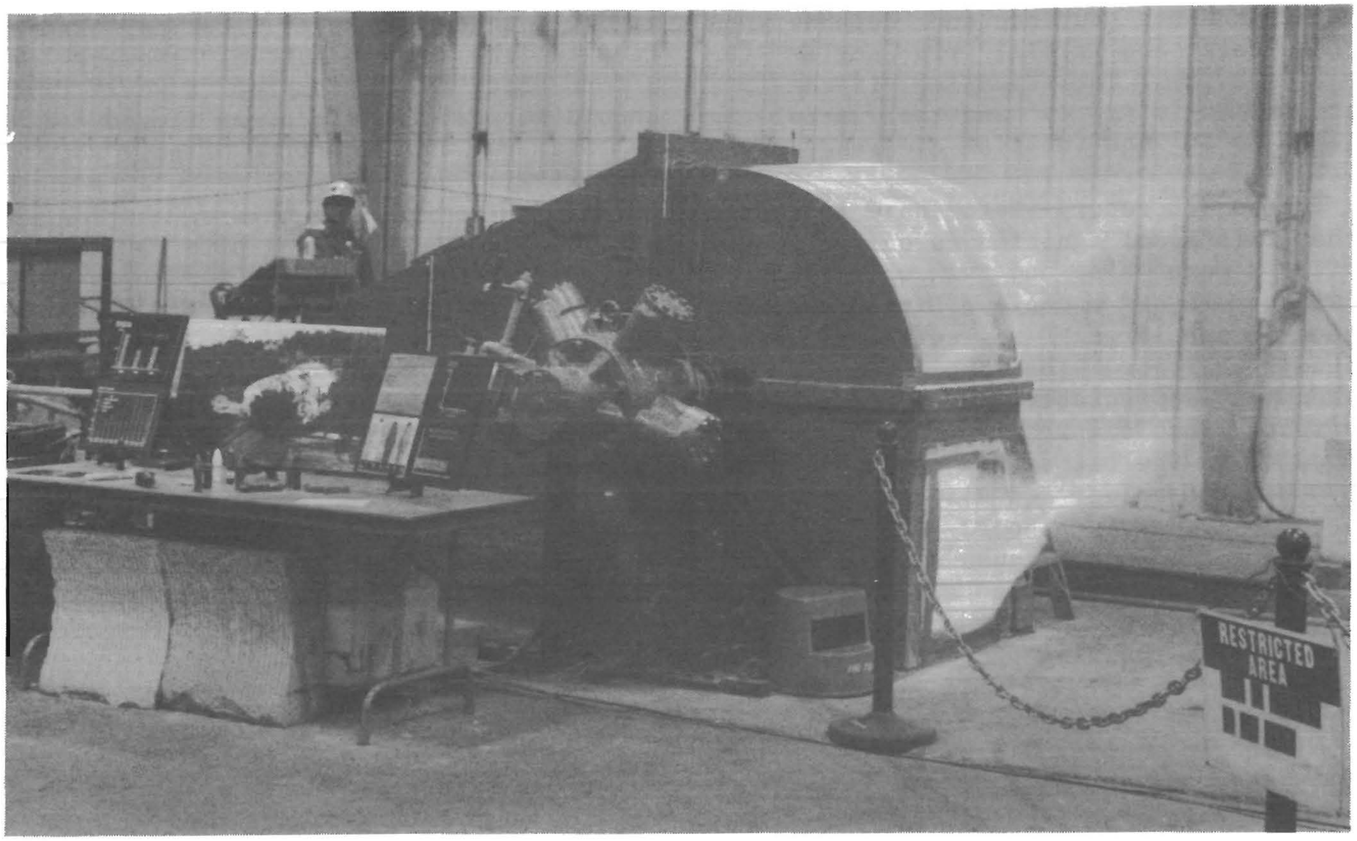

FIGURE 2.—Frictional ignition chamber.

TABLE 1. - Tungsten-carbide-tipped bits used in testing

Bit identification	Primary tip angle[1] (θ_{T1}), deg	Secondary tip angle[1] (θ_{T2}), deg	Tungsten carbide tip, pct Co[2]	Shank steel[3]	Remarks
A..........	75	40	10	4140	Capped.
B..........	75	40	10	8630	Conventional.
C..........	80	45	10	8630	Capped.
D..........	80	50	11	4140	Conventional.
E..........	80	80	9-10	4140	Mushroom.
F..........	90	50	11	4140	Conventional.

[1]Inclusion angle. [2]Nominal value. [3]SAE standard number.

the small commercial carbide tip was used but the shank shoulder was trimmed in order to avoid abrasion of the steel shank, and *mushroom* when a large carbide tip completely covered the untrimmed steel shank to physically protect the entire shank. Drawings of the tip geometries are given in references 4 and 5. Visual examination of the bits after ignition indicated that ignition was always obtained in the laboratory study with only the tip insert being contacted, i.e., the shank portion of the bit was never abraded and never participated in an ignition, even with the less protected conventional tip. A frictional ignition occasionally occurred when the bit was making its first or last strike during a pass. Such an ignition was attributed to the steel shank abrading the *side* of the sandstone block and was not included as a decent strike for the purpose of these tests.

Bits A_1, C_1, D_1, and E_1, were made with their shank steels replacing the carbide tip but with the steel tip having the same geometry as the carbide tip noted in table 2. Tip materials used in this study thus were tungsten carbide (9 to 11 pct Co), SAE 4140 steel, and SAE 8630 steel.

TABLE 2. - Average number of strikes to obtain ignition with tungsten-carbide-tipped bits

Bit identification	Attack angle (θ_A), deg	Initial clearance angle (θ_C), deg	Av number of strikes[1]	Remarks[2]
		75° TIP ANGLE		
A..............	42	4.5	(41)	1 test.
	53	15.0	37	5 tests: 17, 45, 49, [253] [no ignition with 262].
	57	19.5	86	2 tests: 47, 126.
	63	25.5	(21)	1 test.
B..............	42	4.5	(20)	Do.
	53	15.0	(53)	Do.
	57	19.5	33	Do.
	63	25.5	60	2 tests: 11, 108.
Total av.....	42	4.5	(30)	Based on 1 test each.
	53	15.0	45	
	57	19.5	60	
	63	25.5	40	Omitted.
		80° TIP ANGLE		
C..............	50	10.0	21	3 tests: 13, 21, 28.
	57	17.0	45	4 tests: 32, 59, [125] [no ignition with 183].
	62	22.0	80	1 test.
	67	27.0	90	Do.
D..............	50	10.0	13	3 tests: 7, 15, 16.
	62	22.0	18	2 tests: 17, 20.
	67	27.0	65	2 tests: 65. [no ignition with 197].
E..............	50	10.0	10	7 tests: 4, 4, 7, 9, 11, 11, 27.
	62	22.0	42	8 tests: 14, 17, 20, 32, 46, 50, 76, 84.
	67	27.0	63	2 tests: 52, 75.
Total av.....	50	10.0	14	
	57	17.0	45	
	62	22.0	47	
	67	27.0	73	
		90° TIP ANGLE		
F..............	50	5.0	7	4 tests: 4, 6, 8, 10.
	54.5	9.0	10	2 tests: 5, 16.
	62	17.0	21	3 tests: 2, 12, 48.
	70	25.0	42	5 tests: 11, 43, 53, 61, [109].

[1]Numbers in parentheses were a single test.

[2]Numbers in brackets were considered to be outliers for individual sets of data and were ignored in calculating the average number of strikes for ignition.

RESULTS

Table 2 summarizes the average number of strikes to obtain ignition with carbide-tipped bits. Raw data are given in the remarks column. Single tests are identified with parentheses to emphasize that they should be viewed with caution. Reproducibility was marginal: e.g., with bit C and 57° attack angle, ignition was obtained with 32, 59, and 125 strikes in three tests and was not obtained with 183 strikes in a fourth test. Tests that did not give ignition or were considered to be outliers are bracketed and were ignored in calculating the average number of strikes for ignition. Data from bits with the same tip angle were combined since only the tip was involved in the ignition. Hence, the total average is the average values obtained with different bits having the same attack angle, clearance angle, and tip angle: e.g., for a 50° attack angle, 10° clearance angle, and 80° tip angle, the average values of 21, 13, and 10 strikes for ignition with bits C, D, and E were combined to give a total average value of 14 strikes for ignition with these bit geometrics.

The total average number of strikes for ignition with a new bit increased with increasing attack angle and decreasing initial tip angle. Because the attack angle is familiar to, and directly measurable by coal mine workers, attack angles were chosen to be plotted in figure 3 against total average values of the strikes for ignition given in table 2. The physical importance of the initial clearance angle on the ignition problem is realized and, therefore, this information is included in tables 2 and 3. For example, with an initial tip angle of 80°, as the attack angle increased from 50° to 62°, the number of strikes for ignition increased from 14 to 47. With an initial tip angle of 90°, the number of strikes increased from 7 to 21 as the attack angle increased from 50° to 62°. Thus, the number of strikes for ignition increased by a factor of 3 if the bit attack angle was increased by 10° or if the initital tip angle was decreased by 10°.

Table 3 gives similar results observed with steel-tipped bits. Three single tests again are identified with parentheses. Reproducibility was good, e.g., with bit E_1 and 62° attack angle, ignition required three and four strikes in repeat tests. Results are included in figure 3. The ignition hazard was less with SAE 8630 steel than with SAE 4140 steel, i.e., ignition with bit C_1 required about three times more strikes than ignition with bit E_1. The effects of attack and initial tip angles with steel tips were similar to those observed with carbide tips within the scatter of the data.

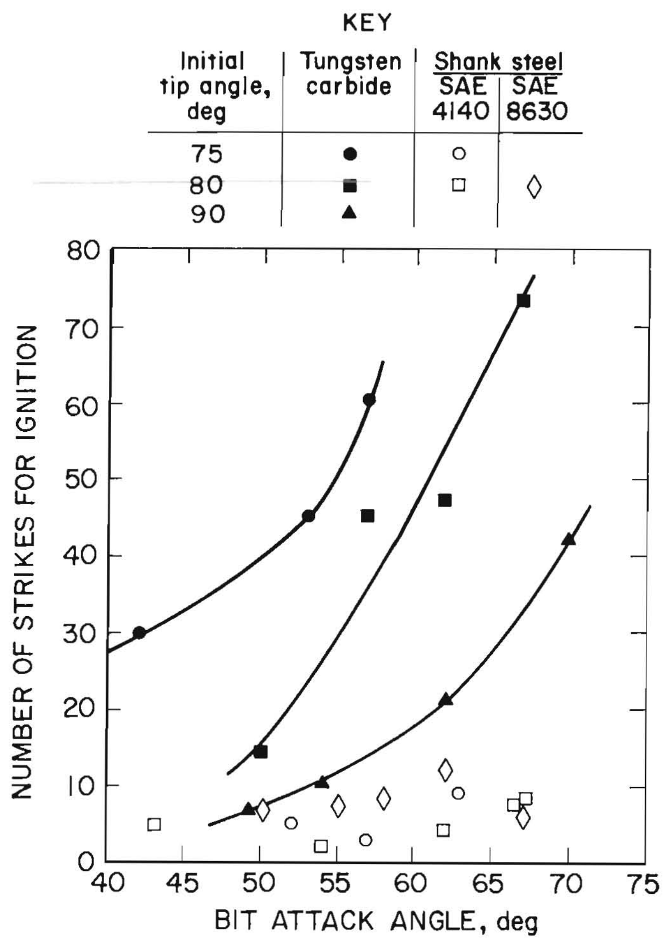

FIGURE 3.—Number of strikes for ignition versus bit attack angle.

TABLE 3. - Average number of strikes for ignition with steel-tipped bits

Bit identification	SAE material	Attack angle (θ_A), deg	Initial clearance angle (θ_C), deg	Av number of strikes[1]	Remarks[2]
			75° TIP ANGLE		
A_1.......	4140	52	14.5	(5)	1 test.
		57	19.5	3	2 tests: 1, 4.
		63	25.5	9	2 tests: 7, 10.
			80° TIP ANGLE		
C_1.......	8630	50	10.0	(7)	1 test.
		55	15.0	(7)	Do.
		58	18.0	8	2 tests: 7, 8.
		62	22.0	(12)	1 test.
		67	27.0	(6)	Do.
D_1.......	4140	43	3.0	5	2 tests: 5, [31].
		67	27.0	(7)	1 test.
E_1.......	4140	54	14.0	2	2 tests: 1, 3.
		62	22.0	4	2 tests: 3, 4.
		67	27.0	(8)	1 test.

[1]Numbers in parentheses were a single test.
[2]Number in brackets was considered to be an outlier and was ignored in calculating the average number of strikes for ignition.

Comparison of table 2 and table 3 indicates that the ignition hazard was reduced by a factor of 7 to 10 with carbide-tipped bits compared to steel-tipped bits having identical geometries. For example, with a 62° attack angle and an 80° initial tip angle, ignition with a carbide tip (bit C) required about 80 strikes and ignition with a steel tip (bit C_1) required only 12 strikes, while bit E with a carbide tip required 42 strikes for ignition and bit E_1 with a steel tip would have required only about 4 strikes for ignition.

During bit use, abrasive wear of its tip caused a flat surface to form at the tip of the frozen bit. The area of this wear flat increased with additional strikes. The area at ignition decreased as the bit attack angle increased.

Figure 4 shows the wear flats obtained with mushroom-tipped bits having an 80° initial tip angle. A new carbide-tipped bit is shown on the left. Two used carbide-tipped bits are shown in the middle, a bit that gave ignition with 11 strikes with an attack angle of 50° is on the middle left and a bit that gave ignition with 52 strikes with an attack angle of 67° is on the middle right. A steel-tipped bit that gave ignition with one strike with an attack angle of 54° is shown on the far right. The decrease in the area of the wear flat at ignition as the attack angle increased is evident by comparing the middle two bits. The similar area of the wear flat with steel is apparent by comparing the middle left and the far right bits.

DISCUSSION

The results of this testing indicate the relative ignition hazard of new conical bits and the reduction in this relative ignition hazard by using tungsten-carbide-tipped bits instead of steel-tipped bits, by using mushroom-shaped bits, and by increasing the bit attack angle or by decreasing the initial tip angle. A coal company was using conical bits with a conventional carbide tip having an initial tip angle of 80° and a bit attack angle of 54°. The company wished to continue using a bit having an 80° tip. The Bureau recommended using a

FIGURE 4.—New (left) and used tungsten-carbide-tipped (middle left and right) and steel-tipped (right) bits after ignition. (Bit tip angle, 80°; bit attack angle, middle left, 50°; middle right, 67°; right, 54°.)

mushroom-tipped bit (bit E) and increasing the attack angle to 67°. The relative ignition hazard then would be reduced by a factor of 6 (63 strikes versus 10 strikes, shown in table 2). The company accepted bit E but preferred only a 57° attack angle to avoid overloading the cutterhead drive system. The relative ignition hazard then should be reduced by a factor of 2 (45 strikes versus 24 strikes, shown in figure 3). Field tests of bit durability are currently being conducted (1985 to date) in an operating coal mine. These tests are an extension of the field tests conducted by the Bureau in 1983. The company has reported a dramatic improvement in bit life with the mushroom-tipped bit and larger bit attack angle compared to the conventional-tipped bit and smaller attack angle.

From a more fundamental viewpoint, as the bit attack angle increased, the occurrence of ignition required more strikes with a new bit (fig. 3) but involved a smaller area wear flat when it did occur (fig. 4). The rate of increase of the area of the wear flat and also the temperature of the hot streak presumably depend upon the nature of the sandstone and bit surfaces, the normal force exerted on the sandstone surface by the wear flat, and the coefficient of friction between the wear flat and the sandstone surface. With a given bit and constant coefficient of friction, increasing the bit attack angle which in turn increases the clearance angle ($\theta_C = \theta_A - \theta_T/2$) decreases the normal force, which in turn decreases the frictional force[6] on the sandstone surface and requires more strikes for ignition. However, the normal force during cutting was not investigated in this project.

The clearance angle appears to play an important role in the ignition hazard associated with a conical bit in that increasing the initial clearance angle

[6] Let F be the cutting force exerted on the sandstone by the wear flat and μ be the frictional coefficient. A force analysis gives the differential of the frictional force, f, that causes ignition as

$$df = -\mu F \, d\,(\theta_C^2/2).$$

increased the number of strikes for ignition with a given bit (tables 2 and 3). It should be noted that even though a rectangular-shank bit does not have an attack angle, experimental tests by the Bureau have shown that increasing the initial clearance angle from 9° to 14° and keeping the tip angle constant increased the number of strikes for ignition from 8 to 26.

At ignition, the wear flat at the tip of a frozen bit probably has a zero clearance angle because of abrasive wear. If the attack angle of the worn bit having a wear flat was increased by a practical mechanical technique before ignition occurred, bit life would be prolonged because the worn bit then would require additional strikes to form a new wear flat. However, such a practical technique does not seem available at the present.

The present technique of testing a new bit to the point of ignition does not separate the wear character of the tip material from the incendivity character of the tip material. However, the results of these tests do indicate the higher incendivity of steel compared with tungsten carbide incendivity and qualitatively agree with earlier results (2-3); although, ignition was observed in tests with frozen carbide-tipped bits without the steel shank becoming exposed. Presumably, with freely rotating bits, wear of the tip of the bit will tend to be evenly distributed around the tip and lead to a general wear of the entire tip. Such a general wear of the tip would avoid the formation of the incendive wear flat but would of course eventually lead to exposure of the steel chank.

Although improved tip and shank materials can probably be located to reduce the likelihood of frictional ignition, it seems unlikely that tip and shank materials with satisfactory physical characteristics and negligible incendivity will be available. However, the general ignition hazard of conical bits, either rotating or fixed, would be reduced by improving the wear character of the tip material and by reducing the incendive characters of the tip and shank materials. The wear and incendive characters of candidate tip and shank materials and the normal force during cutting is being investgated.

CONCLUSIONS

1. The average number of strikes for ignition with a new, frozen (nonrotating) conical bit increased by a factor of 3 if the bit attack angle was increased by 10° or if the initial tip angle decreased by 10°.

2. Frozen carbide-tipped bits required more strikes for ignition than frozen steel-tipped bits by a factor range of 7 to 10.

Caution must be kept in mind because of the scatter in the experimental data from which the conclusions are drawn; therefore, the average number and the range are loosely expressed.

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