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REPORT OF INVESTIGATIONS/1988

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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Library of Congress Cataloging in Publication Data:

Plis, Matthew N.

Preliminary evaluation of the relationship of bit wear to cutting distance, forces, and dust using selected commercial and experimental coal- and rock-cutting tools.

(Report of investigations; 9193)
Bibliography: p. 29
Supt. of Docs. no.: I 28.23:9193.

1. Coal-cutting bits--Testing. 2. Coal mines and mining--Dust control. I. Wingquist, Carl F. II. Roepke, Wallace W. III. Title. IV. Series: Report of investigations (United States. Bureau of Miines); 9193.

TN23.U43 [TN813] 622 s [622'.334] 88-600143

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

m^3	cubic meter	hp	horsepower
°C	degree centigrade	in	inch
ft	foot	in/s	inch per second
ft/min	foot per minute	lbf	pound (force)
gpm	gallon per minute	µm	micrometer
GPa	gigapascal	pct	percent
Hz	hertz	rpm	revolution per minute

OTHER ABBREVIATIONS

ARD	airborne respirable dust	PDC	polycrystalline diamond compact
CM	continuous miner	REDI	respirable dust index
Co	cobalt	WC	tungsten carbide
CSM	cutting system model		
LW	longwall		

PRELIMINARY EVALUATION OF THE RELATIONSHIP OF BIT WEAR TO CUTTING DISTANCE, FORCES, AND DUST USING SELECTED COMMERCIAL AND EXPERIMENTAL COAL- AND ROCK-CUTTING TOOLS

By Matthew N. Plis,[1] Carl F. Wingquist,[2] and Wallace W. Roepke[3]

ABSTRACT

This report describes the initial results of long-range research on bit life conducted by the Bureau of Mines. Three commercial bit designs – a round-nose radial, 60° conical, and 90° conical with tungsten carbide (WC) inserts – and five experimental bits were tested. Four of the experimental bits were radial designs using polycrystalline diamond compact (PDC) inserts. The fifth was a 90° conical with an oversize WC insert. Bits were worn on a high-silica sandstone typical of coal mine roofs. The bits were mounted on a 34-in-diam drum section that provided a bit speed of 565 ft/min. Cutting forces were measured on a modified vertical slotter using a three-axis force dynamometer and recorded on an FM magnetic tape recorder. Changes in cutting forces, bit weight, and airborne dust due to gradual abrasive wear and catastrophic insert failure are presented. Tabulated and graphed data, photographs of the progression of bit wear, and selected qualitative visual and auditory observations of the bits taken throughout the experiment are found in the appendixes. The results show that bit life ranged from approximately 16,000 ft for the WC round-nose radial bit to over 125,000 ft for a PDC round-nose radial. Performance, in terms of bit life, cutting forces, wear rate, frictional sparking, machine vibration, and noise was in general best with the PDC bits, followed by the rotating WC bits, with the nonrotating WC bits (round-nose radial and locked 60° conical) being the worst.

The results show variations in the included tip angles of new conical bits have an insignificant influence on bit performance when the effects are averaged over the life of the bit. In addition, new bits were generally found to entrain more primary respirable dust for a given cutting distance than worn-out bits. It is hypothesized that this is due to the difference in frictional behavior between new and worn bits. The results from these tests are being used in the Bureau's cutting system model (CSM).

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INTRODUCTION

The Bureau of Mines has maintained an extensive research effort concerning the generation, suppression, and detection of respirable dust since the enactment of the Federal Coal Mine Health and Safety Act of 1969. Work on the reduction of primary airborne respirable dust (ARD) generation has focused on the influence of controllable machine design parameters, such as bit geometry, mounting configuration, material properties, and operating techniques. Recent efforts (*1-10*)[4] have dealt with various parameters affecting ARD, frictional ignitions, and energy consumption of the coal cutting system.

The primary purpose of this study was to investigate the relationship between cutting distance, bit wear, and the tangential and normal cutting forces over the total lives of three commonly used bit designs. In addition, five experimental bit designs, four of which utilize PDC inserts, were selected for comparison against the standards. Laboratory tests were originally planned utilizing several spacing, depth-of-cut, and bit-speed combinations in Berea sandstone, but time and budget constraints mandated these variables be held constant for all wear tests.

BIT LIFE

The total useful life of cutting bits for continuous miners (CM) and longwall (LW) shearers is dependent on their wear-and-fracture resistance. These, in turn, are dependent on the bit specifications such as type and geometry; the physical, mechanical, and thermal properties of the bit materials; the mounting configuration of the bit on the drum; depth-of-cut; bit speed; and physical properties of the material being mined, etc. Current understanding of the synergism of these parameters is insufficient to allow the accurate, quantitative prediction of bit life with variable operating conditions. The practical determination of optimum bit design for long life remains a trial-and-error process rarely resulting in optimal cutting system performance.

On an individual basis, deciding when a bit has reached the end of its useful life is a subjective experience. Miners commonly push their equipment until production falls dramatically, stopping only then to perform needed maintenance, including replacement of worn bits. Unfortunately, there are no existing efficiency standards defining and equating the degree of wear exhibited by a bit with profitable life. Although there are a great number of variables to consider, mine operators would benefit from a more thorough quantitative understanding of the interrelationship of bit wear and the efficiency of the cutting system. This information is essential if the mine operators are to make knowledgeable choices in the process of optimizing the cutting system to improve the safety and productivity of the mine.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to American Mine Tool, General Electric's Specialty Materials Department, and V. R. Wesson for supporting this study.

LITERATURE REVIEW

The rate at which wear damage develops on an individual bit in the field depends upon its initial geometry, the orientation and position in which it is mounted on the miner or shearer drum, various operator-controlled parameters, and the physical properties of the bit and material being mined. In general, however, all bits in current use initially experience a high wear rate, in terms of weight loss versus cutting distance, as the bits adjust to the specific cutting conditions (*11-12*). Subsequent to this early stage, the wear rate decreases in proportion to the distance cut as the wear-flat area increases, provided the cutting conditions are such that the critical temperatures at which the bit materials begin to soften are not exceeded. Once the critical temperature is exceeded, the wear rate increases dramatically and rapid bit destruction is assured.

TOOL WEAR MEASUREMENTS

There have been few studies reported in the literature concerning the measurement of bit wear over the life of commonly used coal and rock cutting bits. Mehrotra (*13*) grouped worn bits into four categories following a field trial in which a continuous miner (CM) was used to mine a known quantity of coal when equipped with half standard and half new experimental bits. Bits were weighed and

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

classified according to the severity of damage to the WC insert and tool steel body, and whether or not the wear was symmetric. Hurt and MacAndrew (*14*) adopted a simple classification system similar to Mehrotra's during a field test when a roadheader was used to cut hard limestone. Bits were designated "slightly," "moderately," or "severely," damaged, and assigned a numerical value whereby the consumption of bits for a given volume of rock was quantified. Results obtained from this method were found to be repeatable, allowing the accurate prediction of bit consumption rates within the given operating conditions. Kenny and Johnson (*15*), in a laboratory study, quantified the wear exhibited by worn experimental radial bits by weighing them and measuring their wear-flat widths. In none of the aforementioned papers, however, did the experimental design include the direct, periodic measurement of the weight loss and cutting forces required by conventional bit types throughout their serviceable lives. To the best of the authors' knowledge, therefore, this paper represents the first attempt to quantify the relationship between bit life, bit wear, and cutting forces for commercial coal- and rock cutting bits.

BIT GEOMETRY

The two significant types of coal-cutting bits in general use are the radial and conical designs (fig. 1). A third type called the forward-attack bit incorporates some features of both major types for use on LW shearers. Radial bits have their shanks rigidly fixed to the miner or shearer drum in a position perpendicular to the cutting direction, and are roughly rectangular in cross section. Conical bits have their shanks inclined at 35° to 55° toward the cutting direction, are circular in cross section, and are loosely fixed in their holders so they are free to rotate about their longitudinal axis during the cutting process. Forward-attack bits are rigidly fixed in their holders and are similar in cross section to the radial design but they are inclined toward the cutting direction in the manner of the conical bits. Radial and forward-attack bits are normally used for rock cutting or as gage cutters on CM's. They are the most popular coal-cutting designs in use in Europe and England. Curiously, conical bits are favored on coal-cutting equipment in the United States.

Several authors report that new radial (or wedge-shaped) bits are more energy efficient than new conical (or pointed) bits. (Within the industry the term radial may be considered synonymous with wedge and chisel bits, while the term conical is synonymous with point-attack bits.) Laboratory experiments have been done for cutter evaluation in sandstone and limestone (*15-17*). In situ measurements of coal cutting have been reported for tests in two American mines (*18*), and bit tests have been made using a roadheader to cut hard limestone (*14*). Two of the studies (*14, 17*) showed that radials are more quickly affected by wear than conicals. Conical bits were found to provide a substantially longer serviceable life and were considered more practical than radials. Hurt and Laidlaw (*16*) recommended that bits be selected on the basis of their wear and fracture resistance instead of their

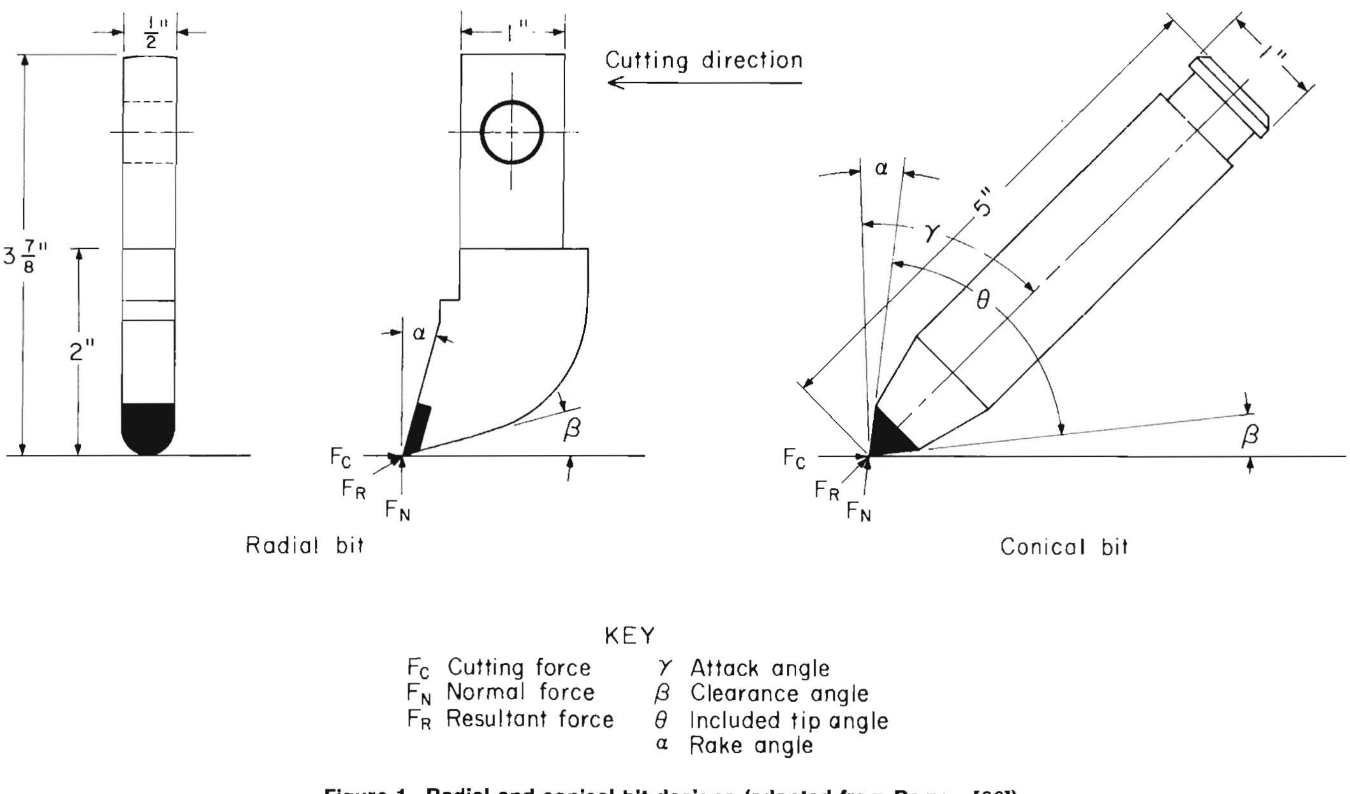


Figure 1.–Radial and conical bit designs (adapted from Demou [*36*]).

performance when new. They have noted that the onset of wear quickly modifies the shape of WC tools so that initial significant differences in cutting efficiency are soon eliminated.

Two studies have shown that the clearance and rake angles of a tool (fig. 1) do not affect the rate at which the tool wears (*11-12*). Other research (*15*) found that new tools with smaller clearance angles are subject to a more rapid increase in wear-flat width and thus forces. These results also show that, for the given cutting conditions, the volume of rock removed by a bit was independent of its clearance and rake angles.

Mellor (*19*) states that, in general, clearance angles greater than +5° have no effect on forces. Kenny and Johnson (*15*) found in a laboratory study of experimental radial bits that new tool forces decreased as the clearance angle was increased up to +30°. They also found that, as the cutting process continues, all bit types develop an initial large (15°) wear angle on the wear flat (fig. 2) which gradually stabilizes at 1° to 10°, depending on the hardness of the rock and bit tip. More recent research (*20*) indicates that rock passing under the bit is crushed and compacted by the negative clearance, increasing both cutting and normal forces relative to a bit with a positive clearance angle. The negative clearance angle has been found not only to increase dust production, but also to present a more immediate hazard to a miner's life. Roepke and Hanson (*4*) state that all tool steel and WC bits with negative clearance can be incendive.

Kenny and Johnson (*20*) report the development of a "nonblunting" radial tool constructed of a hard, 0.035-in-thick, WC layer mounted on a backing of softer WC. Owing to the fact that the softer backing wears more readily than the hard front layer of the bit, the negative clearance angle that is generated with cutting distance is restricted to the thin front layer. Consequently, the volume of rock crushed beneath the small wear area is minimal and remains approximately constant over the life of the bit. This design is essentially identical in concept to that of the successful PDC bits introduced in 1976. Two PDC bits of this type, the 0° and -20°, were included in this study.

Kenny and Johnson found that altering the rake angles of experimental radial bits cutting sandstone did not appreciably affect wear-flat development (*15*). A large negative rake has been reported by Hibbs and Lee to induce high tensile stresses and fracturing of PDC material at the cutting of the bit tip (*21*), and by Collin and Kornecki to cause excessive vibration on LW shearers (*22*). Bit forces were found by Mellor to be influenced by rake angle variations for a variety of conditions. The cutting and normal forces were observed to decrease nonlinearly as the rake angle increases, reaching a low at +20° to +30° (*19*). As the depth of cut becomes very shallow–roughly equivalent to the radius of the tool tip–performance ceases to be affected by the rake angle.

Roepke measured the cutting and normal forces required by three new radial PDC bits having rake angles

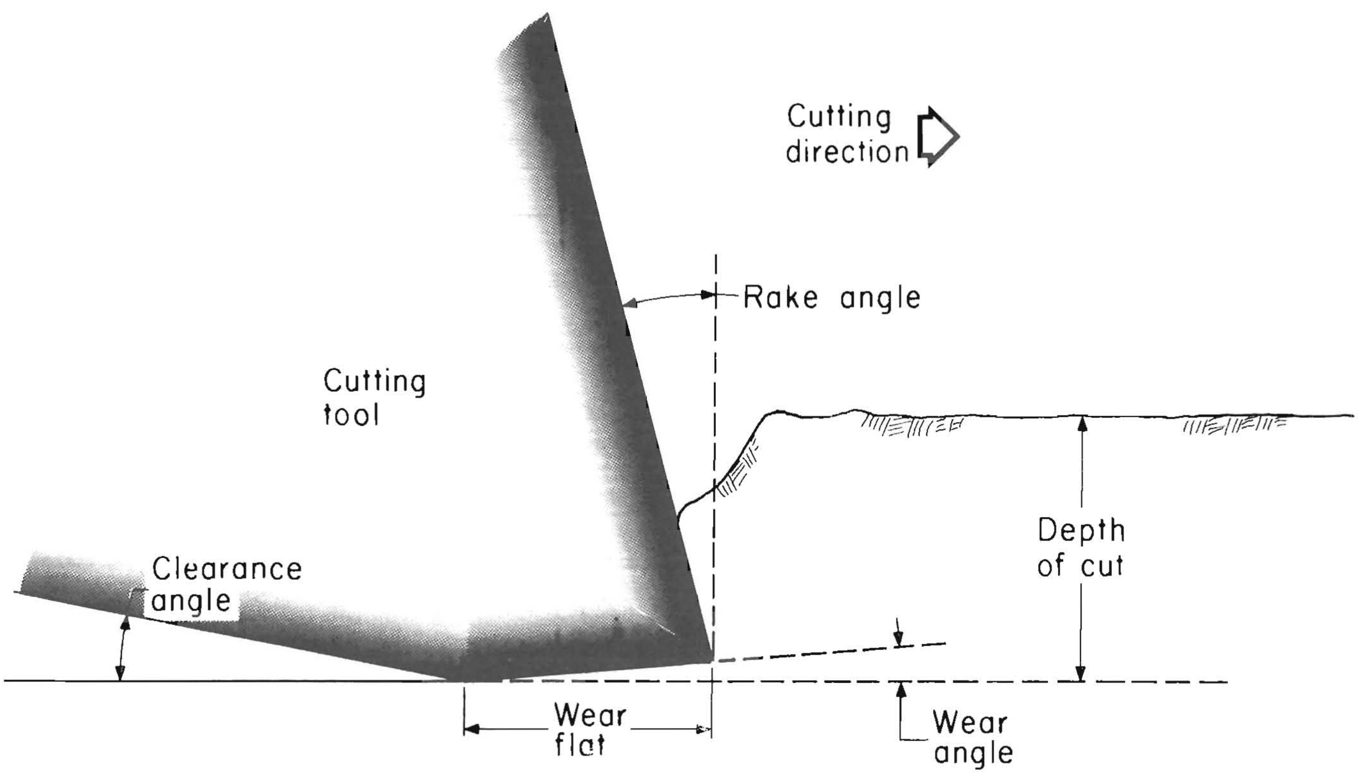


Figure 2.–Illustration of wear geometry of an idealized cutting tool (adapted from Mellor [*19*]).

of -17°, +3°, and +15° (*5*). The +3° bit required the lowest forces at depths greater than 0.39 in, apparently contradicting the statement in the preceding paragraph. One possible explanation is that bit performance is reported (*15*) to be optimum when clearance and rake angles are equal. The included tip, or wedge, angle of unaltered PDC inserts is always 90°, so that the -17°, +3°, and +15° bits would have clearance angles of +17°, -3°, and -15°, respectively. Thus, the +3° bit would have the most nearly equal clearance and rake angles, and would, therefore, provide the best performance. Blunting of the bit tip nullifies the influence of the tool angles, however.

Wear-flat development has been observed to be independent of tool width (*15*), and weight loss, to be proportional to tool width (*12*) at bit speeds low enough to avoid thermal effects. Nishimatsu (*23*) theorized that both cutting and normal forces increase proportionally with tool width. However, experimental evidence indicates that cutting and normal forces increase linearly (*19*), but not proportionally (*15*), to tool width, the factor being about 1.5. The factor for the increase in the amount of rock removed, given tool width variations, was found by Kenny and Johnson to be about 1.3 owing to the effect of the breakout angle; thus, it is probably not advantageous to increase tool width beyond that which is necessary to provide adequate bit fracture resistance (*15*).

Assuring the rotation of conical bits has been stated (*17*) to extend their wear life but not their fracture life. The forces required by rotating, symmetrically worn bits have been observed to be as high as those of nonrotating, asymmetrically worn bits. Most conicals do indeed fail after locking up in their holders, as can be inferred from a field study by Mehrotra (*13*), and personal observation. Another field study by Hurt and MacAndrew (*14*) showed that conical bit life was halved in the given cutting conditions when rotation was prevented through the use of bits with oversize shanks. Rotation was cited as the most important factor responsible for the superior performance of conical bits relative to radials. Larson (*1*), as well as others, state that nonrotating bits nearly always cause methane ignitions in gassy areas, while fewer ignitions occur with rotating bits in identical conditions.

BIT-MOUNTING CONFIGURATION

Three bit mounting parameters that affect wear rates and forces are spacing, attack angle, and position on the drum.

Nothing could be found in the literature relating tool wear to the spacing of parallel bit paths (fig. 3). However, cutting and normal forces are reportedly affected by spacing variations. Mellor (*19*) states that maximum forces occur when spacing is independent ($X \geq 0$). Cutting becomes interactive, and forces begin decreasing, as the spacing decreases past $X=0$. Forces should become nonexistent at $s=0$ after the first cut (*19*). For a given depth of cut, Barker (*24*), and others, have found that cutting efficiency increases to an optimum as spacing initially increases, then decreases as spacing continues to increase beyond the optimum. Barker reports that cutting is most efficient if the spacing-to-depth ratio is high (3 to 4:1) at shallower (0.5 in) cuts, and lower (1.5:1) at deeper cuts. If this were actually true it would be fortuitous, since this is what happens to spacing when cutting with any drum-type miner. The bits enter at zero depth, go to some maximum, and exit at zero. This means that the spacing-to-depth ratio that Barker mentions changes constantly during each cut. Hanson (*25*) found that the quantity of specific dust generated is least when cutting at a spacing-to-depth ratio of approximately 2 to 3:1 at all depths.

The attack angle is defined for rotary cutting as the angle between the bit axis and the drum radius at the bit tip. For linear cutting in the laboratory, it is defined as the angle between the longitudinal axis of a conical bit and

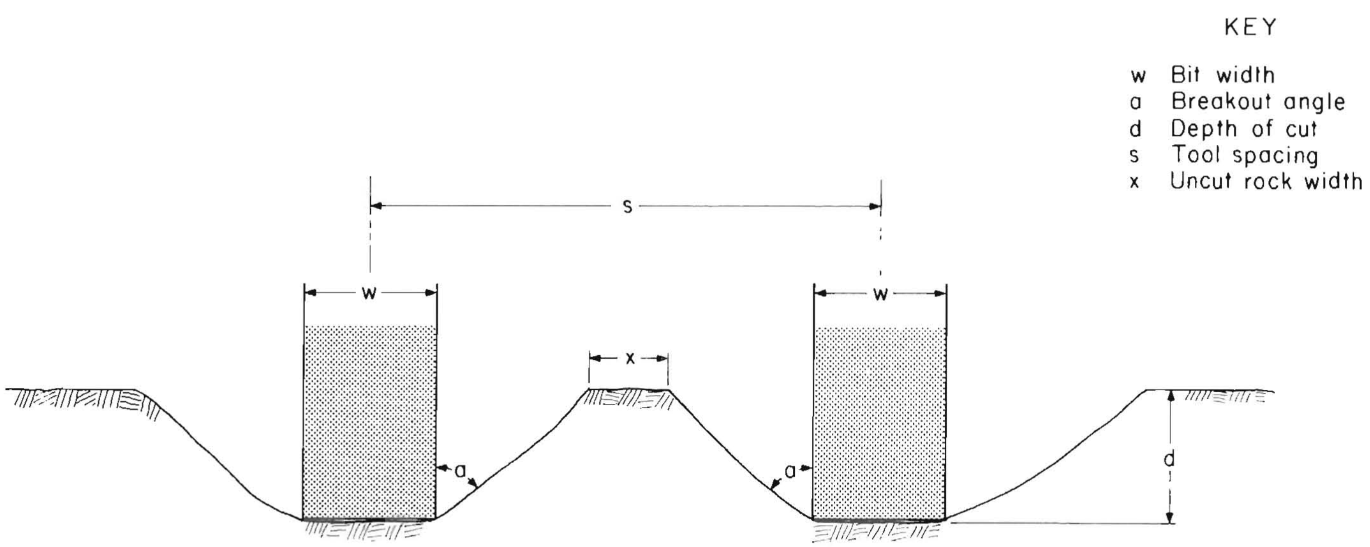


Figure 3.—Illustration of an idealized cutting path geometry (adapted from Mellor [*19*]).

a perpendicular to the cutting direction (fig. 4). Other researchers have described the attack angle as being the complimentary angle of the preceding definition. Lack of a commonly accepted definition has caused a great deal of confusion within the industry. Another potential problem source is the fact that the attack angle for rotary cutting, but not for linear cutting, depends in part on the length of the bit. For example, the attack angle for the 90° conical bit on the rotary cutting system used in this study increased from an initial 45° to 46° as a result of being worn from its original length of 4.75 in to 4.10 in at the end of its life. The 1° increase may seem inconsequential, but some equipment manufacturers attempt to optimize the cutting system by setting attack angles to the nearest 0.5°. Drum designers and mine operators should be aware of the possibility for changes in the cutting action. The benefits of specifying attack angles to such close tolerances may, in fact, not be as important as is sometimes believed. A more detailed examination of this topic is beyond the scope of this paper but will be presented separately in a future publication.

Wingquist (*8*), reported that a 35° attack angle produced more bit rotation than a 45° angle; this should serve to promote symmetric wear and enhance bit life. Cutting forces in coal were reported (*25*) to be minimal at a 45° attack angle for three new conical bits, one having an included tip angle of 90°, and two others with tool tip radii of 0.25 and 0.375 in. Minimal forces for a new 75° conical bit were encountered at an attack angle of 35° to 40° (*17*). However, Bartholomae and Becker (*26*) state that cutting force and specific energy are independent of attack angle, while normal force is very sensitive to it, being maximal at an attack angle of 0°, and minimal at 30°.

OPERATOR-CONTROLLED PARAMETERS

Two operator-controlled variables affecting tool wear rates and forces are bit speed (drum revolutions per minute) and depth of cut.

Although tool life has been reported to vary inversely with bit speed (*27-28*), most authors state that the situation is more complex. Preliminary work by Lung Cheng, of the Bureau's Pittsburgh (PA) Research Center, indicated that at depths less than 0.25 in, depending upon bit type, bit life was greatest when cutting at a relatively low speed (280 ft/min); while at greater depths (to 0.5 in), bit life was greatest at higher speeds (500 to 660 ft/min). No reason was given for the change in performance with speed, however.

Krapivin (*11*) states that a critical temperature exists above which tool alloys soften and wear more quickly. The critical temperature depends not on the bit design, but solely on the thermophysical properties of the alloy; the critical temperature of WC is approximately 500° to 700° C. Tool temperature is dependent on bit speed. The critical speed above which wear is accelerated is a factor of tool design, operating conditions, and rock properties.

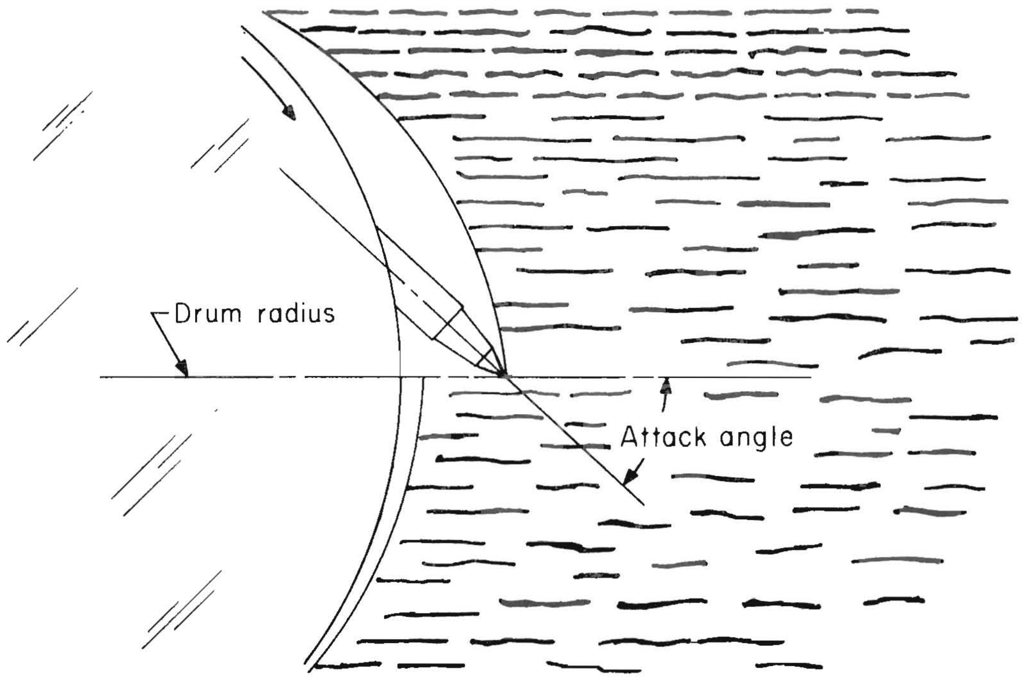
At and above the critical speed, temperatures are great enough to generate 500° to 1,400° C sparks consisting of glowing quartz grains and tool alloy. The bulk of the bit remains relatively cool, however, as such high temperatures are usually confined to a thin surface layer in the area of the bit actually contacting the rock. Bowden and Tabor (*29*) state that the temperature of the surface layer can reach, but not exceed, the melting point of the lowest melting point material being abraded. The melting points of coal-cutter steels, quartz, and WC are approximately 1,500° C, 1,700° C, and 2,800° C, respectively. Blickensderfer (*30*) and others (*1*) report that the ignition frequency of methane increases with bit speed for nonrotating bits.

To insure maximum bit life, critical tool speeds must never be exceeded. The wear rate of tool steel, stellite, and carbide tools is reported to be independent of speed below a critical speed of 165 to 220 ft/min. Wear was observed to increase very rapidly once these speeds were surpassed (*12*). Similarly, other investigators found the wear rate of PDC tools in a highly abrasive sandstone to be six times less at 200 to 400 ft/min than at 600 ft/min (*31*). A reduction in speed from 197 to 110 ft/min, at a constant depth of cut, was found to decrease the consumption of radial bits from 1.8 to 0.13 bits/m^3 in limestone, and of conical bits from 0.8 to 0.55 bits/m^3. Speed had a large effect on the consumption rate at shallow (0.25 in) depths of cut, and a minimal effect at greater (0.75 in) depths (*14*). Equations have been developed (*11, 32*) that predict critical cutting speeds, facilitating the avoidance of the deleterious effects of elevated speeds and temperatures.

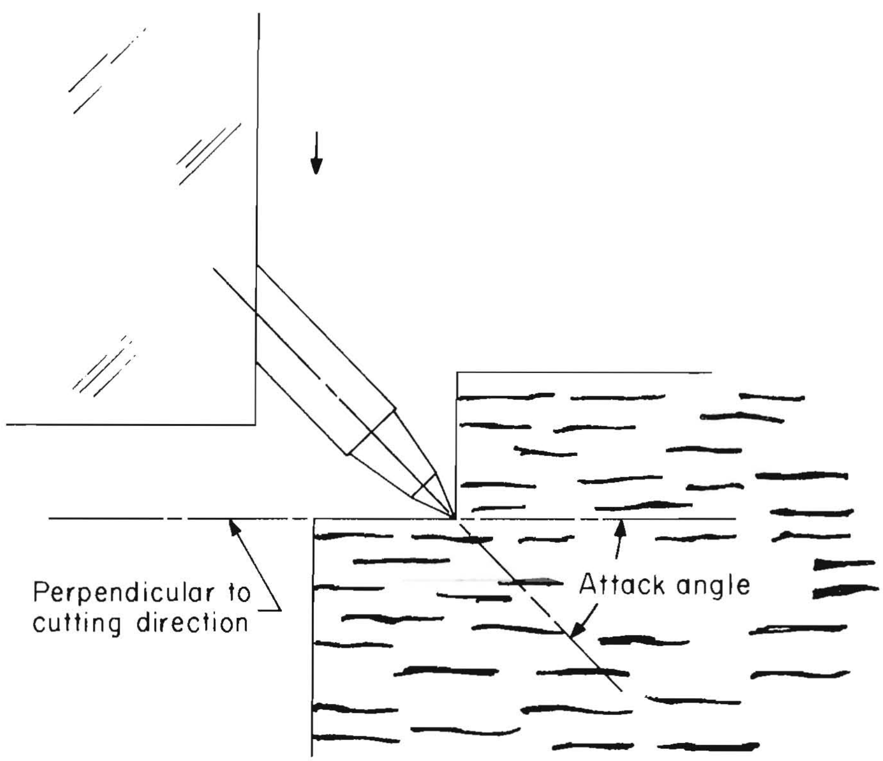
Slower speeds do not necessitate production penalties. A Bureau-sponsored field study (*33*) proved the practicality of a low-revolution-per-minute, deep-cutting CM for reducing levels of respirable dust. Although bit life was not a part of the contract effort, it would be an ancillary benefit of dust reductions.

Tool velocities reportedly have a negligible effect on cutting and normal forces. Nishimatsu (*27*) theorized that cutting force would slightly increase with tool velocity. Laboratory results by several researchers indicate no significant effect on cutting force and specific energy from 200 to 600 ft/min (*34*) and 1 to 1,000 ft/min (*19*), and on cutting and normal forces, or specific energy, from 50 to 335 ft/min (*35*). However, in some experiments, normal force has been observed (*19*) to increase slightly with speed at velocities below 150 ft/min.

Depth-of-cut variations affect both wear rates and forces. The volume of material worn from cutting edges has been found (*12, 15*) to decrease significantly per unit of cutting distance with increasing depths (to 0.4 in); bit speed was 5 ft/min, well below the critical cutting speed. Tool consumption can potentially be reduced by hundreds of times per unit of volume of removed rock by increasing the depth of cut (*11*).



SIDE VIEW OF TYPICAL ROTARY CUTTING SYSTEM



SIDE VIEW OF TYPICAL LINEAR CUTTING SYSTEM

Figure 4.–Bit attack angles.

Cutting and normal forces have been hypothesized (*23*) to increase proportionally with depth of cut. Experimental evidence indicates that up to a depth of 1.0 in, cutting force (*15-17, 19, 23-24, 35*) and normal force (*15, 19, 23-24, 35*), with one exception (*23*), increase with depth, the rate of increase being a function of various design, operating, and material parameters. Specific energy reportedly decreases with increasing depth, rapidly at first, then more slowly (*17*), attaining some minimal value, after which cutting efficiency decreases with increased depth (*19, 24*).

CM's and LW shearers currently in use employ bits mounted on a rotating drum to cut coal and rock. Many of the parameters affecting the cutting system cannot be optimized with the present rotary drum action. As a consequence of the rotary action, bits spend most of their cutting time at relatively shallow, inefficient depths, with continuously varying depths of cut and inefficient spacings. Roepke (*36*) has proposed a rotary eccentric head cutting concept that utilizes slow, linear, constant depth, deep cutting to minimize the amount of energy, number of bits, respirable dust, potential for methane ignitions, and capital, labor, and maintenance costs, required by the cutting process. This slow, deep linear cutting is expected to increase bit life.

PHYSICAL PROPERTIES OF THE BIT MATERIAL

Mineral cutting tools are composed principally of two types of materials. The tool steel body of a typical bit is relatively soft and ductile compared with the hard insert of material used to form the cutting edge. Tool steel wears much more quickly than the insert it supports, so ideally only the insert contacts the rock during the cutting process. Bit wear resistance has been observed to increase, and fracture resistance decrease, with the increase in hardness of the tool materials (*15*). Wear resistance increases sharply when the tool hardness reaches 80 pct of the hardness of the material being cut (*37*).

Two materials, a composite of WC and cobalt (Co), and PDC, are currently used to form the hard inserts of mineral cutting tools. WC tools have been available for more than 50 years, the insert material being composed of WC grains cemented by 5 to 16 pct Co through a high temperature-pressure sintering process. Several investigators report that hardness and wear resistance decrease, and fracture resistance increases, with an increase in Co content; the size and distribution of the WC and Co also have been found to determine the composite's wear characteristics (*14, 38-39*).

PDC tools were introduced relatively recently (1976) and are still being developed. The earliest designs utilized inserts formed by sintering diamond crystals at high temperature and pressure in the presence of a catalytic binder (usually Co), so that the resulting PDC material is bonded to a WC substrate capable of being brazed to a steel body. A typical insert would be composed of a thin (approximately 0.02 in) layer of PDC material sintered to one side of a 0.10-in-thick, 0.5-in-diam, WC substrate. More recently, several manufacturers have introduced "thermally stable" PDC inserts that withstand temperatures up to 1,000° C in a reducing atmosphere without degrading. Many PDC products progressively degrade when subjected to temperatures above 700° C, due to the presence of a residual solvent catalyst. Thermally stable materials have an inert binder phase and are available in a wide variety of geometric shapes. The random orientation of PDC's diamond crystals reportedly increases the overall strength and durability because individual crystals fail by fracturing along preferred cleavage planes (*31, 39*). PDC tools have been found to perform substantially better than WC tools in certain conditions (*5, 22, 40*).

Glowka and Stone (*39*) say wear may be defined as any degradation, macroscopic or microscopic, that reduces bit life by the removal or fracture of material at the cutter surface. They also state that wear characteristics of PDC and WC in rock cutting are substantially different, since the PDC diamonds are harder than any abrasives encountered in cutting. WC fails macroscopically by structural overload with or without fatigue, impact shock with or without fatigue, or thermal shock with or without fatigue. Microscopic failure of WC is by abrasive wear, which includes abrasion; impact shock, with or without fatigue; and thermal fatigue. PDC fails macroscopically and microscopically by impact shock, with or without fatigue, and thermal shock. All of these wear mechanisms probably occur simultaneously to some degree (*39*).

There has been a large quantity of material published concerning the influence of various physical parameters and operating conditions on the wear properties of WC and PDC. Those readers requiring further detailed information are referred to the reviews by Glowka and Stone (*39*) and Perrot (*41*).

ROCK PROPERTIES

The most commonly cited rock property influencing bit wear is abrasivity. Various tests have been developed to measure abrasivity (*32, 42-43*), with the result that sedimentary rocks normally associated with coal have been found to be 15 to 20 times more abrasive than coal itself (*32*). This is probably due to the higher quartz content of the sedimentary rocks. A proportional relationship between quartz content and abrasiveness has been noted by West (*42*). West asserts tool wear may be expected to increase with abrasiveness and quartz content. Schimazek proposed an equation wherein tool wear is a proportional function not only of quartz content, but also of quartz grain size and the tensile strength of the rock being cut (*32*). However, quartz hardness varies at temperatures commonly encountered during cutting. Although the room-temperature Vickers hardness of quartz is 9.8 to 11.3 GPa, a phase transformation occurs at 573° C after which grit hardnesses up to 24.5 GPa may occur (*41*). The room temperature hardness of WC composites ranges from 11 to 17 GPa, but it becomes relatively softer and more ductile at temperatures over 400° C (*38*). Thus, at elevated temperatures, quartz can become significantly harder than WC tools, resulting in a drastic increase in the tool wear rate.

Although cutting and normal forces for rock have been found to increase approximately linearly with unconfined compressive strength, correlation with tensile strength may be more appropriate for laboratory conditions, since rock fails in tension without overburden pressures (*19*). Confining stresses due to overburden pressures are expected to cause an increase in cutting forces. This will change the cutting process from one of tension to one of shear, reducing the applicability of unconfined test results (*44*). It should be noted that some experiments do not show this effect (*19*). Bureau work has shown that for Valders white rock, Indiana limestone, Tennessee marble, and trona, compressive strength and Shore hardness are good indicators of the forces, specific energy, and bit wear that will be encountered (*35*).

IMPROVED BIT APPLICATION

The high capital cost of PDC bits relative to the standard WC bits (approximately \$100 versus \$5 to \$10) has, to date, limited their acceptance by the mining industry. However, PDC tools have been shown to be cost-effective in certain situations. Economic analyses of various LW (*45*) and CM (*46*) systems shows that the total economic benefit of advanced technology bits depends upon their relative durability. Conventional CM and LW bits were assumed to have average lives of two and six shifts, respectively. Results from the LW study showed that at \$100 per bit LW and CM bits have break-even lives of approximately 25 and 30 shifts, respectively. The CM study showed that, at \$100 per bit, the break-even life of CM bits is roughly 20 shifts, and at \$50 per bit, about 13 shifts. Maximum economic benefit is projected at a bit life of 30 shifts.

Examination of the results presented in this publication, given the assumptions and requirements discussed in the preceding paragraph, show that PDC technology can be applied successfully on LW shearers at this time. A field study (*22*) has, in fact, demonstrated that the use of the forward-attack PDC picks on a shearer can result in the following benefits relative to WC picks:

1. Less downtime for tool changes–more production time per shift.

2. Faster average haulage speeds–higher working production rates.

3. Lower and more consistent cutting force–reduced wear and tear on shearer resulting in more production time per shift due to less maintenance downtime.

4. Lower shearer operating costs–less maintenance.

5. Improved work force productivity–resulting from higher production rates.

6. Reduced specific energy consumption.

7. Coarser coal–resulting from higher average haulage speed.

8. Reduced dust levels–a result of coarser coal and sharper tools.

The improvements in dust levels and coal size were not measured directly, but are based on the opinions of miners working the panel. Frictional sparking was noticed only when the steel bit body contacted the sandstone roof. That observation is supported in this publication (appendix D) and by other Bureau work (*5*). The following conditions are those required for the successful use of PDC bits:

1. Shearer not performing to maximum rated production capacity because of conventional tooling limitations under "hard" cutting conditions.

2. Coal transport system from the face is capable of handling the additional shearer production when using PDC bits.

3. Ability of the mine to use the extra production, or to eliminate another production section.

4. Face conditions that allow PDC bit yield in excess of about 15 times that for conventional tools.

CUTTING SYSTEM MODEL

One consequence of the many years of cutting research in laboratories and in the field is that the data base developed by the Bureau and others is so extensive that an individual mine operator might not be able to assimilate and translate the data into actions that enhance the health and safety of the mine environment. In response to this situation, the Bureau has developed an interactive computer program (*47*), called REDI (respirable dust index), that enables mine operators to quantify the relative change in ARD generation induced by cutting system alterations. This program allows the operator to input generic data concerning seam, machine parameters and operating conditions, and, through a process of selectively changing variables, arrive at an optimum cutting system design relative to ARD generation and production constraints. Although the data base used to support the program is inclusive of the most recent findings, a careful literature review indicates that important gaps in the basic understanding of the coal cutting process exist. One such area is the lack of quantitative data concerning the effect of bit wear over the total useful life of the bit with respect to tangential and normal cutting force requirements, ARD generation, and production variables. The program REDI is, therefore, considered to be a precursor to a more sophisticated mathematical cutting system model (CSM) currently under development. This publication describes part of a long-term effort undertaken in support of the evolution of the CSM.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

FACILITIES DESCRIPTION

The test equipment used for this work consisted of two major components, the rotary drum test system and a modified vertical slotter. Since both are described more fully elsewhere (*48*), only a brief description of each is presented here.

The rotary drum (fig. 5) is confined in a chamber 3 by 4.5 by 6 ft, which is constructed of 0.125-in-thick steel plate. The front side of the chamber is open to facilitate maintenance, but is sealed with a 2-mil polyethylene sheet during testing to isolate the airborne dust produced from the surrounding room. The chamber is exhausted to the outside by a centrifugal fan. Operation of the test chamber is from an adjacent room designed to safely isolate both instrumentation and personnel.

Bits are attached to a 34-in-diam drum powered by four hydraulic motors driven by a 100-hp, 100-gpm pump to deliver a maximum force of 5,200 lbf. Rotational speed, which can be varied between 0 and 100 rpm, is monitored by a magnetic gear-tooth sensor near a drive gear.

The rock sample is mounted on a translating table powered by programmable stepper motors that are remotely operated from the control room. The table

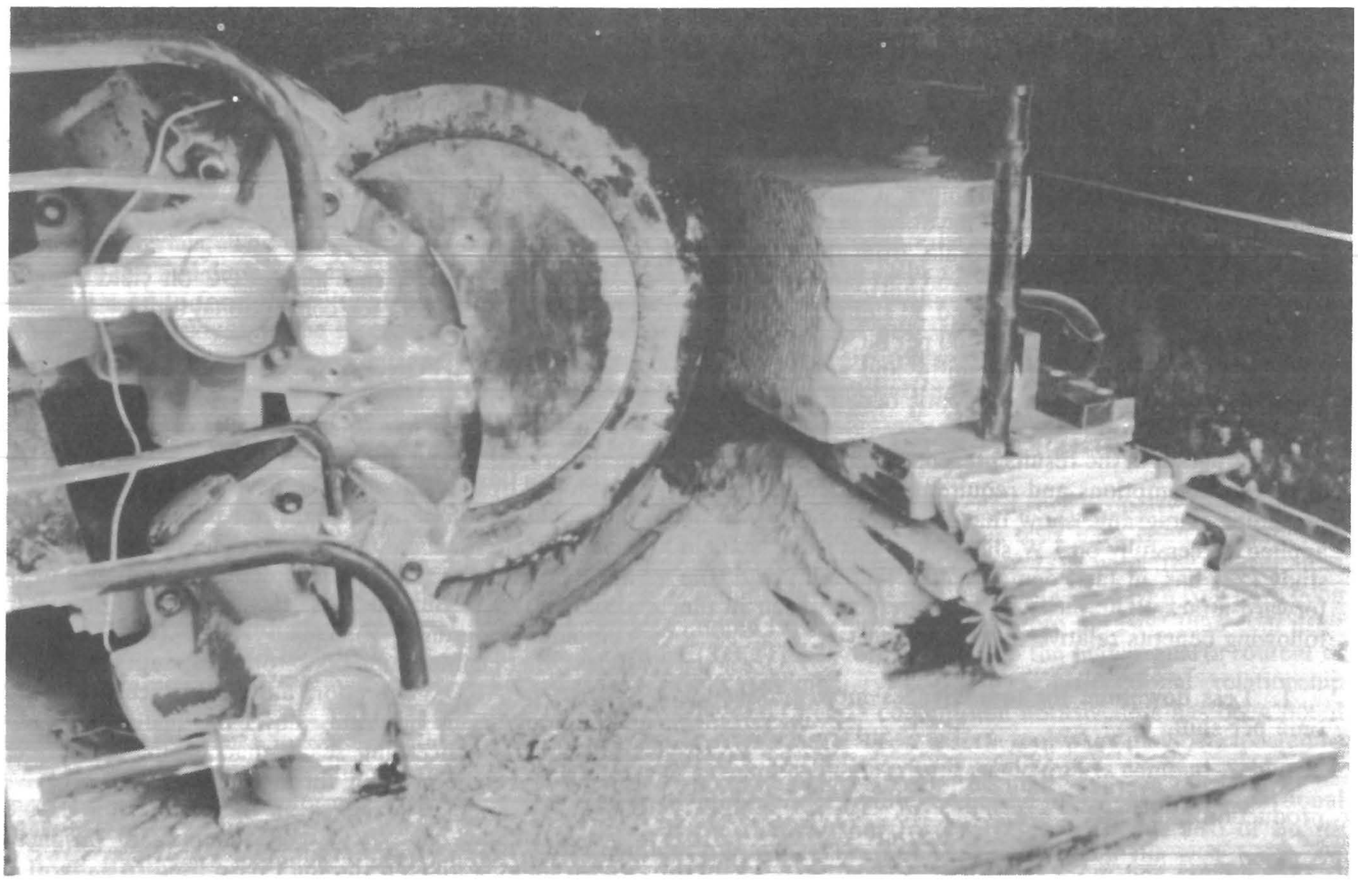


Figure 5.–Rotary test chamber.

automatically translates both across and into the drum at speeds between 0 to 0.75 in/s and 0 to 0.375 in/s, respectively. During bit wear testing, the sample first translates across the drum in discrete steps providing a constant depth of cut and spacing. After the last cut, the sample table automatically advances the assigned depth of cut and reverses direction. The sample table continues to cycle in this manner until reaching the programmed stop or the operator stops the test.

Upon completion of a wear test series, orthogonal cutting forces were measured on a modified vertical slotter (fig. 6). Bits mounted on the movable ram were capable of a maximum force of 11,000 lbf. The sample holder was designed specifically to hold 1-ft cubes of Berea sandstone identical to those used in the wear tests. The sample face and bit configuration are shown in figure 7. The worktable is infed toward the cutter to obtain the desired depth of cut. The cutter ram then cycles up and down vertically, producing a constant-depth linear cut in the sample with each downstroke. The bit retracts on the upstroke to avoid hitting the block while it repositions. The lateral motion of the worktable is synchronized with the vertical movement of the cutter ram so that a crossfeed of a preset distance automatically occurs between cuts.

Bit forces were measured in three mutually perpendicular directions. The sample holder was coupled to the worktable of the vertical slotter through four three-axis piezoelectric load cells. The four outputs for each axis were connected in parallel to the input of the charge amplifier. A multichannel FM magnetic tape recorder was used to record the analog signals from the force measurement system. Data processing and analysis were accomplished by the cutting laboratory computer system.

BIT TYPES AND CHARACTERISTICS

A total of eight bit types were used in these tests (fig. 8). It was possible to examine only one bit of each type due to the lengthy nature of the tests and budget limitations. The authors realize that this does not represent a statistically significant sample of the bits. However, the authors feel the results underscore important ideas that are generally poorly understood and relatively unavailable to the mining community. Additional bit wear studies are currently being conducted at the Bureau's Twin Cities Research Center and a more complete and statistically significant data base will be published in the near future. These preliminary results have been published in an effort to more rapidly transfer the most recent advances in the Bureau's bit wear knowledge.

Three of the eight bits used in these tests were of the conical design. Two of the conical tools were commercially available WC bits having included tip angles of 60° and 90°, and the other (called the 90ET) was an experimental design with an exposed oversize WC carbide insert having an included tip angle of 90° (fig. 9). The insert of the experimental bit measures approximately 0.5 in from the bit tip to the base of the insert, which forms the obvious shoulder visible in figure 9. The design was oversized to reduce bit wear and incendivity by using WC to protect the tool steel body of the bit. All conical tools were mounted with a 45° attack angle and 0° skew angle (the longitudinal axis of the bit lies in the same plane as the drum-bit tip radius) during the tests.

All of the bits with PDC inserts did not use the same diamond compact materials. The 0° rake and -20° rake tools had GE Stratapax[5] inserts while the others used GE's thermally stable Geoset inserts. Both of these materials, for purposes of this paper, are referred to generically as polycrystalline diamond compacts (PDC).

The remaining five bits were of the radial design, only one of which, the round-nose radial, was commercially available (fig. 10). All of the radial bits have had their bit block end shortened to fit the mounting block used in the tests.

The round-nose radial bit utilizes a flat-faced WC insert mounted to provide a +5° rake angle and a +10° clearance angle. The parrot PDC is a round-nose radial with a 110° V-face, +6° rake angle, +4° clearance angle, and a main insert of WC, into the tip of which has been brazed a small, vertical, cylinder of the thermally stable PDC material. The three-insert PDC is similar to the parrot PDC, having a 110° V-face, +6° rake angle, +8° clearance angle, but, in addition to the small, vertical, cylindrical PDC insert, two rectangular thermally stable PDC inserts have been mounted angularly along the face edges to protect the cutting edge of the main WC insert. The 0° PDC bit has a 0° rake angle, +17° clearance angle, and an insert composed of a thin (approximately 0.02 in) layer of PDC material sintered to a 0.10-in-thick, 0.5-in-diam, WC substrate. The -20° PDC is similar to the 0° PDC bit, except that its rake and clearance angles are -20° and +20°, respectively. Both the 0° and -20° PDC's have one small rectangular PDC insert, each mounted in the clearance area behind their main inserts in order to mitigate the effects of wear on the clearance side of the tool steel bit bodies.

The Co content of the WC inserts of five bits was determined by atomic absorption and X-ray spectrographic techniques. The -20°, parrot, and three-insert PDC bits were not measured as their inserts were unavailable for testing. Results of these tests are presented in table 1.

[5]Reference to specific trade names or manufacturers does not imply endorsement by the Bureau of Mines.

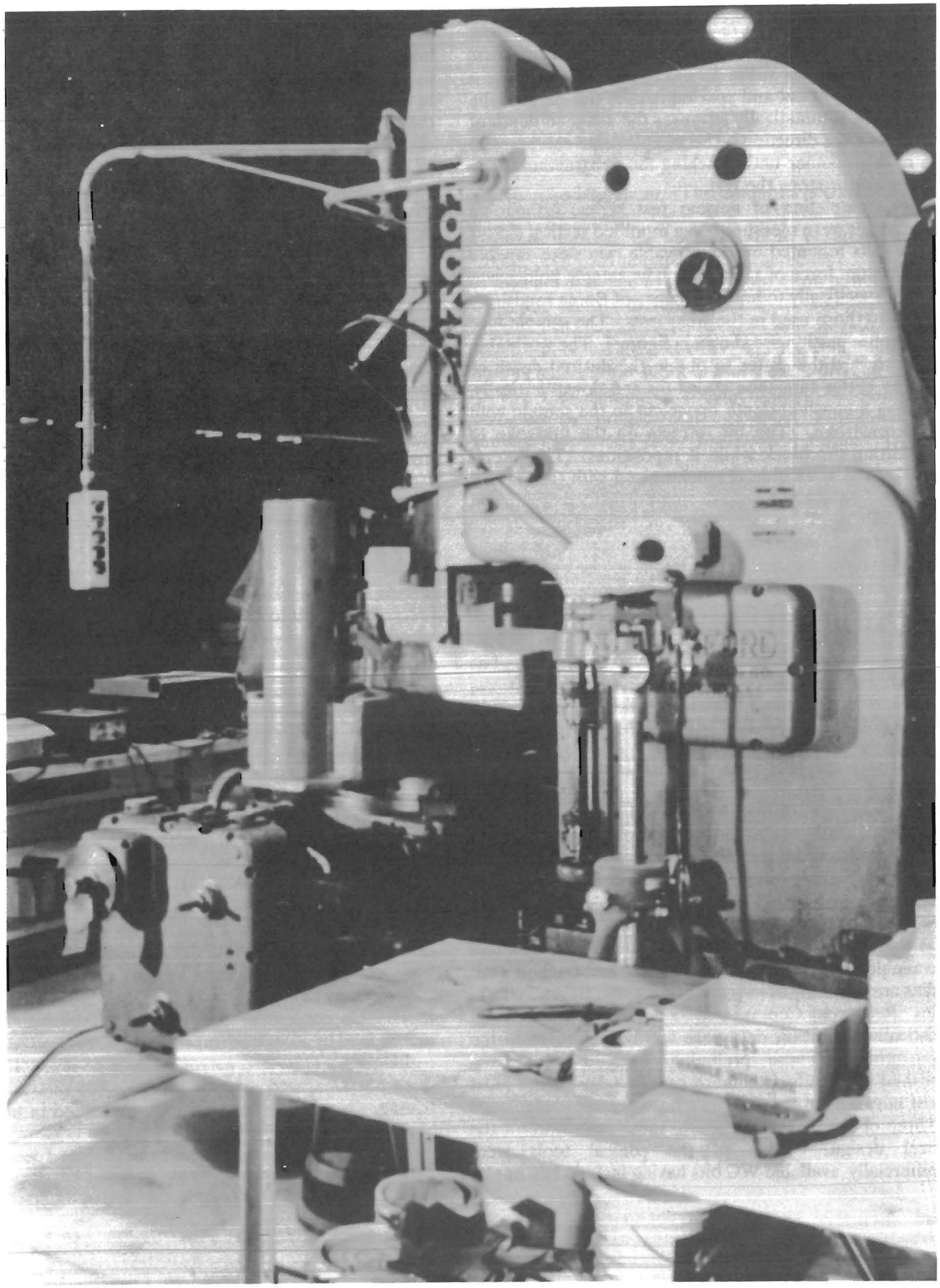


Figure 6.–Vertical slotter.

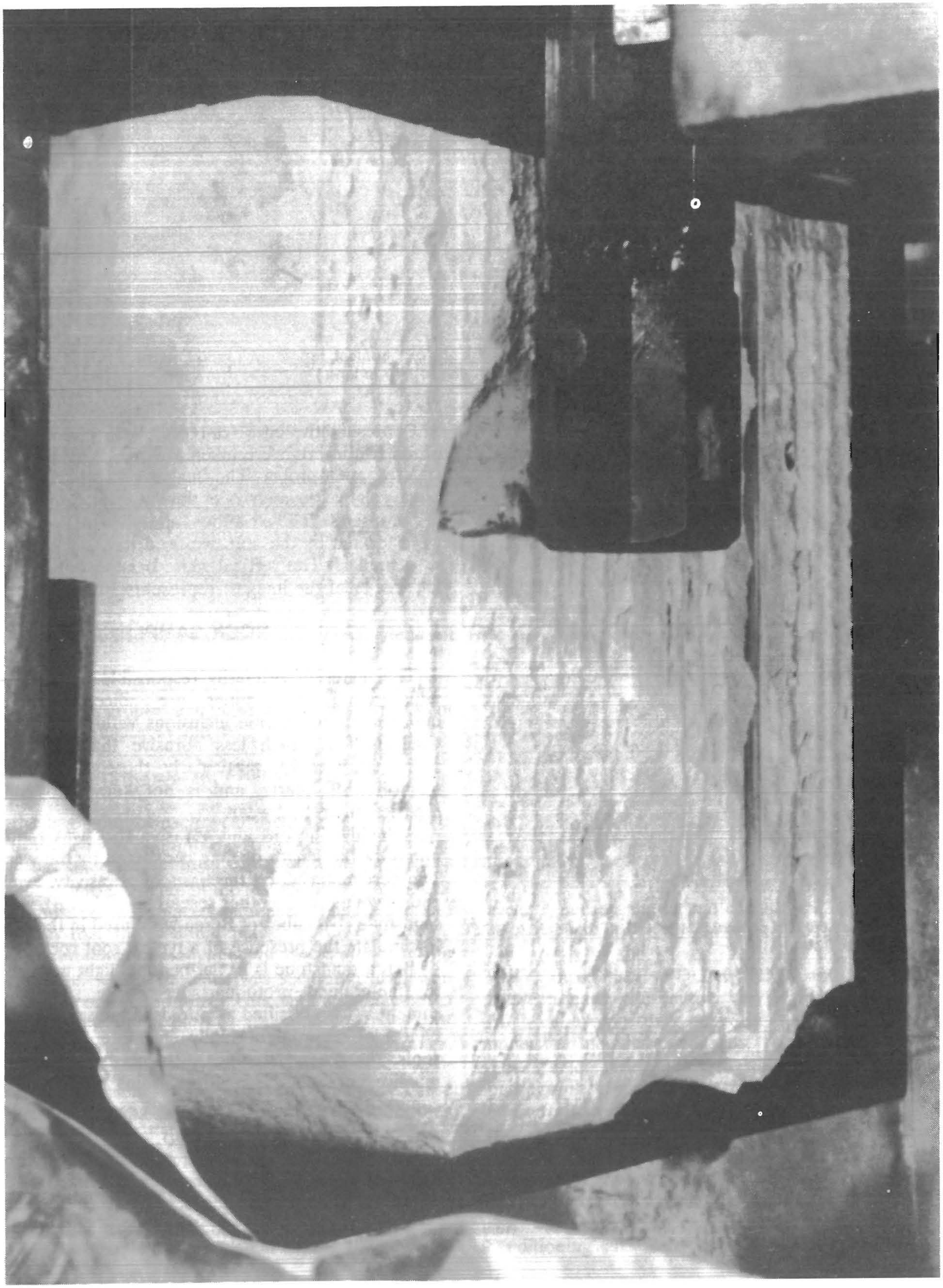


Figure 7.–Force measurement configuration.

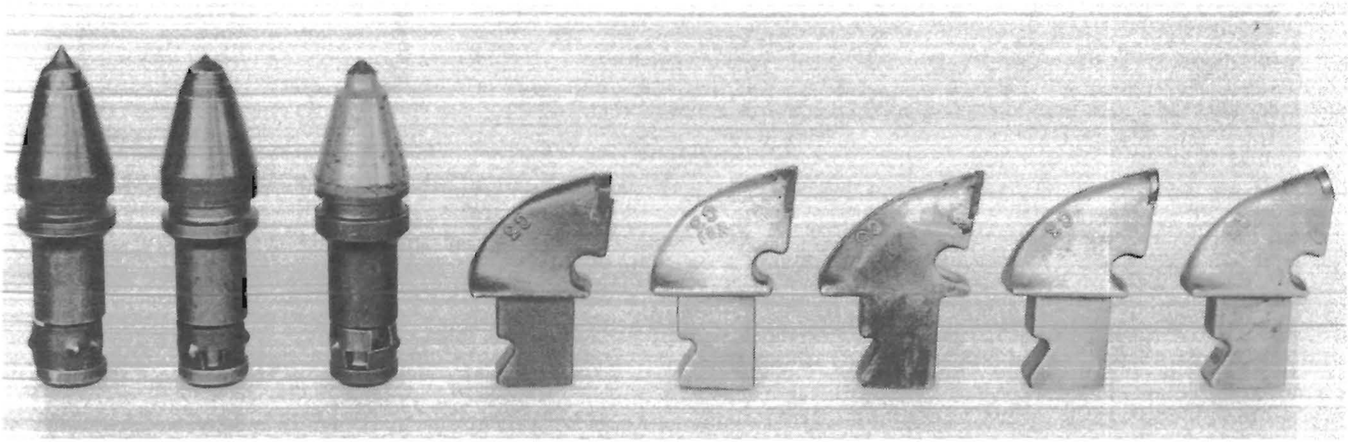


Figure 8.–Bits tested. (From right to left: 60° conical, 90° conical, 90ET conical, round-nose radial, parrot PDC, three-insert PDC, 0° PDC, -20° PDC; 60° conical is 4.85 in long, and round-nose radial is 3.15 in long.)

Figure 9.–Close view of conical bits tested. (From right to left: 60°, 90°, and 90ET bits.)

TABLE 1. – Cobalt contents of the tungsten carbide inserts of five bits used in the wear tests

Bit	Co, wt pct
Round-nose radial	9.7
0° PDC	12.8
Conical:	
60°	12.8
90°	13.9
90ET	7.9

Representative back-scattered electron images (fig. 11) of the five inserts were taken at X 4,000 using JEOL 733 electron microprobe. The images provide a general idea of the relative geometries of the WC grains and Co matrix of the inserts. The striations faintly visible in each image were formed by the abrasive used to polish and prepare the samples. The vertical white bar located in the lower left corner of the images represents 10 μm length.

ROCK SAMPLE

The materials primarily responsible for tool wear in underground coal mines are siliceous roof rock, middleman, and pyritic inclusions within the coal seam. Coal itself is much less abrasive than its associated sedimentary rocks, particularly those containing large quantities of quartz, and is not known to contribute significantly to tool wear.

A highly siliceous and abrasive rock was required to minimize the length of time consumed by the wear tests. The best material, on the basis of abrasivity, availability, and previous use by other researchers (*1, 5, 8*), was Berea sandstone; 1-ft cubes of Berea were used in the wear tests to simulate the presence of a typical roof rock.

Berea sandstone is a flat-bedded, light gray, medium- to fine-grained protoquartzite with a silica and clay cement. It is classified as a feldspathic sandstone, and is typical of material normally encountered in coal mine roofs, floors, and partings. Its petrographic texture is massive, granular, sand-size grains of quartz. The composition of Berea sandstone is as follows, in percent:

Quartz	77.5	Muscovite	0.5
Feldspar	16.0	Carbonate	0.5
Kaolinite	5.0		

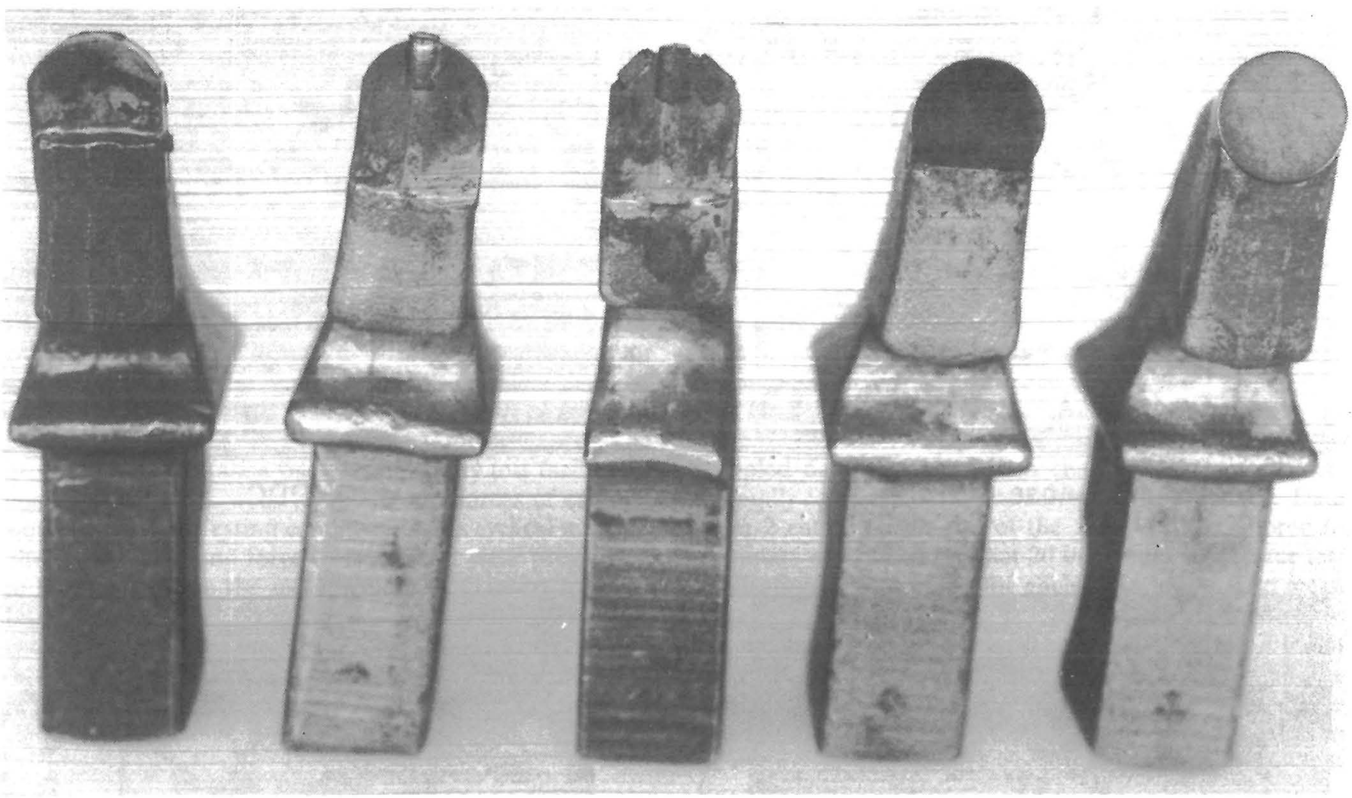


Figure 10.–Close view of radial bits tested. (From right to left: round-nose radial, parrot PDC, three-insert PDC, 0° PDC, and -20° PDC.)

A complete petrographic and physical property description is found in references 44 and 49.

EXPERIMENTAL PROCEDURE

At the beginning of each wear cycle, the group of bits being examined was taken to the rotary test facility, where one bit was selected and installed, along with the proper tool holder, onto the drum in the test chamber. A cube of Berea sandstone was placed in the sample holder and oriented so that the bedding planes of the rock were vertical to minimize the spalling of the sample bottom during cutting. After the rock was securely clamped in place, a series of 0.0625-in-deep cuts, with a spacing of 0.5 in between adjacent bit path centers, and a bit speed of 565 ft/min (60 rpm), was made across the sample face. The relatively shallow depth of cut and high bit speed were selected to represent a CM trimming a roof. These conditions would maximize tool wear rates, and thus minimize the length of time consumed by the wear tests. Upon completion of each pass across the face, the sample holder automatically advanced 0.0625 in toward the drum, and the cycle repeated. Cutting continued in this manner until the bit path nearly intersected the translating table supporting the sample, at which point cutting was stopped. The sample was then either repositioned if more volume remained to be cut, or replaced. The number of sandstone cubes cut prior to the measurement of a bit's cutting and normal forces on the vertical slotter was determined by the amount of footage cut and wear exhibited. Cutting was stopped after a predetermined number of cubes were cut, based on the anticipated life of the bit, or when a sudden and significant geometry change (i.e., fracturing of an insert) occurred in the bit tip. Thus, during each wear test cycle, generally one to two cubes were cut by the round-nose radial bit, two to four by the 60° and 90° conicals, four to six by the parrot PDC, and up to eight by the 90ET, three-insert PDC, 0° PDC, and -20° PDC bits between each consecutive set of force measurements. Each cube represents approximately 2,400 ft of cutting under the specified conditions.

After each wear test cycle, the bits were weighed and photographed prior to the measurement of their cutting and normal forces on the vertical slotter. Each force test began by installing a bit in its appropriate tool holder on the slotter's movable ram. The sample of Berea sandstone was placed in the sample holder with its bedding plane oriented parallel to the direction of cutting. The sample was clamped in place, and a series of interactive conditioning cuts were made to provide a more natural

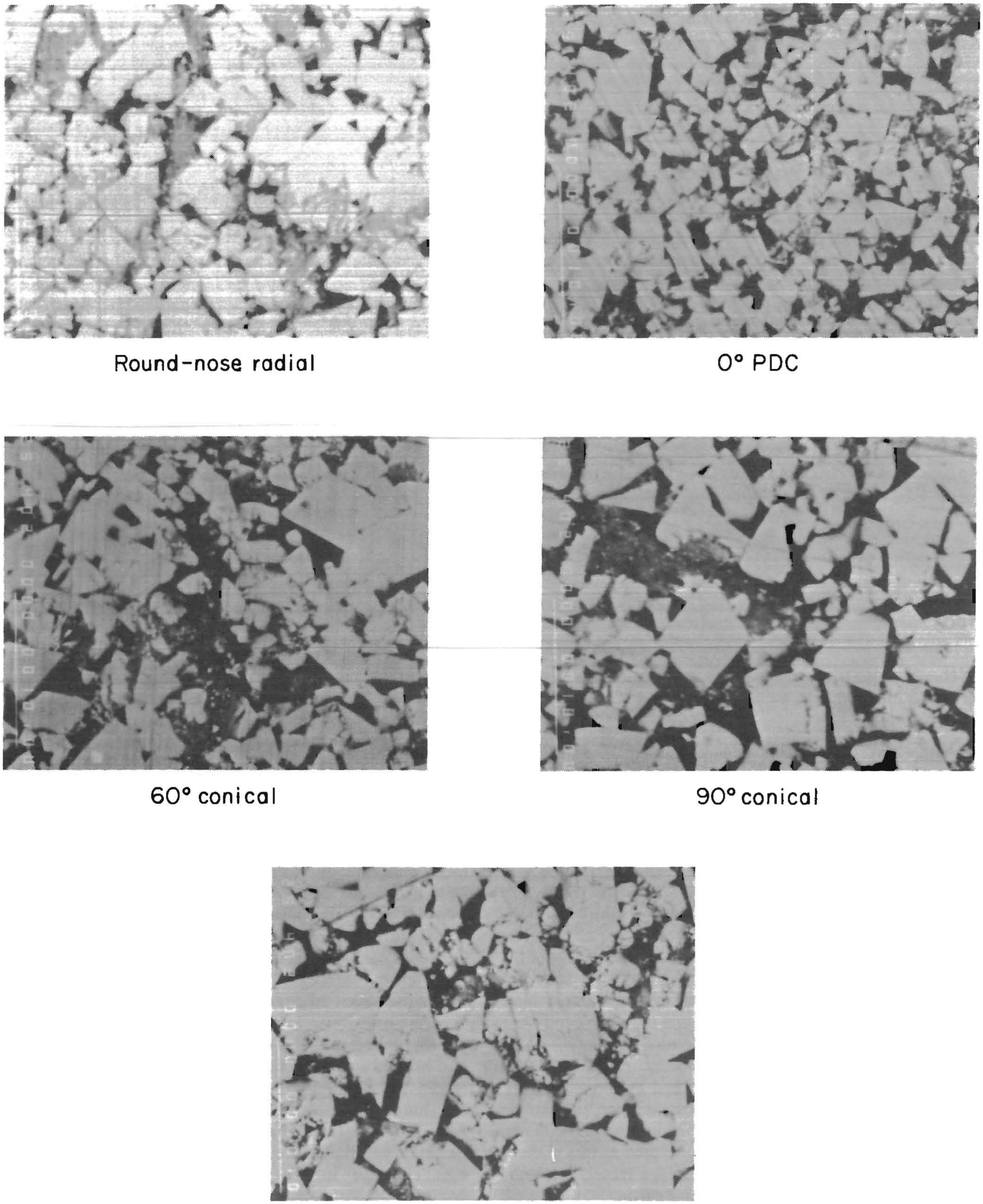


Figure 11.–Back-scattered electron images of the tungsten carbide inserts of five bits used in wear tests (X 4,000).

cutting surface truly parallel to the crossfeed direction. The worktable was infed to produce a 0.25 in depth of cut and positioned laterally so that the first cut of the subsequent force test occurred at the extreme edge of the sample. The crossfeed increment control was set to provide a spacing of 0.5 in between adjacent bit path centers, and a voice announcement of the test number and conditions was placed on one channel of the tape recorder at playback speed (3.75 in/s). The recorder was then adjusted to data recording speed (15 in/s), and the slotter engaged to produce a series of parallel vertical cuts across the sample face at a bit speed of 12 in/s. Bit forces during cutting were measured by a three-axis force dynamometer and recorded on the FM magnetic tape recorder. A complete force test was defined as the series of 20 to 22 cuts resulting from one pass across the sample face. The group of bits was taken back to the rotary test facility for continuation of the wear tests once the forces of each bit were measured. Testing continued in this cyclical manner, alternating wear and force tests until bit wear progressed to the point where the main WC or PDC insert for each bit was destroyed or lost. Cutting and normal forces were usually observed to rise dramatically once the inserts were destroyed, and the bits were subsequently defined as being "worn out" and withdrawn from the wear and force test series.

DATA RECOVERY

The data reported in this paper are distance cut (ft), degree of wear (pct wt loss), cutting force (lbf), normal force (lbf), and resultant force (lbf). Tabulated data, graphed data, photographs of stages of bit wear development, and excerpts of pertinent subjective auditory and visual observations from the experiment notebook are presented in appendixes A, B, C, and D, respectively.

Distance cut was determined by multiplying the number of cuts made with each tool by the arc length of the cut (nominally 1 ft). Degree of wear was quantified by measuring the weight loss of the tool and is expressed as a percent loss of the original tool weight.

Bit force data were recovered from the tape onto which they were recorded during the force tests by playing the tape back into an analog-to-digital converter interfaced to a computer where the bit force signals were sampled at 500 Hz per channel. Average force values for each cut were obtained by taking the arithmetic mean of the sampled data points for each channel. Each force test normally consisted of 24 cuts across the sample face. Data from 2 cuts on each end of the sample were ignored to eliminate end effects, so that 20 individual cuts (force test replications) were made for each wear level. The mean values obtained for these cuts were again averaged to obtain the final value reported in this paper. The resultant force was calculated by taking the vector sum of the cutting and normal forces. Although a net lateral force was usually observed during cutting, it was small enough to be considered negligible in the calculation of the resultant force.

DISCUSSION OF RESULTS

As discussed in the "Bit Types and Characteristics" section, the results described herein were taken from tests on only one bit of each of eight bit types, for a total of eight bits. Although this does not represent a statistically significant sample of the bits, the results underscore important ideas that are generally poorly understood and relatively unavailable to the mining community. Additional bit wear studies are currently being conducted at the Bureau's Twin Cities Research Center, and a more complete and statistically significant data base will be published when it is available. Owing to the lengthy nature of the tests, these preliminary results have been published in an effort to more rapidly transfer the most recent advances in the Bureau's bit wear knowledge.

The discussion in this section is based upon results presented in several formats.

Raw numerical data from the wear and force tests are presented in appendix A, table A-1. These data have been graphed to examine the relationships between cutting distance and resultant force, cutting distance and bit weight loss, and weight loss and resultant force. Composite graphs for the radial and conical bits are found in this section (figs. 12–13), and composite graphs for all eight bits tested are shown in appendix B (fig. B–1). For the sake of clarity, particularly with regard to the weight loss versus resultant force data, graphs for individual bits have also been included in appendix B.

Photographs of the bits were taken at intervals throughout the wear test. Selected photos illustrating the various stages of wear development for each bit are found in appendix C. Nearly all photos contain images of two bits, the new bit on the left being included as a reference to the worn bit on the right, unless otherwise specified. A typical photo is included in this section (fig. 14).

Qualitative visual and auditory observations of the bits and related equipment were recorded throughout the wear tests. Selected excerpts from the experiment notebook are found in appendix D. They include subjective comments on system vibration relative to bit geometry changes and references to visual hot spots (streaking) pertinent to ignition potential. These observations are important indicators of bit performance and should serve not only to guide other researchers in designing further experimental work, but also to assist operators to enhance the safety and efficiency of the mine environment.

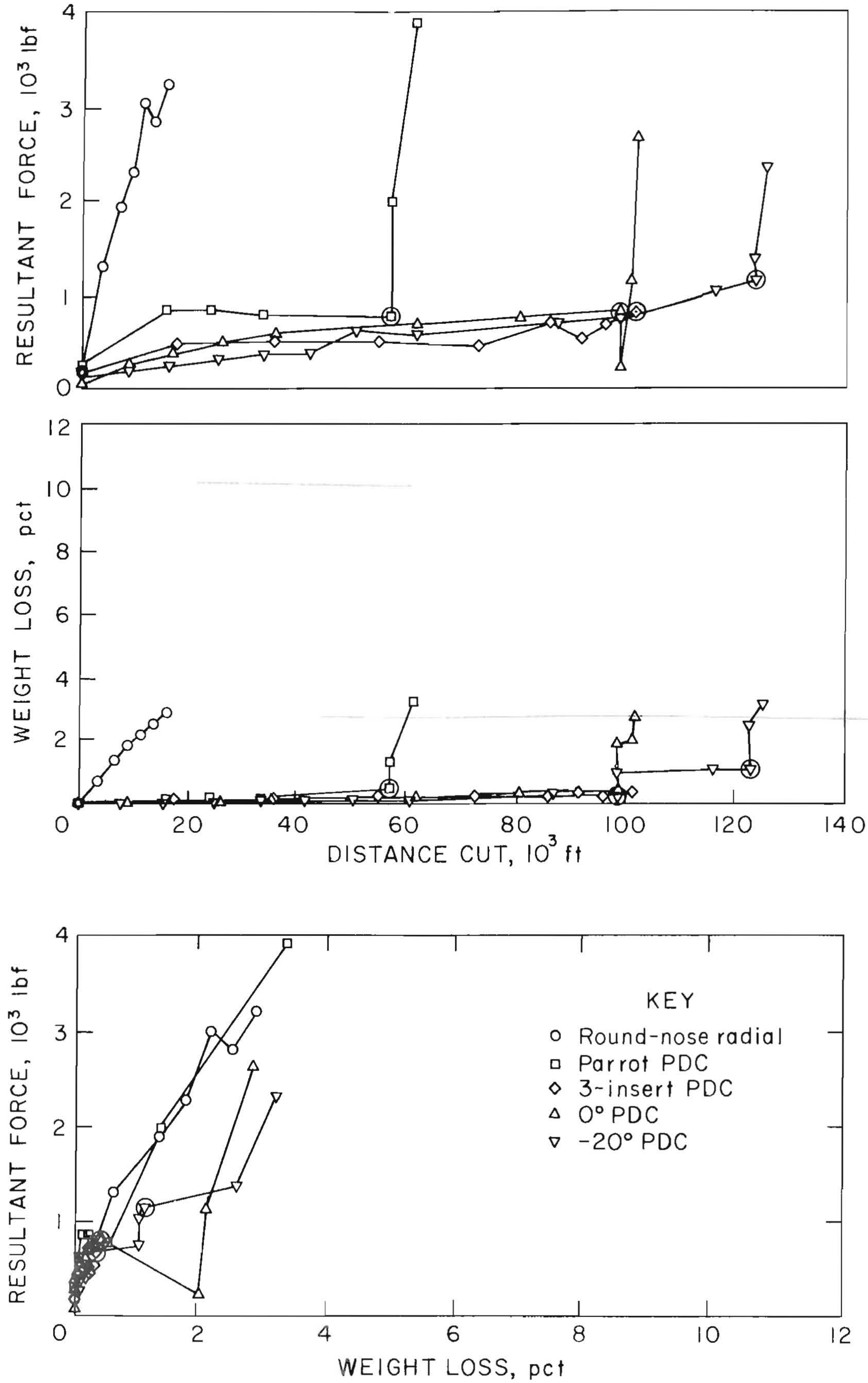


Figure 12.–Composite performance graphs for all radial bits tested.

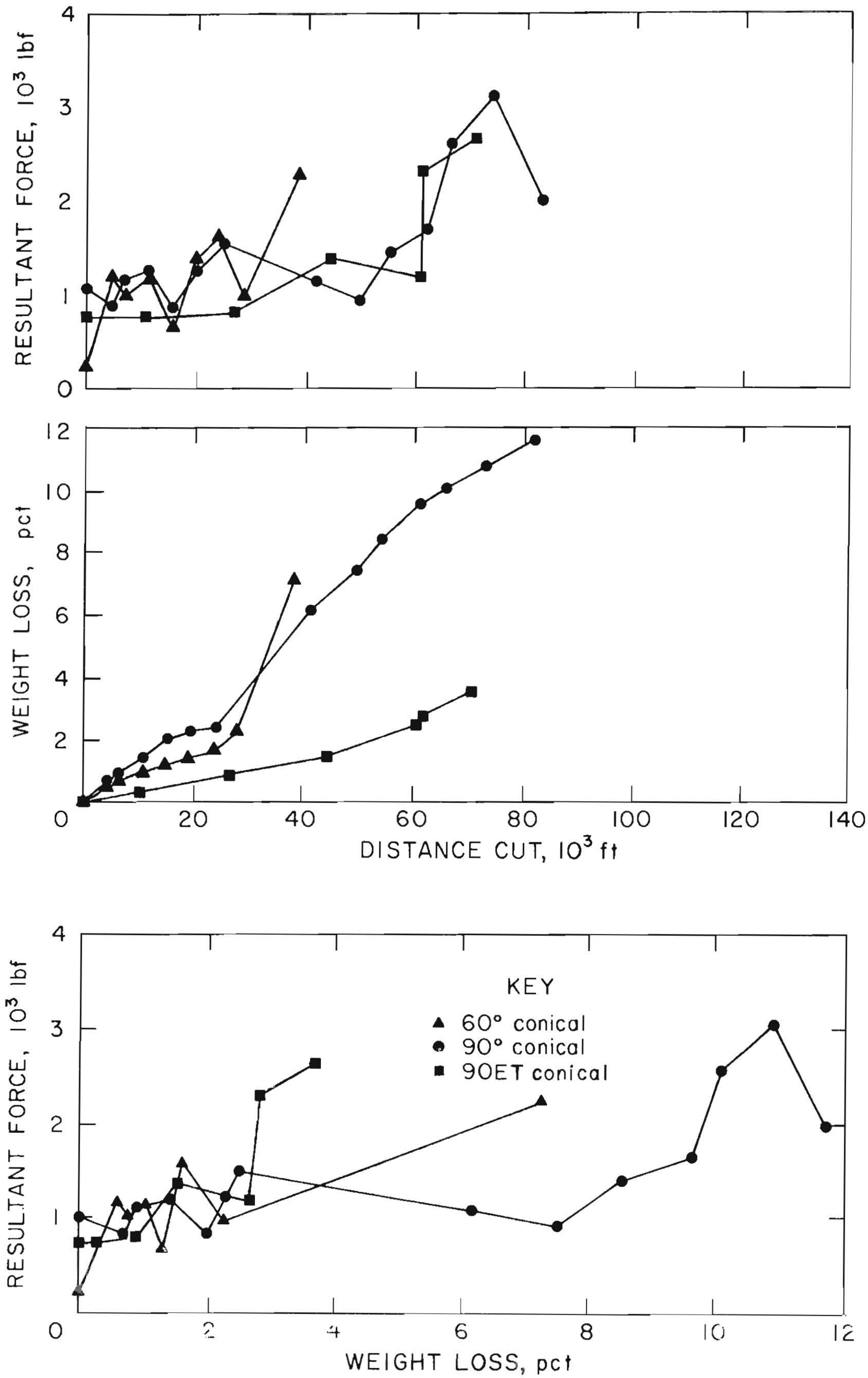


Figure 13.–Composite performance graphs for all conical bits tested.

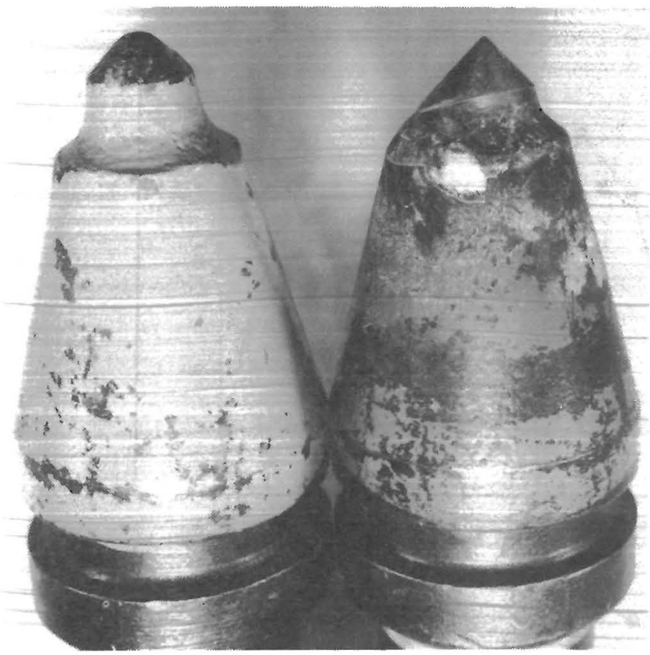


Figure 14.–Front view, 90ET. (Left, new bit; right, asymmetrically worn bit at a cutting distance of 27,000 ft.)

BIT PERFORMANCE

Examination of the results of the wear and force tests shows that the bits tested can be grouped into three general categories based on their performance. Generalized distance versus force curves for each of the three categories are drawn from the data presented in figures 12 and 13. These generalized curves are shown in figure 15. Curve I represents nonrotating bits having WC inserts; curve II, rotating bits with WC inserts; and curve III, nonrotating bits with PDC inserts.

Characteristics of category I performance include bit forces and wear rates (figs. 12-13, 15; appendix B) that increase rapidly and linearly with cutting distance, a relatively small weight loss prior to bit failure, and a relatively short bit life. The round-nose radial bit was the only bit tested that exhibited this behavior because it was the only radial bit tested not having a PDC insert. These results are believed to be typical of all conventional, wedge-shaped, nonrotating bits having WC inserts, but additional testing is being done to confirm this finding.

Bit forces increased generally hyperbolically and wear linearly with cutting distance for bits in category II. Both forces and wear increased more slowly than for the first category. A relatively large quantity of weight was lost prior to bit failure, with the result that tools in the second category had longer lives than that in the first. Three of the bits tested, the 60°, 90°, and 90ET conicals, belong in this category. These results are believed to be typical of all conventional, rotating, conically shaped tools with WC inserts. The 60° conical bit was locked in its holder at 23,928 ft. Once its rotation was prevented, the 60° bit exhibited the behavior characteristics of category I.

The four PDC bits are grouped into category III. Bit forces and wear for this category were roughly equivalent to those of the other categories only during the first few hundred feet of cutting. PDC wear characteristics were such that subsequent force and weight loss increases with cutting distance were relatively small. Thus, the force and wear rate curves remained nearly horizontal until bit wear advanced to the point that the PDC inserts could no longer be retained in their mountings. Performance radically changed once the main PDC insert of each bit was thrown, with the force and wear curves assuming the steep, nearly vertical slopes characteristic of category I.

Although it was possible to group the bits tested into general performance categories, the characteristics of each bit are sufficiently unique to merit a discussion of their individual behaviors.

Round-Nose Radial

The round-nose radial bit had the shortest life of the eight bits tested. Wear-flat development occurred rapidly, as is characteristic of nonrotating bits with WC inserts, altering bit geometry such that the required resultant force climbed quickly and linearly with cutting distance. The critical temperature at the clearance side of the bit had been exceeded at 9,264 ft as evidenced by the presence of melted tool steel and melted and recompacted quartz (appendix C, (fig. C-1*B*). The round-nose geometry and shallow depth of cut (0.0625 in) resulted in a relatively small area of the bit contacting the rock when the bit was new. Due to the radial bit geometry, the contact (wear flat) area enlarged, with its width generally being constant but its length increasing, as wear progressed into the steel body. Frictional sparking became increasingly common as bit wear advanced (appendix D). The use of this bit must be restricted in gassy environments to the period prior to the attainment of the critical temperature after which sparking becomes more prevalent.

Parrot PDC

The parrot PDC is similar to the round-nose radial except for the V-face WC design and the addition of a small, cylindrically shaped insert in the bit tip. The PDC insert served to protect the carbide bit tip and greatly slow the wear rate of the adjacent WC cutting edges. The geometry of the cutting edge initially changed quickly as the bit adjusted to the cutting conditions, resulting in a moderately rapid increase in the required resultant force between 0 and 15,864 ft. After attaining the optimum geometry for the given conditions, however, the wear rate slowed to such a degree that the resultant force remained essentially constant over the next 40,000 ft of cutting. No frictional sparking and only light machine vibration and noise were observed during these same intervals.

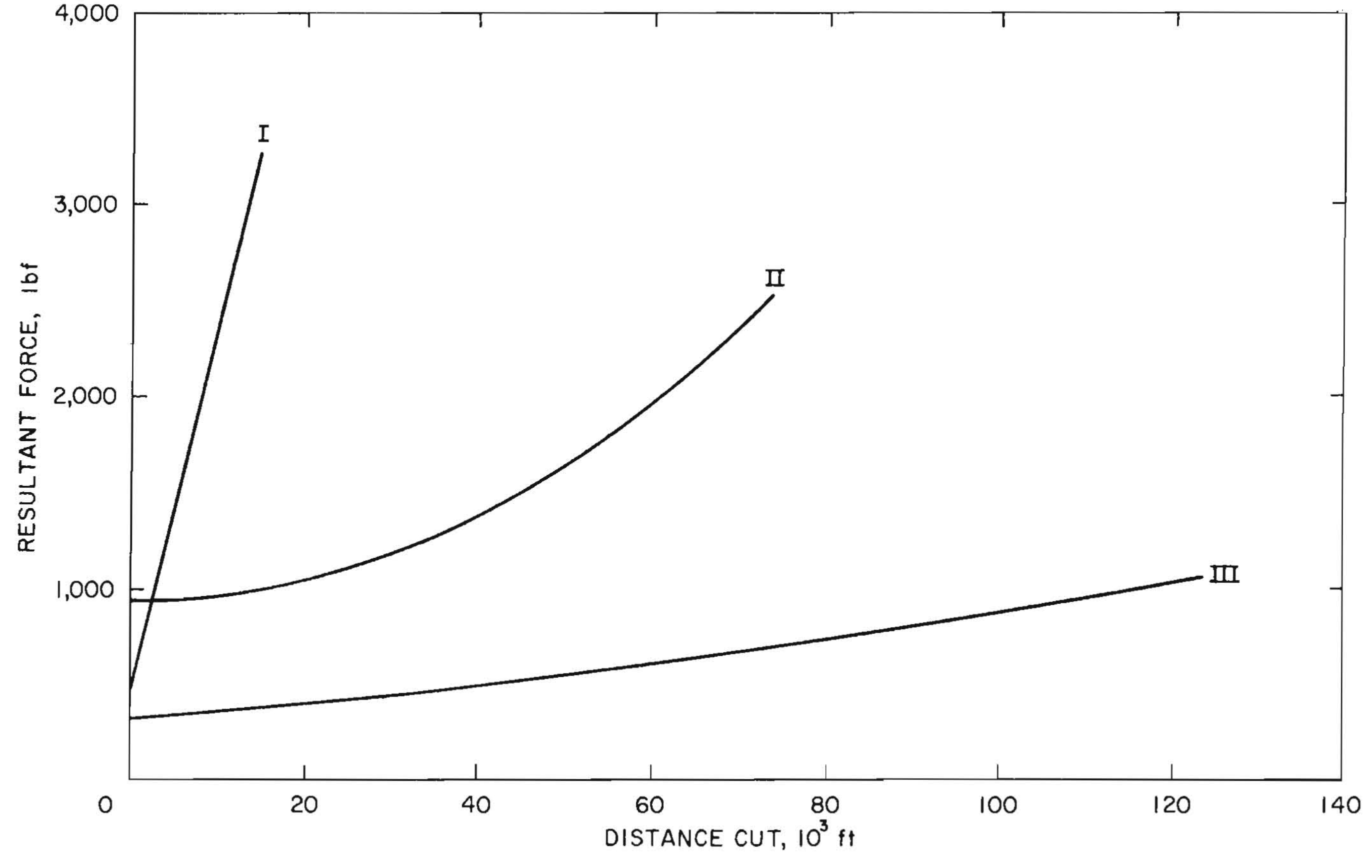


Figure 15.–Generalized curves illustrating typical performance of three categories of bits.

The PDC insert fell out at 57,000 ft of cutting as a result of excessive wear of its WC support. The data points at that distance, as well as the corresponding failure points for the other PDC bits, were extrapolated by averaging the force and wear rates over the preceding two sample intervals. After loss of the PDC insert, the force and wear rates, frictional sparking, and machine vibration and noise increased dramatically. The critical temperature, evidenced by the presence of melted and recompacted quartz on the bit, was exceeded only after the loss of the PDC insert. The addition of the PDC insert, therefore, effected a fourfold increase in the operating life of the round-nose radial design.

Three-Insert PDC

The three-insert PDC is essentially identical to the parrot PDC except for the addition of two rectangular pieces of PDC to protect the cutting edge of the WC. The weight loss and resultant force required by the three-insert bit were significantly lower than that of the parrot PDC prior to the loss of the side inserts at 95,736 ft, due to the absence of a large area extending into the WC support. Only occasional minor frictional sparking, and light machine vibration and noise levels, were observed throughout the tests. Testing of this bit was stopped shortly before the center PDC insert fell out during a subsequent force test. Bit performance after the last data point at 101,184 ft was expected to be similar to the performance of the parrot PDC with one insert after 57,000 ft. Thus, the addition of the two rectangular PDC inserts extended the life of the single-insert parrot PDC by approximately 44,000 ft.

0° PDC

The wear and resultant force rates of the 0° PDC were nearly identical to those of the three-insert PDC prior to the premature loss of the insert of the 0° PDC. Only one instance of minor frictional sparking and machine vibration, and higher noise levels was observed over the same interval. The forces remained low until shortly after loss of the insert. Failure of the brazing used to bond the WC support to the tool steel body occurred at a cutting distance of 98,644 ft. This appeared due to either impact fatigue of the braze material or a poor-quality braze. The insert is estimated to have a remaining life of at least 100,000 ft, as no cracking or heat discoloration of the insert or bit body was visible.

Immediately after the separation of the insert from the bit body, the forces were measured. The resultant force was found to have dropped significantly, as indicated in figure B-5, because the cutting edge of the tool steel bit was essentially new and sharp. The resultant force increased rapidly, however, over the next 2,000 ft of cutting, as a large wear flat quickly formed in the relatively soft body steel. The wear rate increased over the same interval, but not as rapidly as the force rate, since the PDC clearance insert remained intact and served to protect the bit tip to some degree. The clearance insert fractured at 100,440 ft, assuring the attainment of the critical temperature, with an immediate resulting increase in frictional sparking intensity, machine vibration, and noise levels. This tool should provide 10 to 20 times the bit life of the standard round-nose radial design if the brazing technique is improved to keep the PDC insert in the bit body until significant insert wear develops.

-20° PDC

This bit is identical in construction to the 0° PDC except that its insert is mounted to provide a -20° rake angle. The required resultant force rate was nearly always slightly less than, and the wear rate essentially identical to, that of the 0° PDC prior to the accidental fracturing of the -20° PDC's main insert (see appendix D for detailed description of geometry change). Heavy machine vibration and noise levels were recorded, beginning at a cutting distance of 62,267 ft and continuing until the fracturing of the insert at 98,619 ft. This was apparently induced by the bit's large, negative rake angle, as this can reportedly cause excessive vibration in LW shearers (*22*). Noise and vibration levels fell dramatically, and the wear rate remained low, when cutting was resumed with the "modified" bit, although the resultant force continued to increase. Insert width was significantly reduced relative to the undamaged bit, causing a reduction in the impact force and an increase in the cutting efficiency, as evidenced by the subjectively determined size increase in the cuttings, for the given spacing and depth of cut combination. Curiously, most of the large chips in the cuttings were found in a pile off to the side of the bit that had been sheared off, possibly as a result of being deflected there after impacting the newly formed angle of the fracture surface in the body steel behind the main insert (fig. C-5*G*, *H*). The remaining part of the main PDC insert, and a small part of the clearance insert, separated from the bit body at a cutting distance of 122,815 ft after the rock sample split, allowing part of it to fall forward and jam between the bit body and the worktable. The resultant force, wear rate, and noise and vibration levels, subsequently increased dramatically (fig. 12). Only a relatively small amount of sparking was observed until the front two-thirds of the PDC clearance insert broke away at 124,543 ft. The insert apparently protected the bit tip and prevented attainment of the critical temperature. Once the clearance insert was no longer in place, however, the critical temperature was easily reached, as evidenced by the large quantity of melted and recompacted quartz in appendix C, figures C-5*M* and C-5*N*. The forces and wear rate then increased significantly. This tool is suitable for cutting the most difficult sedimentary rock. The excessive noise and vibration levels suggest the use, however, of a bit with a more positive rake angle, such as the 0° PDC.

60° Conical

This bit initially required the lowest resultant force of the three conical bits tested, owing to the narrow profile of the bit tip. Wear quickly altered the bit tip geometry and induced a large amount of frictional sparking as the bit adjusted to the cutting conditions, so that at a cutting distance of approximately 6,600 ft, the 60° bit required the highest resultant force of the three conical bits. Thereafter, to a cutting distance of about 23,900 ft, the profiles of the 60° and 90° conicals were very similar, resulting in nearly identical resultant force rates. The wear rate of the 60° bit was lower than that of the 90° conical over the same interval. Bit rotation was not continuous for any of the conical bits tested, resulting in a sporadic pattern of asymmetric wear that varied in amount for each bit. Although an attempt was made to eliminate the effect during force tests by positioning each bit so that its largest wear flat formed the bit clearance angle, the asymmetry is believed to be responsible for the relatively large amount of scatter in the conical force data compared with the radial bit data. This same scattering effect is evident in graphed data reported by other researchers (*14*) in a field comparison of radial and conical bit designs.

The geometry and performance of the 60° and 90° conicals were similar up to a cutting distance of about 23,900 ft. Since both the 60° and 90° bit had achieved essentially the same geometry by rotating freely, the 60° bit was locked in its holder to evaluate the effect of bit rotation on performance. After an additional 4,700 ft of cutting, the resultant force dropped. This is considered to be due to the fact that the large negative clearance area present immediately after rotation stops is worn away and replaced by a large wear flat having a clearance angle of nearly zero. As cutting continued, forces, wear rate, frictional sparking, and machine vibration and noise increased significantly. When the carbide insert fell out of the bit at a cutting distance of 38,520 ft, testing was discontinued.

90° Conical

The 90° conical initially required the highest resultant force of all eight bits tested due to its large included tip angle and relatively wide tool tip. A large amount of frictional sparking was noticed during the first several thousand feet of cutting as the tool adjusted to the conditions. Sparking abated after this initial geometric change and was minimal over the next 35,000 ft of cutting. The resultant force rate increased hyperbolically, and the wear rate linearly, over the life of the tool. Machine vibration, noise, and sparking intensity became particularly evident after about 40,000 ft of cutting. Melted and recompacted quartz was noticed on the bit at 54,974 ft (fig. C-7*D, E*), indicating that the critical temperature had been reached. Chipping and cracking of the carbide insert was first observed at the same distance. Separation of the insert from the bit body occurred at 61,766 ft (fig. C-7*H, I*) as a result of normal wear processes. Machine vibration and noise subsequently remained fairly heavy owing to the relatively large wear area in contact with the rock, but frictional sparking was surprisingly light until testing was discontinued at 83,150 ft.

Bit rotation was inexplicably relatively more continuous toward the beginning and end of the life of the 90° bit. The large wear flat evident in the photos at 54,974 ft (fig. C-7*D, E*) indicates that rotation was nearly nonexistent at that point. A comparison of the lives of the 60° and 90° bits clearly shows that assuring the rotation of conical bits is a major factor in maximizing bit life, although the force levels required by rotating and nonrotating bits are similar. It should be remembered, however, that rotation does not maintain bit sharpness. As Hurt (*17*) has pointed out, rotation only assures symmetric blunting. Frictional sparking seems to be induced when rotation is inhibited, as has been previously reported (*1*).

90ET

The particular bit tested had its oversize WC insert skewed at an angle of about 1.5° off the longitudinal axis of the bit. The bit wore asymmetrically (fig. 14) throughout its life, but the misalignment of the insert appeared to have a minimal effect on the wear pattern. Sparking intensity, machine noise, and vibration varied widely over the life of the bit, seemingly in relation to changes in the clearance angle, and consequently normal force, that occurred with the intermittent rotation of the asymmetric bit.

The resultant force and wear rates increased hyperbolically and linearly, respectively, over the life of the bit. Force levels were initially low as only the insert was cutting the rock. After about 24,000 ft, wearing of the wide, abrupt shoulder of the tool steel bit body began and forces increased quickly. The degree of scatter in the force data also appeared to increase once the bit body wear had started.

Extensive cracking of the carbide insert was evident at 61,008 ft (fig. C-8*C, D*) and approximately one-half of the insert fractured away at 61,704 ft. The resultant force subsequently increased markedly, so testing was discontinued at 70,776 ft.

A comparison of the performance of the 90° conical and 90ET bits indicates little significant difference between them. Although the required resultant force was initially somewhat lower, the force rate of the 90ET increased more rapidly than that of the 90° conical. Bit life of the 90° conical and 90ET was similar, as was machine vibration and noise. Sparking intensity of the 90ET was unexpectedly high.

BIT WIDTH, SPACING, AND FORCES

One potential problem with the experimental design used for these tests was noticed as the wear tests neared completion. Cutting and normal forces were reported by others (*15, 19, 23*) to increase with tool width, and yet the approximately 1.0-in-wide worn 60° and 90° conicals, and the roughly 0.7-in-wide worn 90ET, were requiring resultant forces nearly equivalent to, or slightly lower than, the 0.5-in-wide worn radial bits. All wear and force tests were run at a spacing of 0.5 in, and it was belatedly realized that only one-half of the width of the worn conicals was actually cutting rock, while the other one-half was merely sliding over the previously cut adjacent bit path. Thus, the measured cutting and normal forces of the conical bits were speculated to be lower, by as much as a factor of 2, than would be the forces of the same bits cutting interactively at a spacing slightly greater than the bit width. The forces of the worn radial bits were thought to be only slightly lower than would be expected. Since spacing equaled bit width for the radial bits, the volume of rock normally encountered in the breakout angle (fig. 3) between adjacent bit paths was missing. This should result in slightly lower required resultant forces relative to interactive cutting at a spacing greater than the bit width.

A brief series of force tests were conducted to clarify this situation. The tests were nearly identical to the original tests but with variations in the spacing between adjacent bit paths and the number of replications of each test. The cutting and normal forces of all eight bits were measured at bit spacings such that, referring to figure 3, $S - W \cong 0.5$ in. Thus, the tests were run at a spacing of 1.0 in for all the radial bits and the 90ET, and 1.5 in for the 60° and 90° conical bits. The results of these tests, along with approximations of wear-flat areas of the worn bits, are found in table 2 and figure 16. Results from the 0.5-in spacing tests are included in figure 16 for ease of comparison. Each test was repeated six times on each bit, except as noted in the table.

Examination of figure 16 shows that, as expected, the resultant forces of the conicals increased, relative to the original tests, more significantly than those of the radials. The forces of the two bit types became more nearly equal when the spacing was increased, except for the results of the three-insert and -20° PDC bits. The results of the three-insert bit test can be explained by noting that its center PDC insert fell out after the 0.5-in spacing tests, and before the 1.0-in test. Thus, the three-insert bit tip changed between tests from a convex PDC surface to a concave WC surface, resulting in a significant increase in the required resultant force. The lowering of the -20° PDC's forces during the 1.0-in test cannot be similarly explained and is considered anomalous.

The wear flats of six of the eight bits were measured to study the relationship between wear-flat area and forces. The 90° conical and 90ET bits were not included because they were free to rotate in their holders throughout the wear tests and consequently did not develop any single,

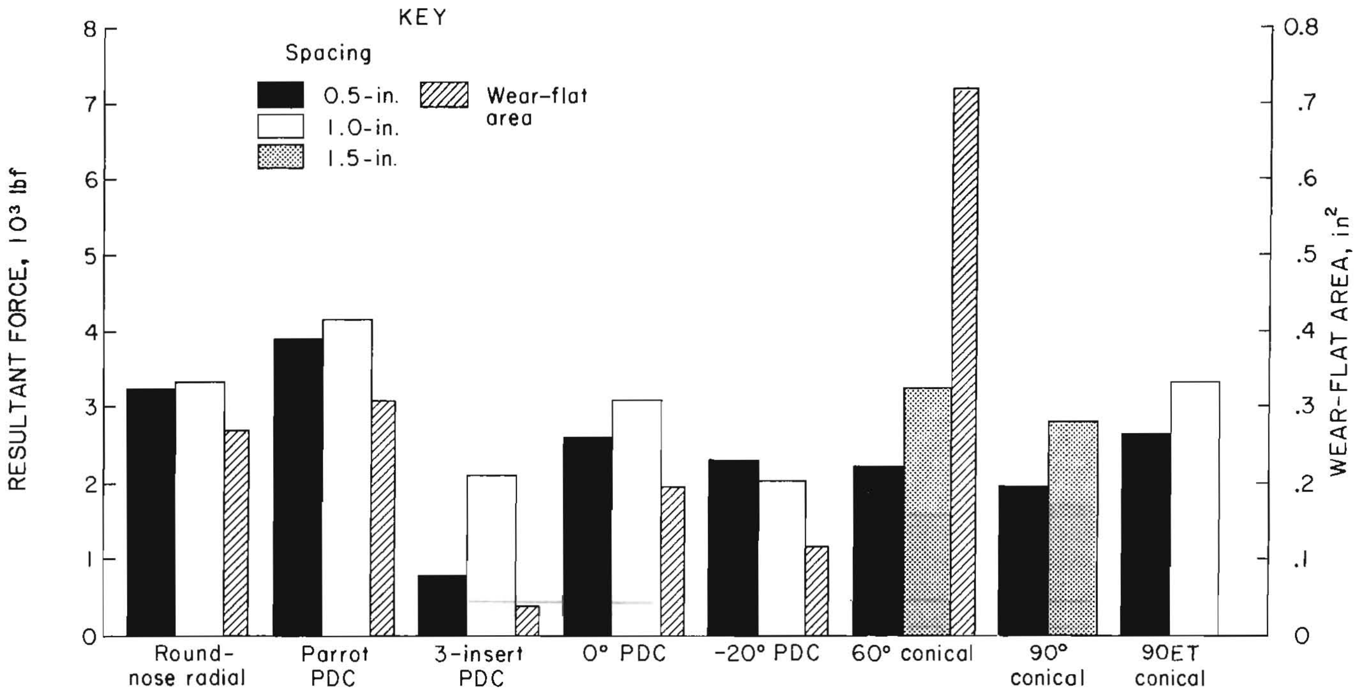


Figure 16.–Histogram of forces and wear-flat areas for spacing tests.

TABLE 2. - Average force and wear-flat data rom the increased spacing tests

Bit	Force, lbf Cutting	Normal	Resultant	Wear-flat area, in²
Round-nose radial	1,863	3,756	3,326	0.27
PDC:				
Parrot	2,263	3,473	4,145	.31
3-insert[1]	1,531	1,455	2,112	.04
0°[1]	1,620	2,659	3.114	.20
-20°	1,353	1,575	2,076	.12
Conical:				
60°	1,589	2,295	3,246	.72
90°	1,669	2,257	2,807	NM
90ET	2,033	2,602	3,302	NM

NM Not measured.

[1]Results averaged from only 5 test replications.

large, asymmetric wear flat. The results in figure 16 show that the resultant force and wear-flat area of all the radial bits are related. The three-insert PDC required the lowest forces and had the smallest wear flat, the -20° PDC was next, and so on; the parrot PDC had the highest forces and largest wear flat. The wear-flat area of the 60° conical, however, is more than twice as large as that of the largest radial, the parrot PDC, although the resultant force of the 60° conical was significantly lower than that of the parrot PDC. The area of the asymmetrically worn 90° conical bit actually in contact with the sandstone during cutting is estimated to be roughly two-thirds as large as the wear-flat area of the 60° bit. The area for the 90ET is probably somewhat smaller, but is still larger than that of the parrot PDC. The forces of the 90° and 90ET bits are significantly lower than those of the parrot PDC. A possible explanation for these discrepancies is that the geometries of the radial and conical designs are sufficiently dissimilar to account for the different wear-flat area versus resultant force performance characteristics, or, that the geometry of the bit mounting configuration may have changed slightly for the conical bits, but not the radial.

The geometry of the worn-out 60° conical appears at first glance to be very similar to that of a radial tool with a large rake angle, raising the possibility that the beneficial effect of a large rake angle reported by others (*19*) is responsible for the lower-than-expected forces. However, the rake face of the 60° bit had been worn such that at the cutting edge of the tool, the wedge angle (90° - rake angle-clearance angle) is in actuality approximately 90° (fig. C-6*H*). Thus, the geometry of the worn-out 60° bit is more nearly identical to that of a radial tool having approximately 0° clearance and rake angles and a convex cutting edge. The required resultant force of the 60° bit should, therefore, be roughly equivalent to that of a similarly shaped radial bit in identical cutting conditions.

The worn-out 90° conical and 90ET bits, on the other hand, do not closely resemble radial bits, and it could be speculated that the different geometries behave differently in identical cutting conditions, resulting in variations in the wear-flat area versus resultant force relationship between the two bit types. Other researchers (*17*) have examined the possibility that the two bit types might induce rock failure via different mechanisms. They concluded that, on the basis of theoretical calculations and laboratory observations, radial and conical tools break rock in the same fundamental way. Thus, it seems reasonable to expect a general similarity in the wear-flat area versus resultant force relationship between the two bit types. The fact that the resultant forces of the relatively large conical bits were only roughly equivalent to the smaller radial bits after the spacing effect had been corrected cannot, therefore, be explained by citing the basic geometric differences between the two bit types.

The other possibility is that the geometry of the bit-mounting configuration for the conical bits, but not the radial bits, was different between the rotary and linear cutting systems used in this experiment. Careful measurement of the two systems confirmed that they had been built to the required specifications. However, the unanticipated degree to which wear affected bit length was suspected to be responsible for a subtle change in the attack angles, and thus the wear and clearance angles of the conical bits over their lives. The 60°, 90°, and 90ET bits lost a total of 0.35 in, 0.65 in, and 0.30 in, respectively, of bit length due to wear. Simple calculations based on the geometry of the rotary drum, bit block, and bit lengths, show that the attack angles of the 60°, 90°, and 90ET bits increased by a total of 0.6°, 1.0°, and 0.5°, respectively, as a result of the decrease in bit length over the lives of the bits. The radial bits are not similarly affected by bit length changes, because their shanks are mounted parallel to the drum radius. The net effect of the increased attack angles is that when the worn-out conical bits were transferred from the wear tests on the rotary-cutting system to the linear-cutting system for the force measurement tests, the clearance angles of the bits were increased by the aforementioned amounts, while the radial bits were not similarly affected. Other investigators (*19*) have observed that at clearance angles between 0° and +5°, increases in the clearance angle can dramatically reduce tool forces. In essence, then, it was speculated that, although an accurate comparison between the radial and conical bit forces could be made for new bits with the given experimental design, the forces of the conicals would rise more slowly with cutting distance relative to weight loss of the radials, than might reasonably be expected.

To quantify the effect of conical bit length changes on their resultant forces for this experimental design, the linear-cutting system was modified to decrease the clearance angle of the bits by 1.0°, and a brief series of force tests otherwise identical to those for which results are reported in table 2 were conducted. The 60° and 90° conicals were run at a spacing of 1.5 in, and the 90ET at 1.0 in; the depth of cut for all bits was 0.25 in. Results from these tests are found in table 3.

A comparison of tables 2 and 3 shows that the 1° clearance angle decrease resulted in a 10.8 pct increase, 0.5 pct decrease, and a 7.6 pct decrease in the resultant forces required by the 60°, 90° and 90ET conical bits, respectively. The force increase for the 60° relative to the other conicals was anticipated because its wear flat was the largest, but the actual increase of 10.8 pct was smaller than expected. The wear flat of the 90° bit was only about two-thirds as long, and the 90ET's, about one-half as long, as that of the 60° bit, but the 1° clearance angle decrease was expected to result in a modest force increase for each bit. The relatively smaller wear flats of the 90° and 90ET bits apparently were not large enough to significantly increase their resultant forces after the clearance angle was decreased. The large force decrease for the 90ET bit cannot be readily explained, but is considered to be within one standard deviation. The net effect of conical bit length changes on their resultant forces for this experimental design, although tangible for the 60° bit is, therefore, considered to be inconsequential relative to the spacing problem previously described.

TABLE 3. - Average force data with increased spacing and decreased clearance angles, pounds

Conical bit	Cutting	Normal	Resultant
60°	1,991	2,996	3,597
90°	1,616	2,277	2,792
90ET	1,889	2,396	3,051

There is one other unanticipated potential difficulty with the experimental design worthy of note. Given the approximately 17.5-in drum-bit tip radius, simple calculations show that for bits with 1.0-in wear-flat length, the clearance angle of all bits, regardless of type, will increase 1.6° when they are transferred, after being worn on the rotary-cutting system, to the linear-cutting system. The effect will be more pronounced on bits having relatively longer wear flats, the overall result being that the forces, measured on the linear system, of bits worn on the rotary system, would theoretically be slightly lower than if the forces had been measured on the rotary system. This inconsistency is not believed to have significantly affected the bit wear and force data reported in appendix A, or the relative ranking of the bits' performance.

In conclusion then, the relatively narrow (0.5-in) bit spacing of the original force tests significantly affected the force data reported in appendix A, while the clearance angle discrepancies did not. Spacing was adequate to provide an accurate comparison between the radial and conical bits only when the bits were relatively new. As the wear of the conical tools advanced, their bit widths became larger than the spacing between the centers of the adjacent bit paths, resulting in lower-than-expected force measurements. The forces of the radial bits were not greatly affected because the wear-flat widths were roughly equal to the spacing. Thus, the cutting distance versus resultant force graphs in figures 12 and 13 and appendix B, would have shown the forces of the radial and conical bits to be more nearly equal at the end of their respective lives, had the spacing and widths of the worn bits been compensated for in the original tests. The distance versus force curves of the conicals would still have increased hyperbolically, albeit relatively more quickly, in that case, with the curves for the radial bits remaining essentially unchanged.

RELATION OF BIT WEAR TO DUST PRODUCTION

A series of tests have been made to measure and compare the quantity of primary ARD generated per unit of cutting distance by bits in new and worn-out conditions. A summary of the results is presented in table 4. Since a complete description of the equipment and experimental technique have been presented elsewhere (*36*), it will not be repeated here.

A review of table 4 shows only one bit, the 60° conical, producing significantly more ARD when worn out than when new. Given that badly worn bits require higher forces, and, thus, greater energy than new bits to fragment a given volume of coal, more dust should theoretically have been produced by the worn-out bits. These results suggest that bit geometry changes due to wear result in a reduction of the ability of dust produced by worn bits to become entrained.

The difference in dust entrainment due to bit geometry is hypothesized to be due to the difference in frictional behavior between new and worn bits. A new tool has a relatively small contact area that produces low, normal, static breakaway, and kinetic (sliding) friction forces. When the new tool produces a chip that breaks free of the cutting path, the stored energy release in the bit causes a rapid forward motion (snapping) of the bit, inducing a certain amount of the crushed zone around the bit tip to become airborne. As a bit wears, the force distribution changes at the bit-mineral interface due to the change in contact area on the clearance side of the bit. The increase in normal force raises the static friction or breakaway force of the tool at the interface. The result of this geometry change is an increase in kinetic friction when a chip is released ahead of the tool. The stored tool energy does not provide a rapid "snapping" action to the tool when the energy release takes place with this higher kinetic friction force. Thus, less dust is entrained with a worn bit because the energy release takes place more slowly, although more total dust may be produced Additional research is needed to verify this hypothesis.

TABLE 4. - Summary of results from the comparison of ARD new and worn-out bits, million dust particles per gram coal

Bit	New	Worn out
Round-nose radial	3.805	1.342
PDC:		
Parrot	1.102	1.251
3-insert	1.843	.180
0°	1.286	.862
-20°	3.717	.327
Conical:		
60°	1.236	3.194
90°	1.854	.791
90ET	2.595	.929

A comparison of tables 2 and 4 shows that there is a relationship between the wear-flat areas of the worn-out radial and 60° conical bits and ARD generation. Dust entrainment generally increased with the wear-flat area, with the exception of the worn-out round-nose radial and parrot PDC bits.

Any actual mining operation would be expected to show an increase in ARD measured for a system cutting with bits in the condition of the worn-out bits used in these tests. This is partially due to the crushed fraction of dust already generated becoming airborne, as a result of secondary impacts, before the fragmented coal clears the face. Another factor that must be considered is the operator response to the "feel" of the cutting system being used. The amount of normal force required by the cutting system to maintain the same advance rate increases as the bits wear. Machine noise and vibration increase correspondingly, at some point becoming severe enough to cause the operator to start reducing the advance rate. Cutting distance per unit volume of coal then increases as the advance rate decreases, resulting in an increase in dust production as the bits wear.

APPLICABILITY OF RESULTS

The results show that conical bits with WC inserts can provide a substantially longer and more efficient life than radial bits with similar inserts. To achieve this, however, the rotation of the bits must be assured. The nonrotating conical bit performed as poorly as the round-nose radial bit. Rotation can be promoted by mounting the bits at a skew angle greater than 10° (*8*) and providing adequate clearance between the bit shanks and holders (*14*). Current Bureau work is examining the possibility of mechanically inducing rotation. Rotation does not automatically result in lower resultant forces, however, because the rotating bits required forces at least as great as the nonrotating bits toward the end of their lives. Frictional sparking was observed to be generally less intense with rotating, versus nonrotating, bits, although at times sparking could be severe with rotating bits as well.

The included tip angle of a new conical bit was found to be relatively unimportant in terms of the subsequent performance of the bit. A comparison of the results for the 60° and 90° conicals shows that, although the tip angles did initially influence the resultant force levels, wear rapidly modified the tip geometries such that both bits exhibited essentially identical profiles and performance after only a few thousand feet of cutting, given that both bits were free to rotate. The 60° bit did initially have relatively lower force and wear rates, however, so there is initially a slight advantage in choosing a bit with a smaller included tip angle. Mine operators are advised to be unconcerned if the smaller tip angle bits are not available because it is much more important to select bits on the basis of their wear and fracture resistance in the site-specific cutting conditions.

Machine vibration and noise levels and the resultant forces required by the new radial bits were all generally lower than those of the new conicals. However, wear quickly altered the bit tip geometries of those bits having only WC inserts, so that after just a few thousand feet of cutting, the conicals had lower force and wear rates, and generally lower sparking, vibration, and noise levels than the round-nose radial. The conicals continued to outperform the round-nose radial until bit rotation was prevented, or the tools became relatively blunt. Frictional sparking was a problem for both bit types, however.

In general, then, the results show that rotating conical bits having WC inserts outperform nonrotating bits with WC inserts in terms of bit life and forces. Four of the radial bits tested, however, had varying degrees of PDC material incorporated into their inserts. Three of the bits, the three-insert, 0°, and -20° PDC's, performed substantially better than the round-nose radial and conicals in terms of the resultant force, bit life, machine vibration, noise, and frictional sparking. The parrot PDC required slightly higher resultant forces than the 60° conical and 90ET over a small portion of its useful life, but otherwise it too outperformed the conical bits. The superior performance of the radial PDC's relative to the conventional conicals is wholly dependent upon the retention of the main PDC insert in the bit tips. In every case, resultant force, machine vibration, noise, and frictional sparking increased dramatically once the main PDC insert was thrown from the bit.

The design concept used in the 0° and -20° PDC's appears to offer potentially longer life than that used in the parrot and three-insert PDC's. The cutting edges of the parrot and three-insert bits were not protected by PDC material to the same degree as the edges of the other bits, resulting in the accelerated wear of their WC supports and premature fracturing and loss of the PDC material. The total life of the parrot PDC was 61,440 ft. That of the three-insert PDC would have been about 105,000 ft but its center PDC insert fell out during a force test shortly after 101,184 ft. The PDC inserts of the 0° and -20° bits, on the other hand, showed relatively little wear prior to the loss of the 0° bit insert at 98,664 ft owing to brazing failure, and the accidental damage of the -20° bit insert at 98,619 ft. The 0° bit appears to be the most promising of the four PDC bits tested because it cuts without the excessive noise and vibration of the -20° PDC and can potentially provide a substantially longer life than the parrot or three-insert PDC's. If the brazing technique used to bond its insert to the bit body can be refined, or another method developed, to insure the retention of the insert, the 0° PDC can probably deliver a bit life of at least 200,000 ft with efficient performance in the given cutting conditions. As PDC bits have been shown by others (*22, 42-43*) to be safer and more efficient, in certain situations, than conventional WC tools, mine operators are encouraged to investigate the possibility of applying them to their specific cutting conditions.

Bits that fail through relatively gradual wear processes are much harder to identify as being inefficient than those that fail by locking in their holders, gross body fracture, etc. Examination of the individual weight loss versus resultant force curves (appendix B) suggests that it should be possible to develop a method whereby the point at which gradually wearing bits become inefficient can be precisely determined in the field. The method would allow miners to knowledgeably decide whether or not to replace gradually wearing bits. The graphs show that a method is required only for bits having WC inserts. The PDC bits always required low forces as long as their main PDC inserts remained at least partially intact.

Although it would be impractical to weigh bits underground, it would be fairly simple to make as a training tool a template based on the geometry of the specific bit design in use. Assuming the weight loss versus resultant force relationship for that bit, and the force level after which cutting in the site-specific conditions become inefficient, are known, a template based on the break-even bit geometry could easily be fabricated. The miner would then simply compare gradually worn bits to the template, discarding those worn past the break-even geometry. Any asymmetrically worn conical bits, even if only moderately affected, should automatically be changed, since they will generally have only a short period of usefulness left under field conditions. Although the rotating 90° conical bit was able to regain a fairly symmetric shape (fig. C-7*L*) after developing a large wear flat (fig. C-*D, E*) in the dry laboratory conditions, the symmetrically worn bit required high forces and was certainly cutting inefficiently. Generally speaking, nonrotating, asymmetrically worn conical bits cannot be made to cut efficiently by merely freeing them to rotate again. The wet, gritty conditions normally encountered in the face can be expected to increase the tendency for those bits to rotate back to the position in which they had previously locked up and do so once again. These bits are particularly dangerous in gassy mines.

SUMMARY AND CONCLUSIONS

The results of the wear and force tests show that the eight bits tested can be grouped into three categories based on their performance.

The round-nose radial bit was the only bit of those tested that exhibited force and wear rates increasing rapidly and linearly with cutting distance, a relatively small weight loss prior to failure, and a relatively short bit life. These characteristics define performance category I and are believed to be typical of all conventional radial (wedge-shaped), nonrotating bits having WC inserts.

The 60°, 90°, and 90ET conical bits all manifested performance characteristics of category II initially. Forces for the 90° and 90ET bits increased hyperbolically, and wear rates increased linearly, with cutting distance, but the increases occurred more slowly than for the first category. Tools in the second category lost relatively more weight prior to failure and had substantially longer lives than the round-nose radial bit. These results are believed to be typical of all conventional, rotating, conical (point-attack) tools with WC inserts. The 60° conical bit exhibited behavior characteristic of the second category prior to being locked in its holder at 23,928 ft. Once rotation was prevented, the force and wear rate curves of this bit became similar to those of the round-nose radial bit in category I.

The four bits with PDC inserts are grouped into the third category. The initial performance characteristics of these bits in the first few hundred feet of cutting were roughly equivalent to those of the other categories. However, PDC material is much more wear resistant than WC in the given test conditions, so that the rate of change in force and weight with cutting distance was substantially less over the balance of the tests prior to complete failure. The force and wear rates continued to increase very slowly until bit wear advanced to the point that the PDC inserts could no longer be retained in their mountings. Performance radically changed once the main PDC insert of each bit was thrown. The force and wear curves almost immediately assumed the steep, nearly vertical slopes characteristic of category I.

In general then, the results show that the PDC bits provided substantially longer bit lives with more efficient performance levels than the WC bits. The design concept used in the 0° and -20° bits is more durable than that used in the parrot and three-insert bits; the cutting edges of the former designs are uniformly protected by PDC material, while the edges of the latter designs are not. Of the 0° and -20° bits, the 0° has better potential, as it cut with only slightly more force, and much less vibration and noise, than the -20° bit, prior to the premature failure of both bits. The 0° bit can probably provide at least 200,000 ft of bit life at efficient performance levels if the insert brazing can be improved compared with the 15,700 ft of the commercial WC round-nose radial. Frictional sparking was nearly nonexistent with the PDC bits as long as the main PDC inserts remained in the bits. Mine operators are particularly encouraged to examine the possibility of applying these tools to cutting conditions in gassy mine areas.

With regard to conventional WC tools, rotating conical bits were found to outperform nonrotating bits in terms of total bit life and forces over the lives of the tools. Although the machine vibration, noise, and resultant forces required by the new round-nose radial were, in general, lower relative to the new conical bits, wear quickly altered the bit tip geometries so that the conicals were superior performers after only a few thousand feet of cutting. The conicals provided a substantially longer bit life and continued to outperform the radial bit until bit rotation was prevented or the bits became relatively blunt. Frictional sparking was a problem for both bit types, although it was generally less so for rotating versus nonrotating conical bits. Bit forces for relatively symmetrically worn, rotating conical bits were found to be as high as those for asymmetrically worn, nonrotating conical bits.

The included tip angles of new WC conical bits were found to have a relatively unimportant influence on bit performance when the effects are averaged over the life of the bit. A comparison of the 60° and 90° conical bit results shows that although the included tip angle did initially influence the resultant force levels, wear quickly modified the bit tip geometries so that the two bits were essentially identical performers after only a few thousand feet of cutting, given that both were free to rotate. The 60° bit did initially have relatively lower force and wear rates, so there may be a slight initial advantage in choosing a bit with a smaller tip angle. Operators are advised, however, to select bits on the basis of their wear and fracture resistance in the site-specific cutting conditions, rather than their performance when new.

Results for the worn-out radial bits indicate a relationship between their wear-flat areas and required resultant forces. The three-insert PDC required the lowest forces and had the smallest wear flat, the -20° PDC was next, and so on; the parrot PDC had the highest forces and largest wear flat. There is also a general relationship between the wear-flat areas and ARD production for the worn-out radials and 60° conical bits. Additional work is needed to validate these hypotheses as the results are from observations of only six bits.

Bit length changes due to wear were found to gradually increase the attack angles of the conical bits over their lives by a total of as much as 1.0° in the rotary-cutting system used for this work. Some equipment designers set attack angles to the nearest 0.5° in an attempt to optimize the cutting system. The results presented in this paper show that specifying attack angles to such close tolerances may not be as important as is sometimes believed. Limited tests showed that the forces of conical bits with relatively small areas of their surface in contact with the rock during cutting are probably insensitive to small changes in attack angles.

New bits were generally found to entrain more dust for a given cutting distance than worn-out bits. The difference is hypothesized to be due to the difference in frictional behavior between new and worn bits. Practically speaking, however, the airborne dust production per unit volume of coal would be higher with worn, relative to new, bits, because worn bits require higher forces that necessitate the slowing of the advance of the cutting head into the coal, resulting in shallower cuts that produce relatively more dust per unit volume of coal.

Those bits that fail through locking in their holders, gross body fracture, etc., are easily deduced to be cutting inefficiently and should be changed as soon as noticed. Examination of the weight loss versus resultant force graphs for conical bits suggests that it may be possible to design a template to help miners optimize bit usage when the bits rotate. Miners could easily compare the worn bits with the template. This method would only be useful when miners are faced with WC bits that fail through relatively gradual wear processes. No template would be needed for PDC bits since they always cut efficiently as long as any of the PDC insert remains intact.

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APPENDIX A.–BIT WEAR AND FORCE DATA

Distance cut, ft	Weight loss, pct	Force, lbf Normal	Force, lbf Cutting	Force, lbf Resultant
		Round-nose radial		
0	0	141	155	210
3,744	.61	1,042	802	1,315
7,056	1.29	1,535	1,147	1,916
9,664	1.72	1,773	1,458	2,295
11,472	2.13	2,442	1,787	3,026
13,632	2.48	2,295	1,676	2,842
15,744	2.83	2,629	1,909	3,249
		Parrot PDC		
0	0	207	220	302
15,864	.15	701	468	843
23,904	.20	703	470	846
33,336	.29	682	453	819
57,120	1.31	1,557	1,239	1,990
61,440	3.25	3,192	2,267	3,915
		3-insert PDC		
0	0	135	149	201
17,496	.19	404	309	509
35,568	.23	423	312	526
54,384	.25	420	329	534
72,456	.26	371	285	468
85,752	.29	595	397	715
91,536	.32	440	313	540
95,736	.34	517	464	695
101,184	.41	626	537	825
		0° PDC		
0	0	27	82	86
8,808	.01	217	194	291
16,488	.04	312	230	388
25,968	.06	400	281	489
35,544	.10	475	349	589
61,416	.23	584	367	690
80,136	.32	516	549	753
98,644	1.96	142	186	234
100,440	2.06	859	744	1,136
101,520	2.79	2,232	1,400	2,635
		-20° PDC		
0	0	122	171	210
8,160	.01	130	171	215
15,648	.03	183	183	259
24,641	.03	208	277	346
33,473	.05	280	259	381
41,369	.06	286	266	391
		-20° PDC–Continued		
50,163	0.09	481	381	614
60,987	.13	475	337	582
86,907	.24	584	367	690
98,619	.98	516	549	753
116,215	1.01	736	741	1,044
122,815	2.52	971	982	1,381
125,071	3.11	1,858	1,405	2,329
		60° conical		
0	0	169	177	245
4,512	.62	980	731	1,223
6,672	.78	802	651	1,033
11,016	1.04	943	724	1,189
15,384	1.32	495	464	678
19,536	1.49	1,160	811	1,415
23,904	1.62	1,269	1,021	1,629
28,608	2.26	762	647	1,000
38,520	7.17	1,931	1,184	2,265
		90° conical		
0	0	792	679	1,043
4,416	.72	661	565	870
6,624	.92	894	713	1,144
11,064	1.46	976	742	1,226
15,408	2.07	643	600	879
20,064	2.29	998	742	1,244
24,768	2.46	1,213	927	1,527
41,928	6.15	883	696	1,124
50,366	7.44	741	611	960
54,974	8.48	1,122	909	1,444
61,742	9.56	1,332	1,014	1,674
61,766	9.58	1,332	1,014	1,674
66,182	10.03	2,131	1,473	2,591
73,910	10.84	2,575	1,735	3,105
83,150	11.67	1,644	1,122	1,990
		90ET conical		
0	0	589	502	774
11,160	.29	607	498	785
27,000	.91	633	555	842
44,712	1.55	1,122	848	1,406
61,008	2.61	949	735	1,200
61,704	2.76	1,805	1,492	2,342
70,776	3.63	2,183	1,551	2,678

APPENDIX B.–PERFORMANCE GRAPHS

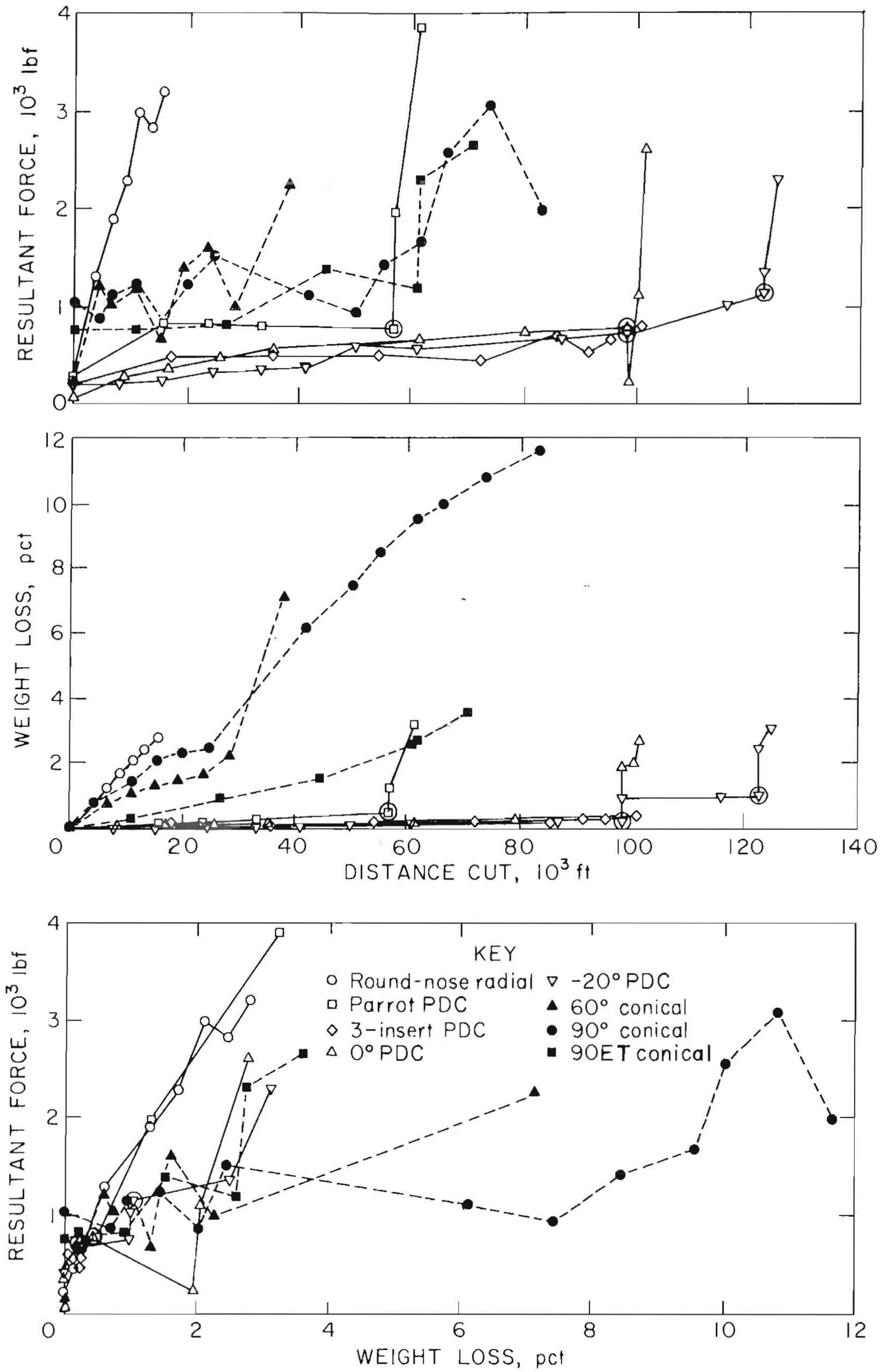


Figure B-1.–Composite performance graphs for all bits tested.

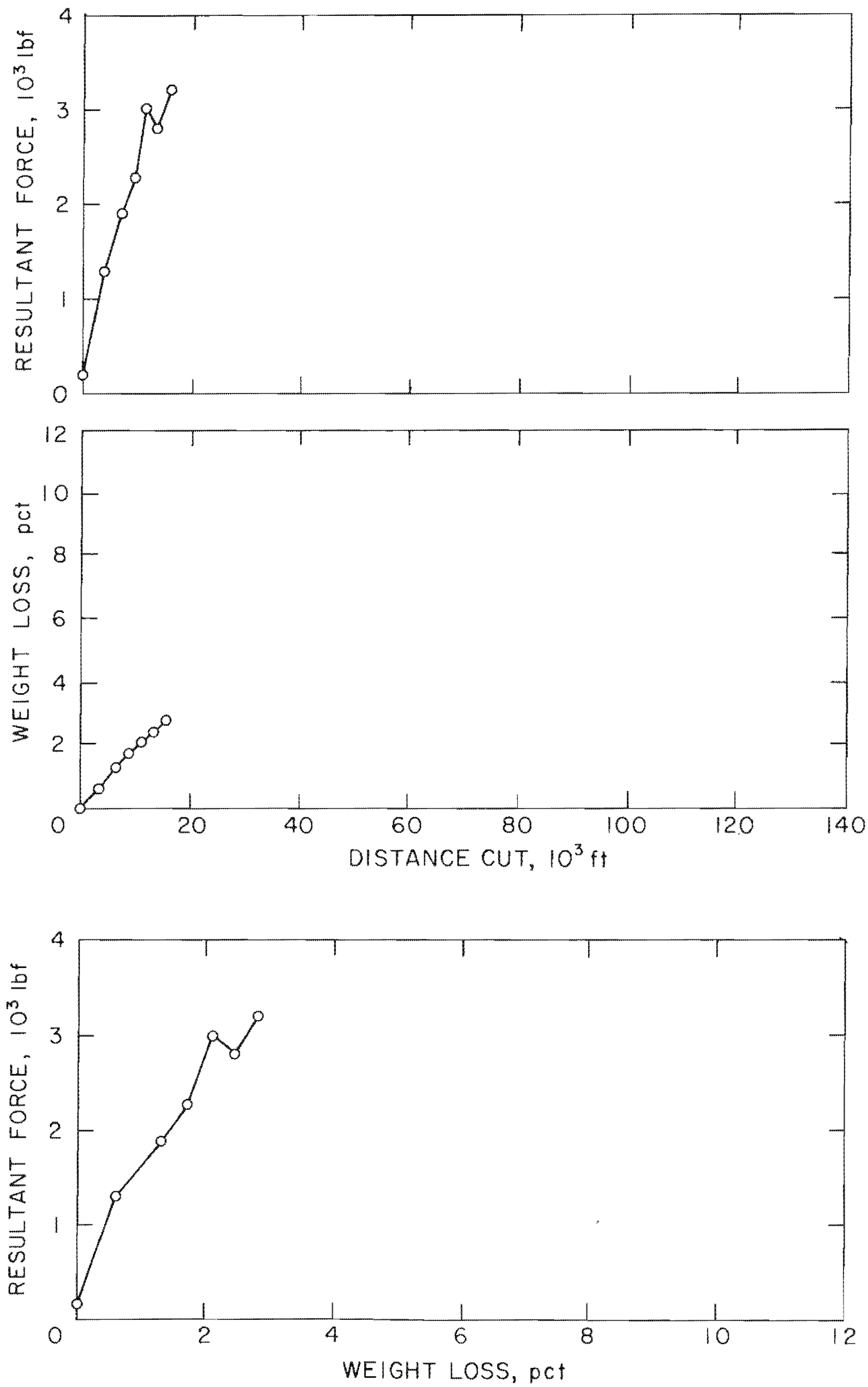
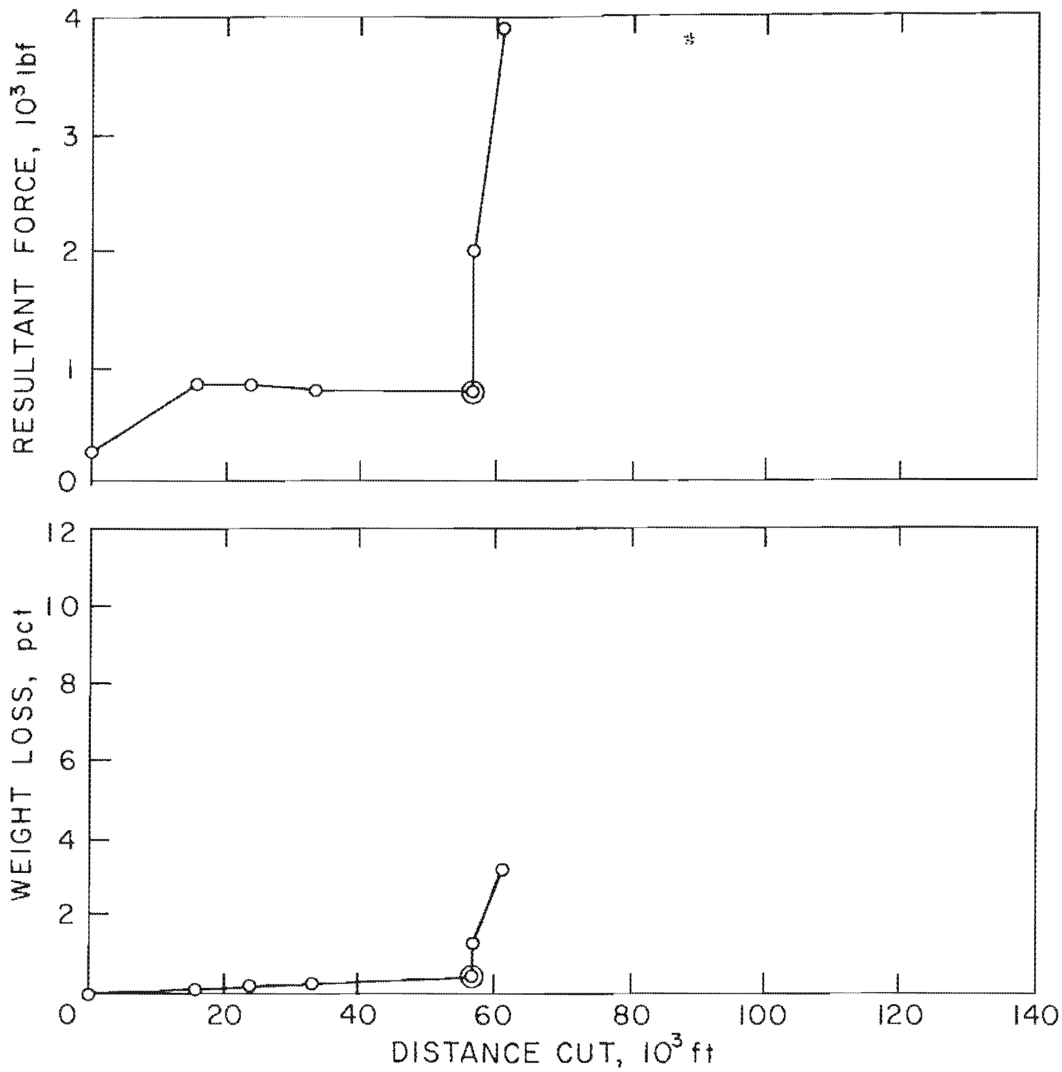


Figure B-2.–Performance graphs for the round-nose radial bit.



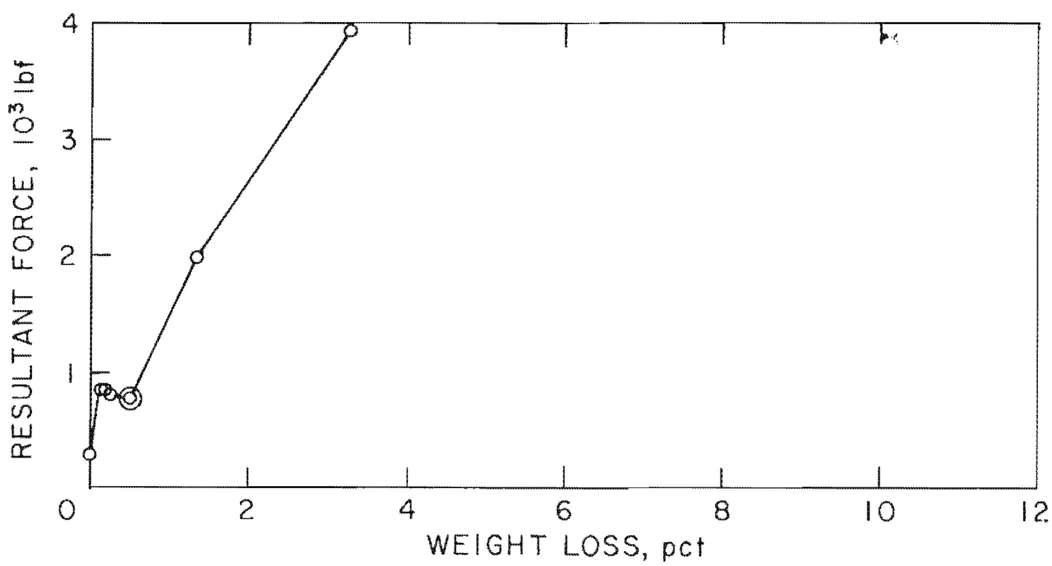
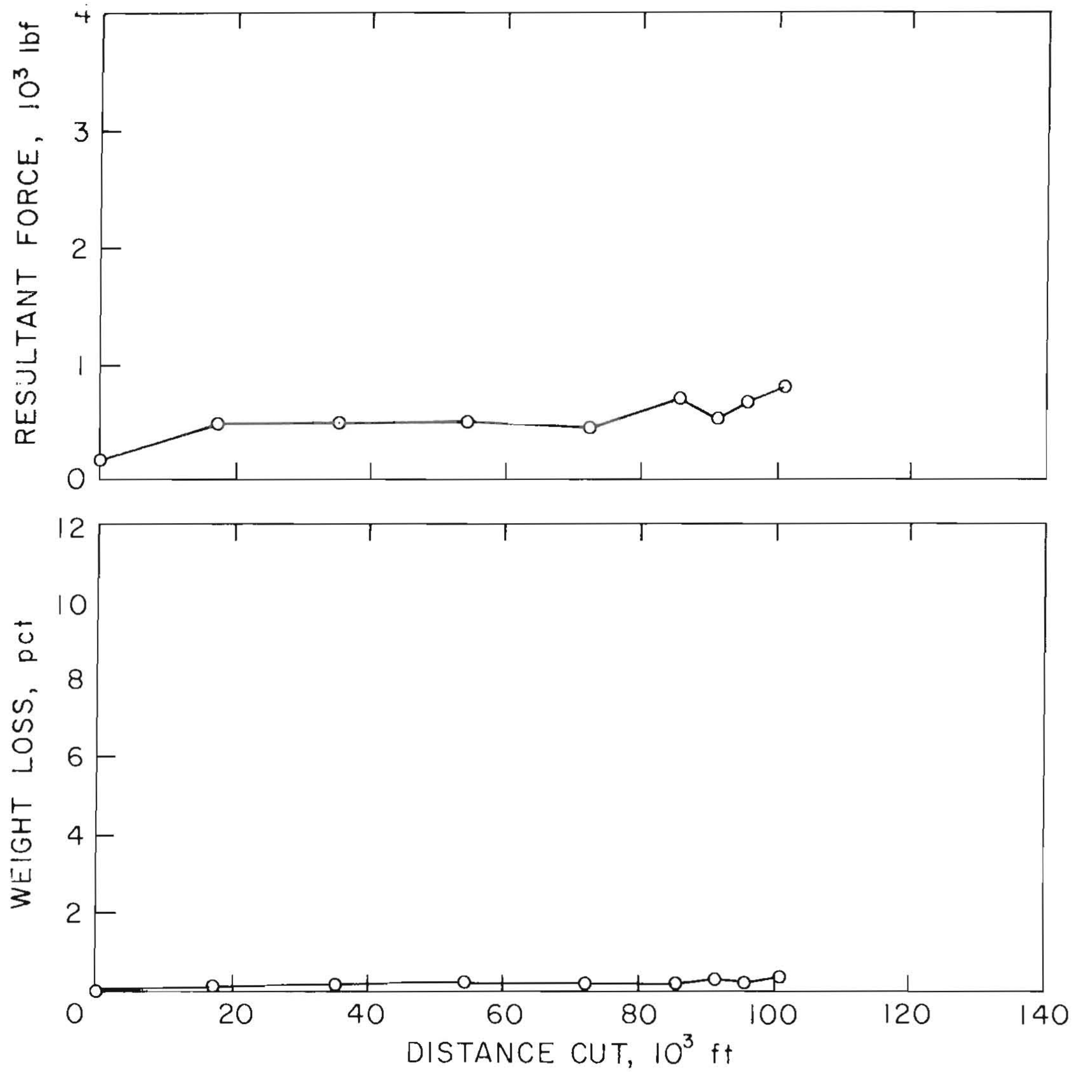


Figure B-3.–Performance graphs for the parrot PDC bit.



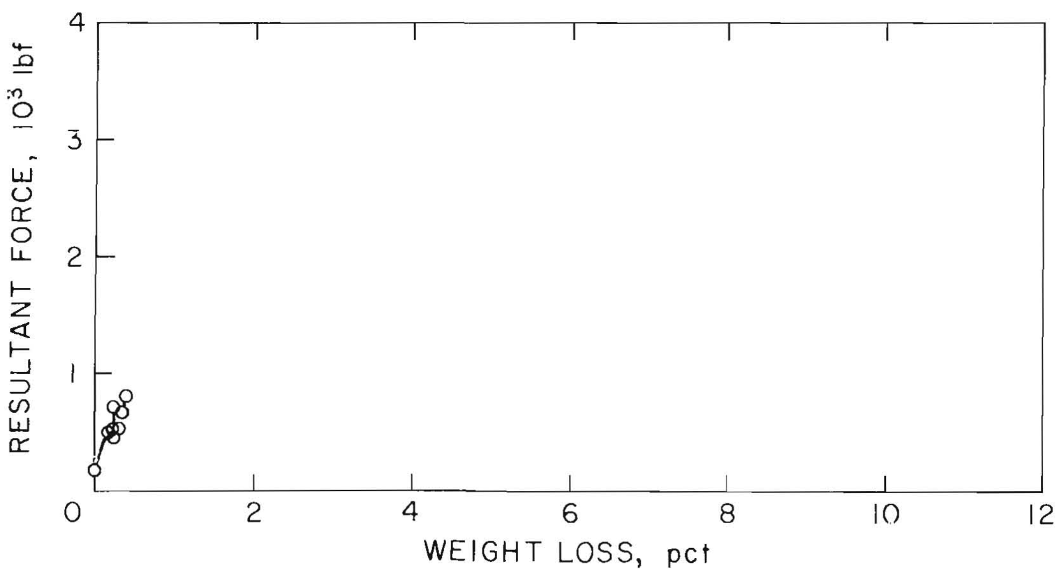


Figure B-4.–Performance graphs for the three-insert PDC bit.

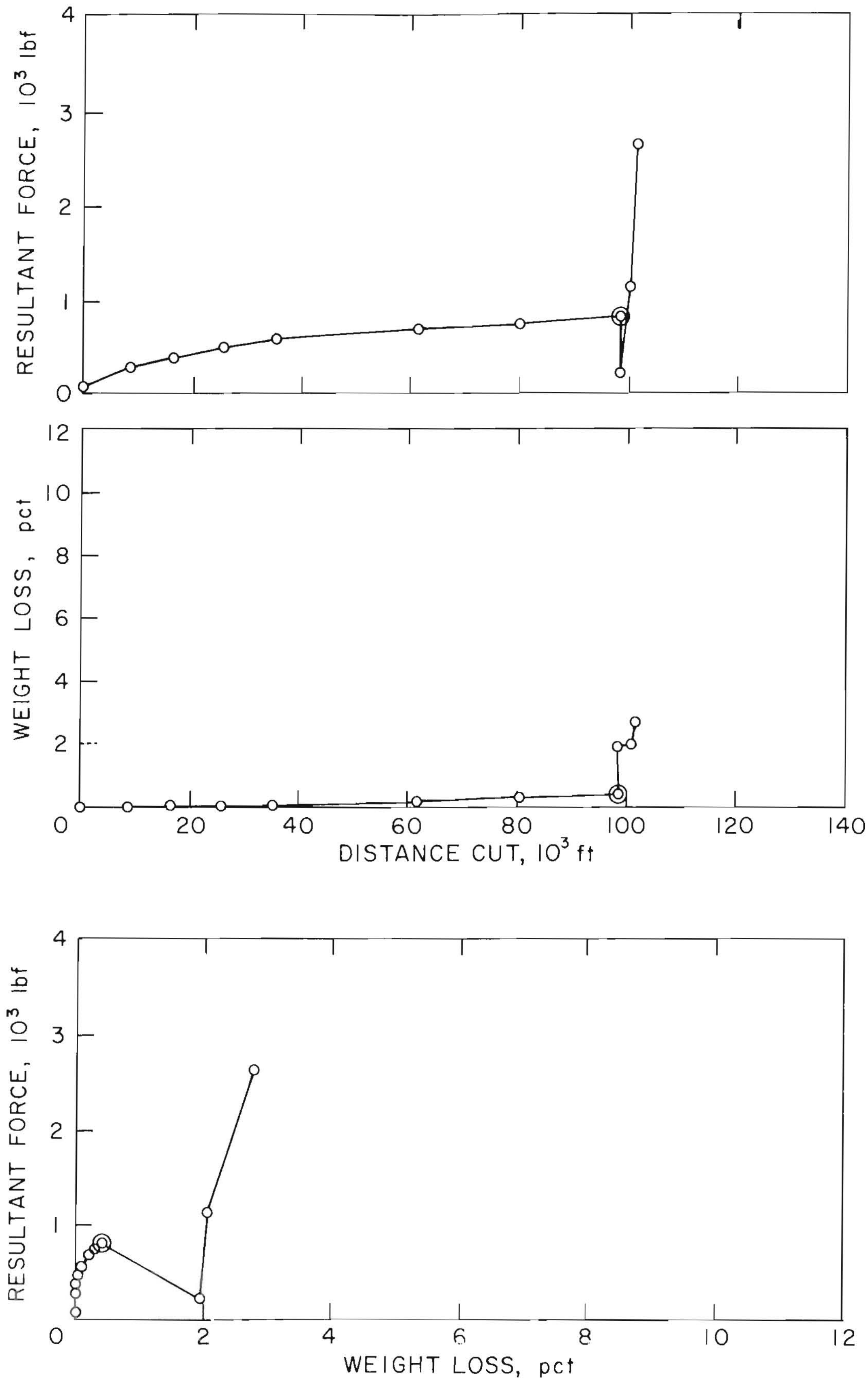


Figure B-5.–Performance graphs for the 0° PDC bit.

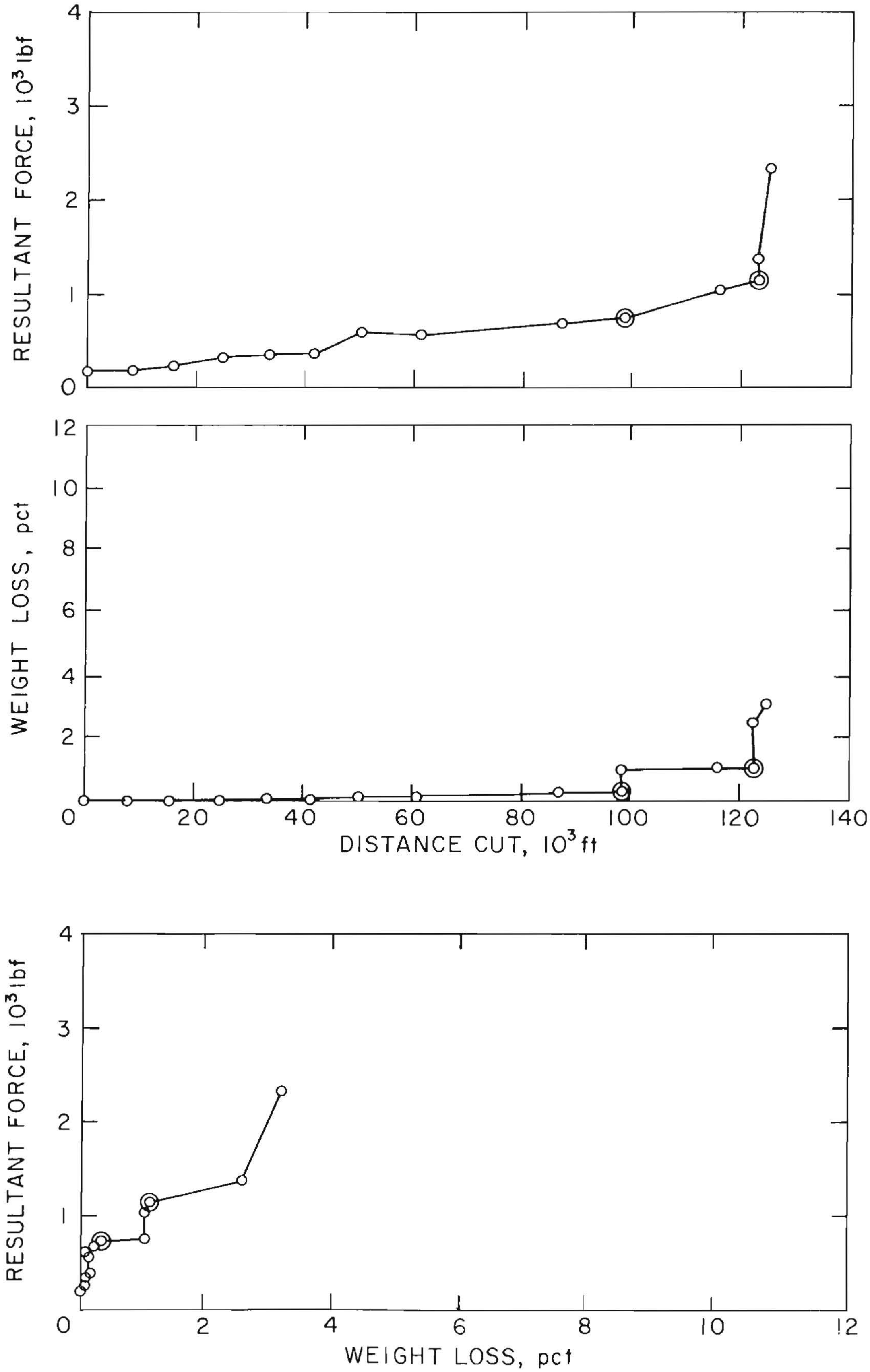


Figure B-6.—Performance graphs for the -20° PDC bit.

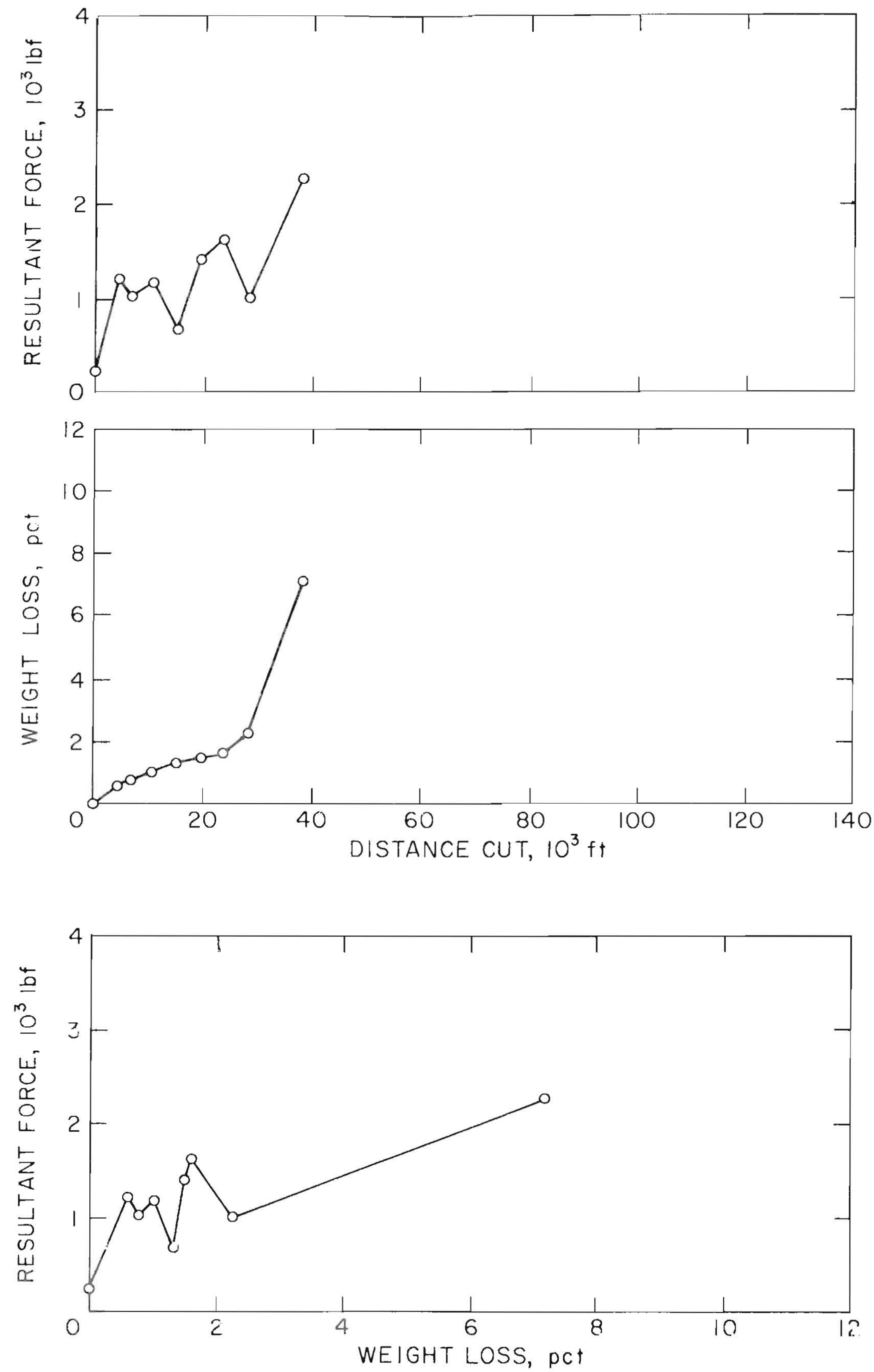


Figure B-7.–Performance graphs for the 60° conical bit.

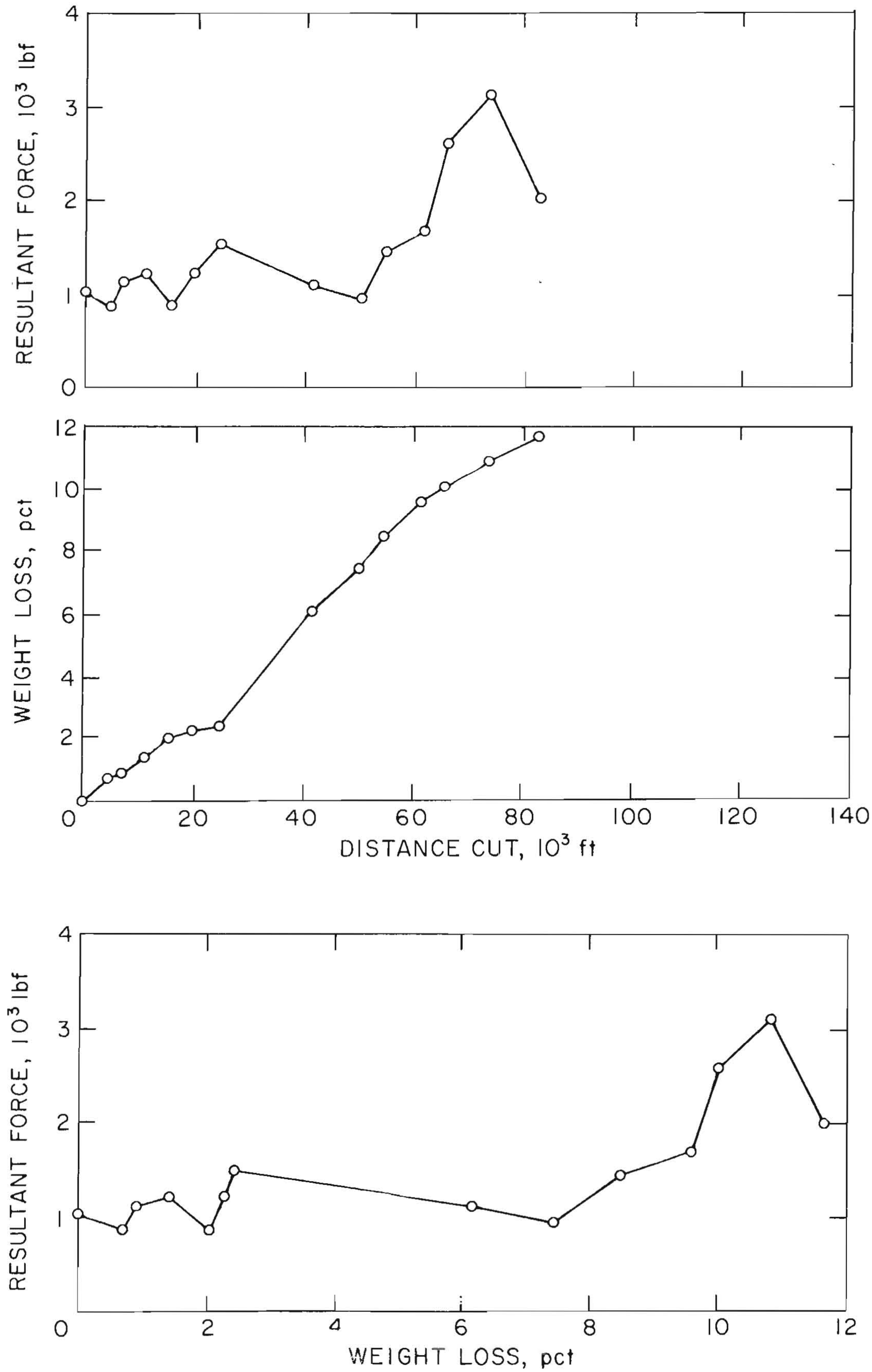


Figure B-8.–Performance graphs for the 90° conical bit.

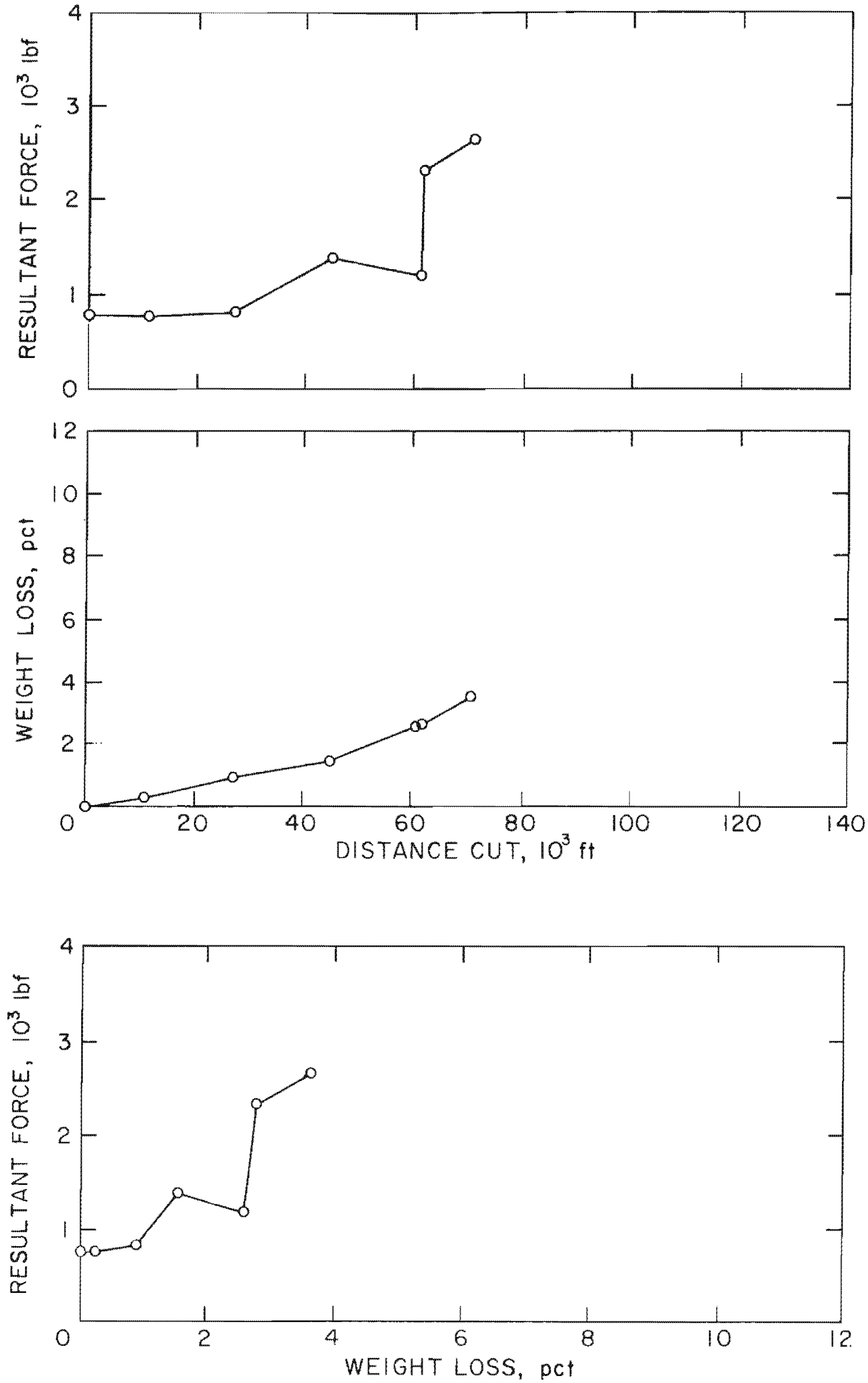
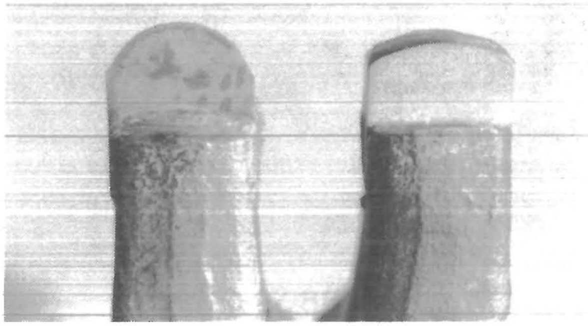


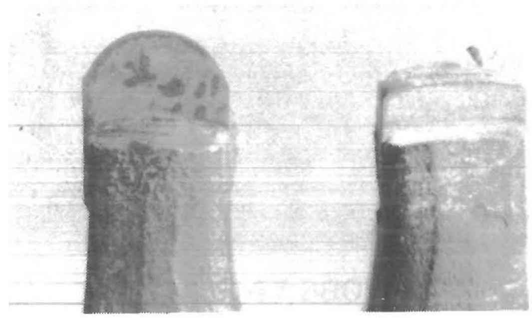
Figure B-9.–Performance graphs for the 90ET bit.

APPENDIX C.–PHOTOGRAPHS ILLUSTRATING BIT WEAR DEVELOPMENT

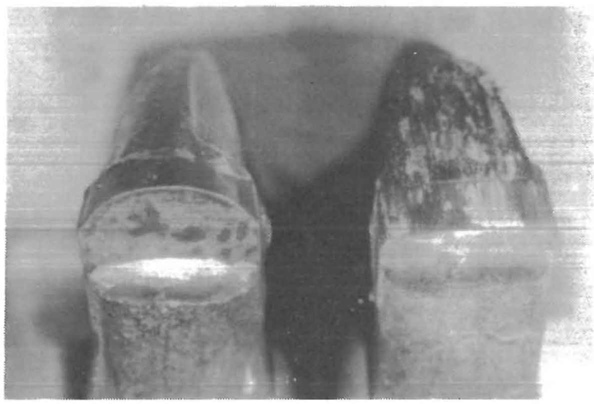
All photographs in this appendix depict a new bit (left) as a reference to the worn bit (right), unless otherwise specified.



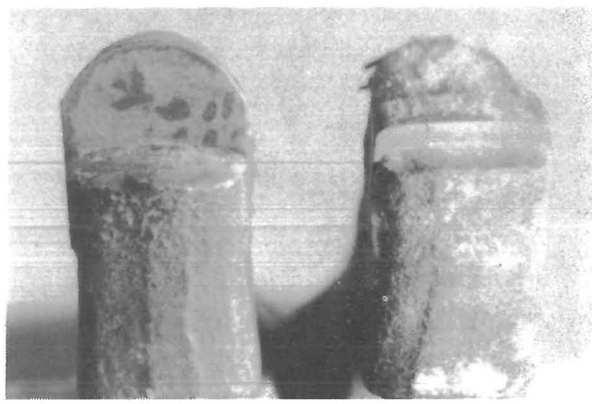
A, 3,744 ft



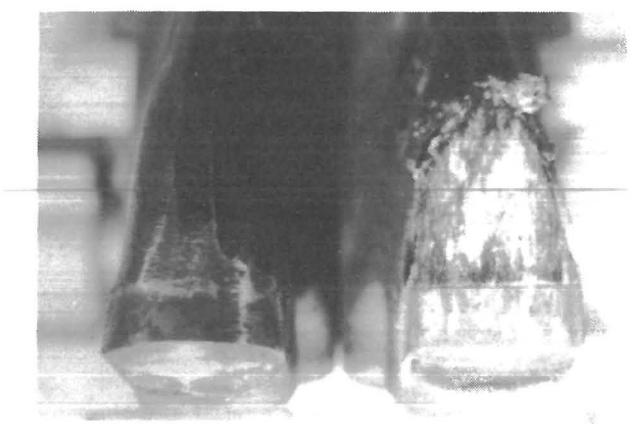
B, 9,264 ft



C, 13,632 ft

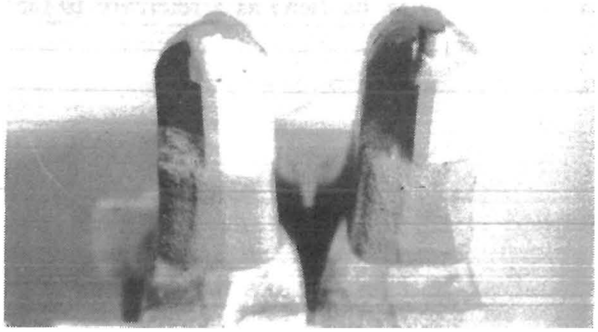


D, 15,744 ft

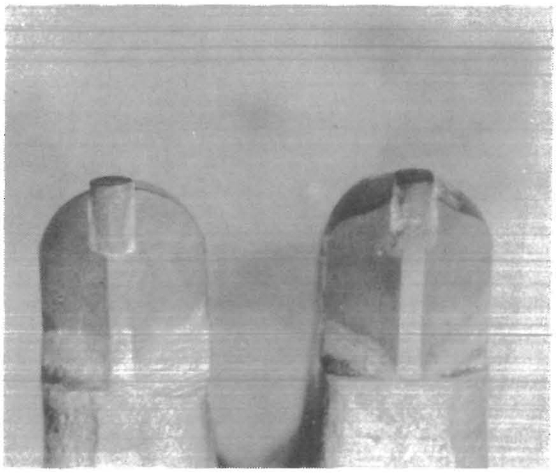


E, 15,744 ft

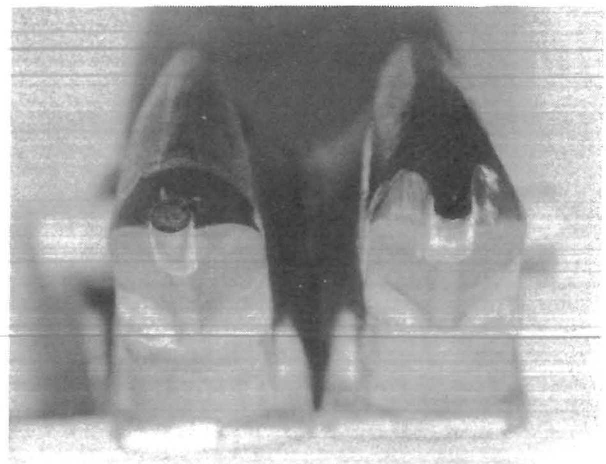
Figure C-1.–Round-nose radial bit at various cutting distances. *A*, **Front view;** *B*, **front view (note presence of melted and recompacted quarts; melting of tool steel has begun);** *C*, **top view;** *D*, **front view;** *E*, **top view.**



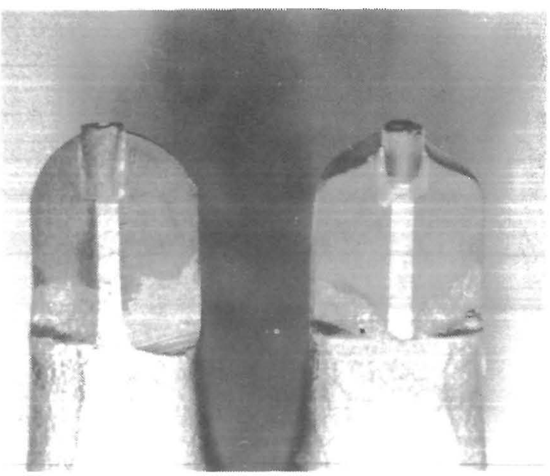
A, 6,582 ft



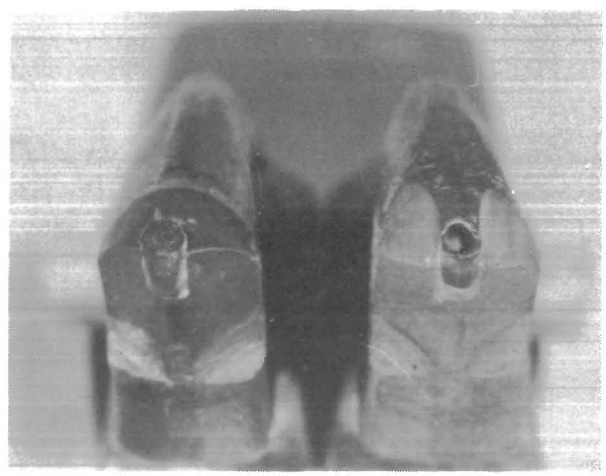
B, 15,864 ft



C, 15,864 ft

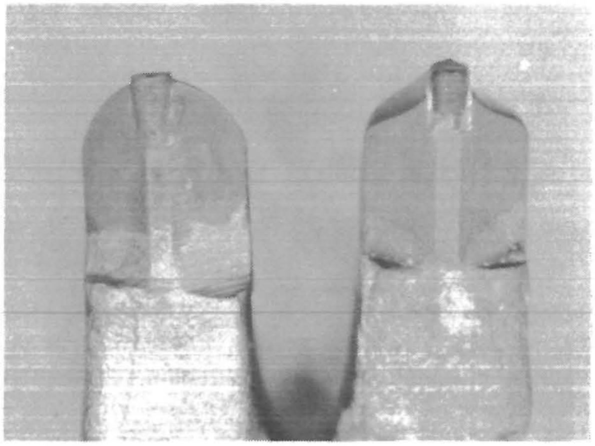


D, 33,336 ft

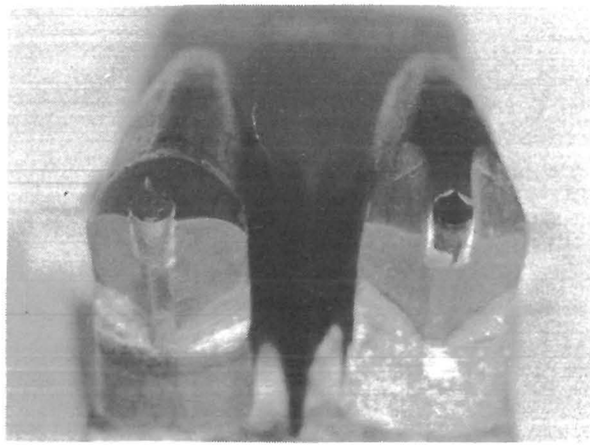


E, 33,336 ft

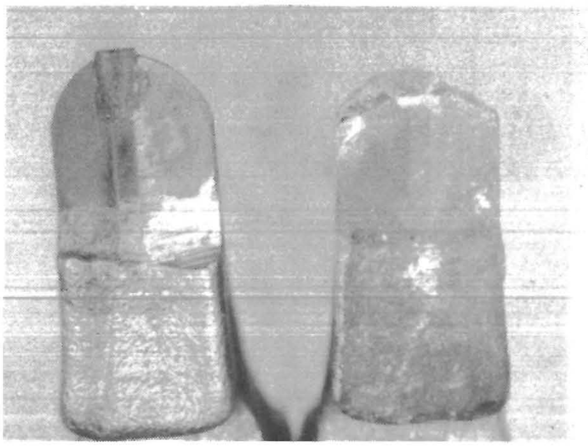
Figure C-2.–Parrot PDC bit at various cutting distances. *A*, **Front view;** *B*, **front view;** *C*, **top view;** *D*, **front view;** *E*, **top view.**



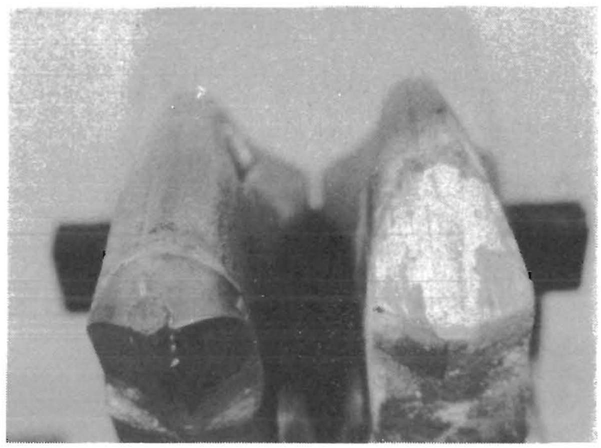
F, 47,880 ft



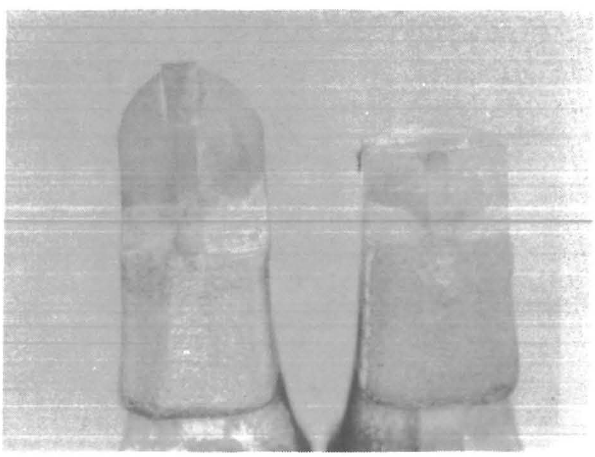
G, 47,880 ft



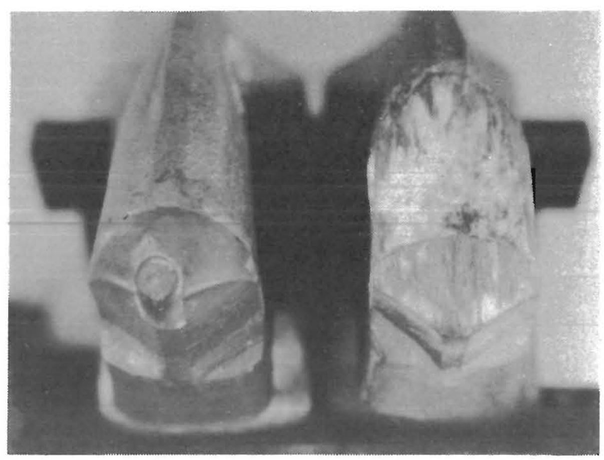
H, 57,120 ft



I, 57,120 ft



J, 61,440 ft



K, 61,440 ft

Figure C-2.–Parrot PDC bit at various cutting distances–Con. *F*, **Front view;** *G*, **top view (note chipped rear edge of PDC insert);** *H*, **front view;** *I*, **top view (note missing PDC insert and extensive presence of melted and recompacted quartz);** *J*, **front view;** *K*, **top view.**

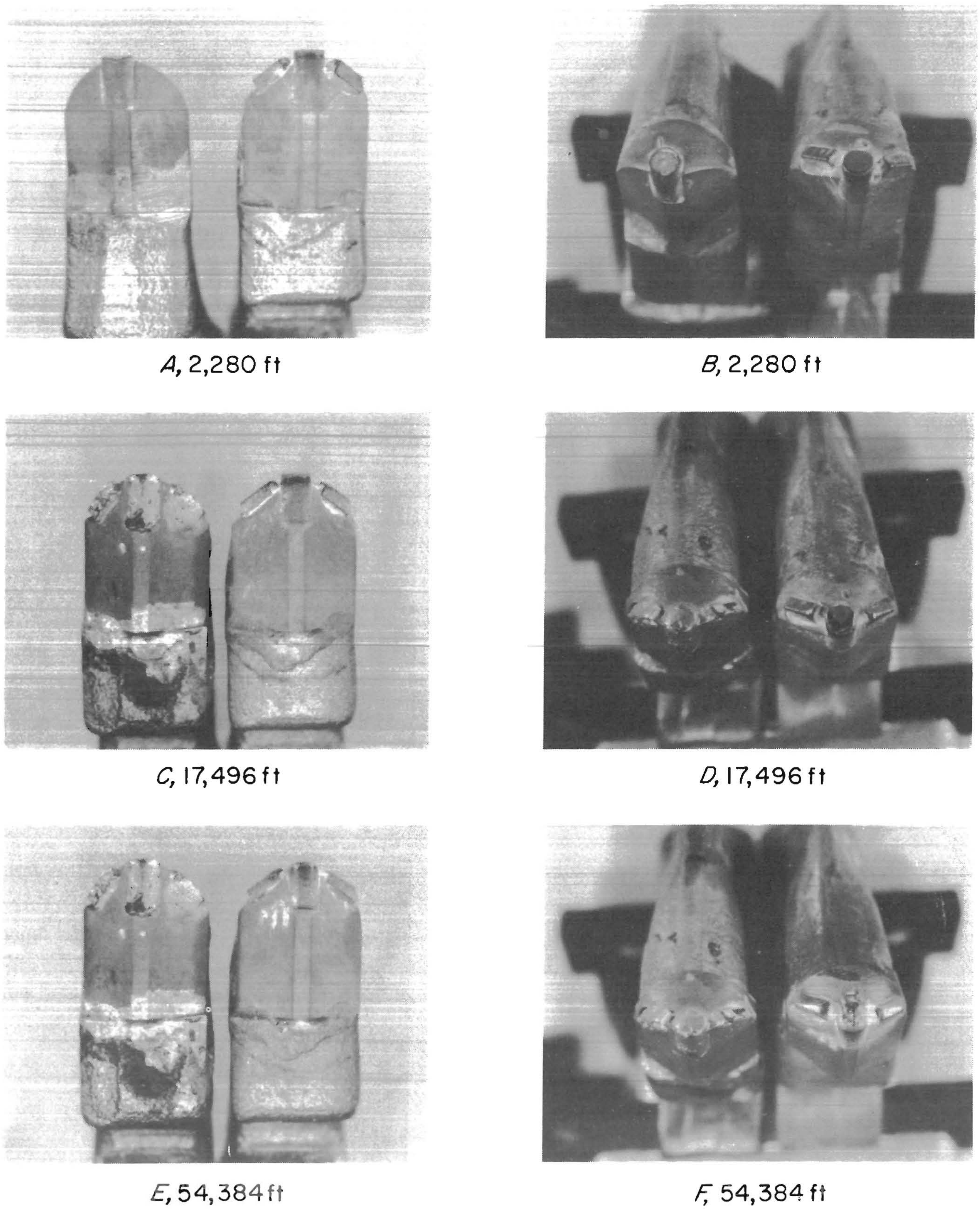
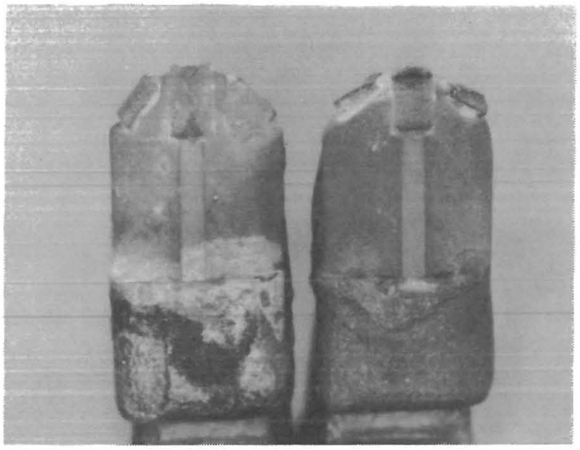
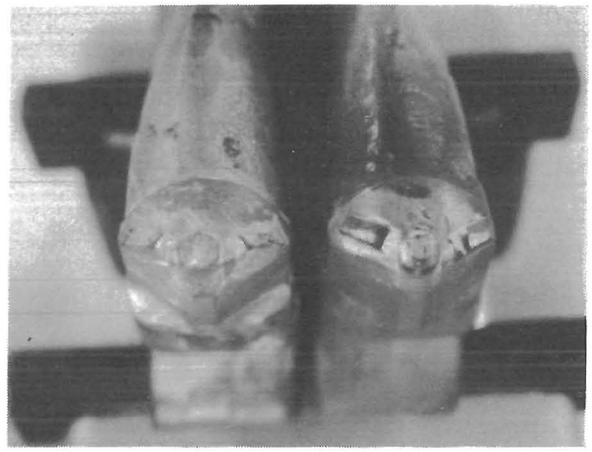


Figure C–3.–Three-insert PDC bit at various cutting distances. In panels *A* and *B*, the bit on the left is a new parrot PDC; in the other panels, the left bit is a new three-insert PDC. *A*, Front view; *B*, top view; *C*, front view; *D*, top view (note scuffing on cutting edges of PDC inserts); *E*, front view; *F*, top view.

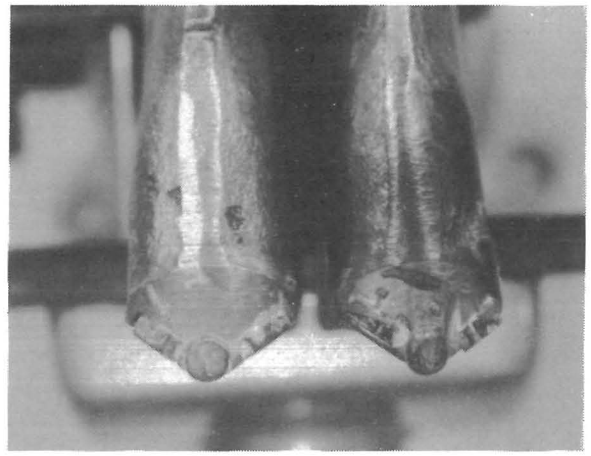


G, 72,456 ft

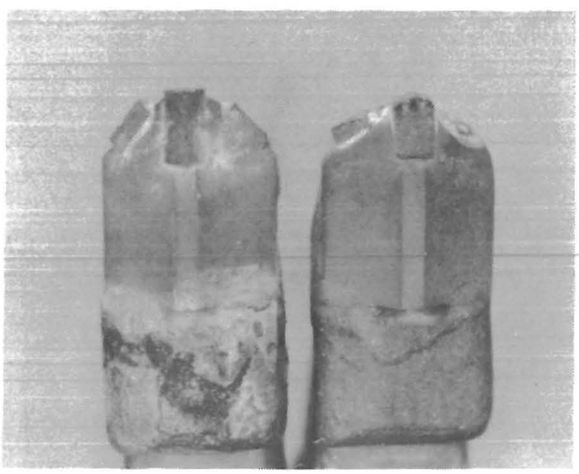


H, 72,456 ft

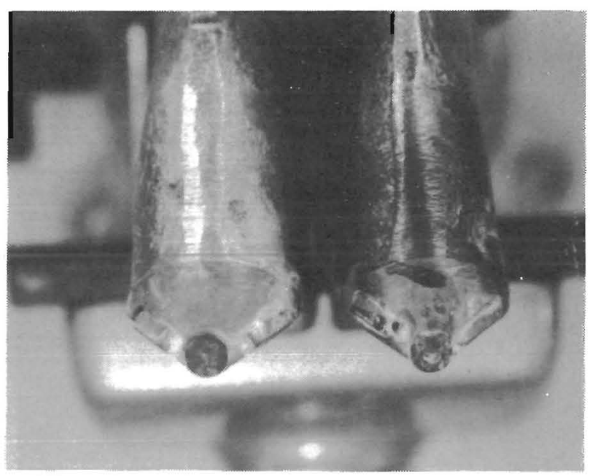
I, 85,752 ft



J, 85,752 ft



K, 91,536 ft



L, 91,536 ft

Figure C-3.–Three-insert PDC bit at various cutting distances–Con. ***G*, Front view; *H*, top view (note that right PDC insert has cracked; wear of tungsten carbide backing has begun); *I*, front view; *J*, top view (note both right and left PDC inserts cracked); *K*, front view; *L*, top view (note right PDC insert and one-third of left insert are missing).**

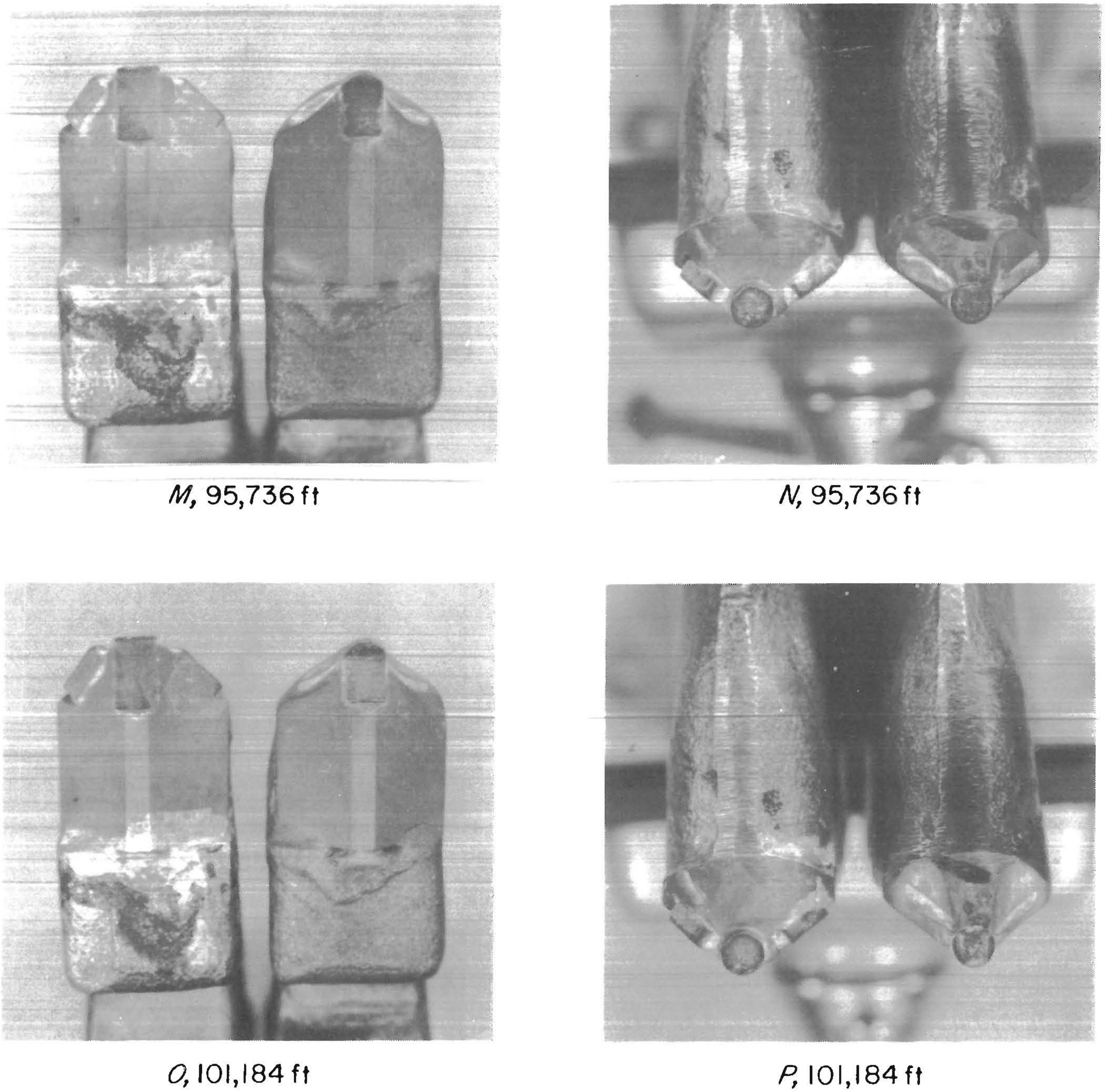
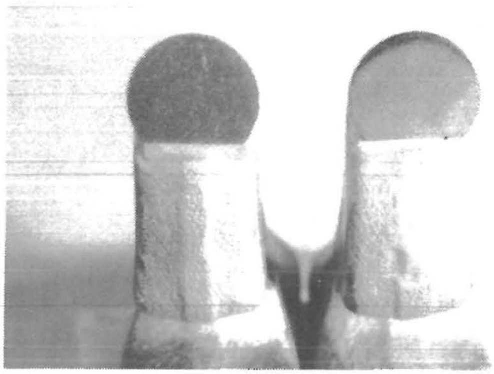
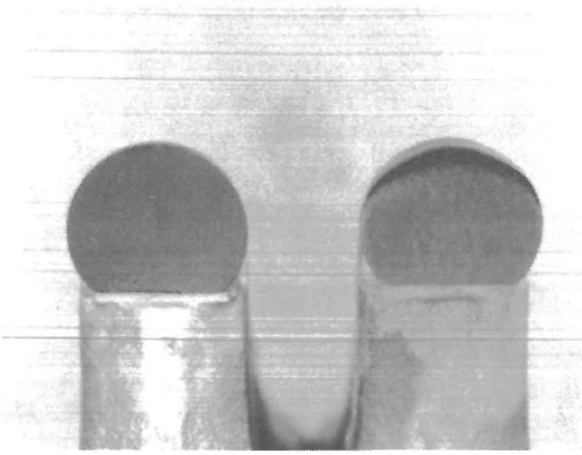


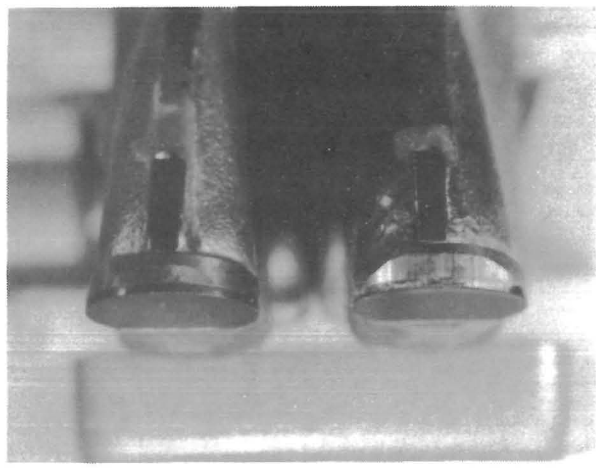
Figure C–3.–Three-insert PDC bit at various cutting distances–Con. *M*, **Front view (note both side PDC inserts are missing);** *N*, **top view;** *O*, **front view;** *P*, **top view (note main PDC insert fell out during a subsequent force test, shortly after wear testing had been terminated).**



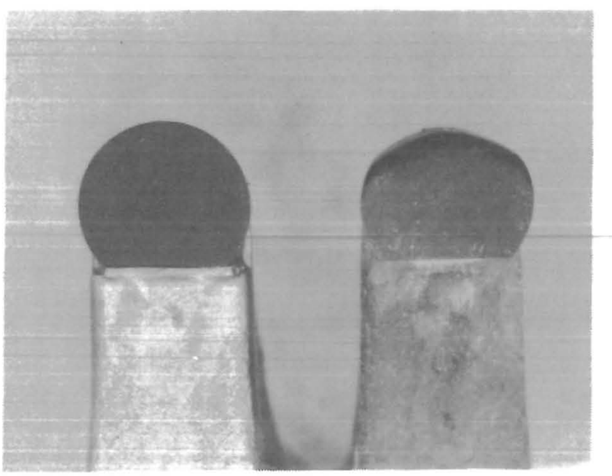
A, 8,808 ft



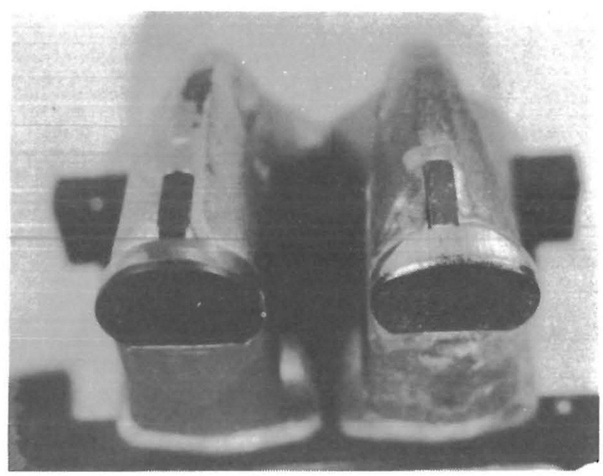
B, 35,544 ft



C, 35,544 ft

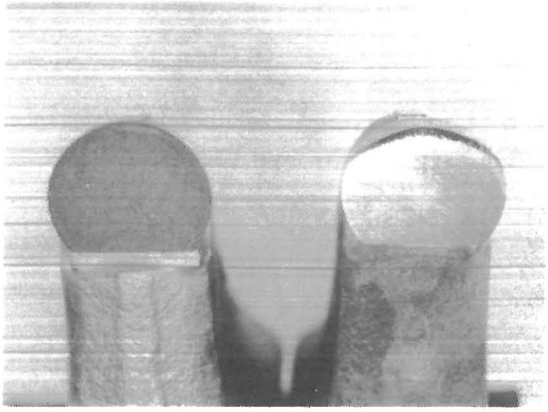


D, 61,416 ft

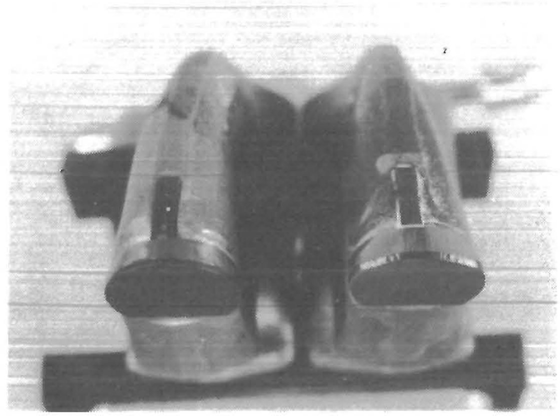


E, 61,416 ft

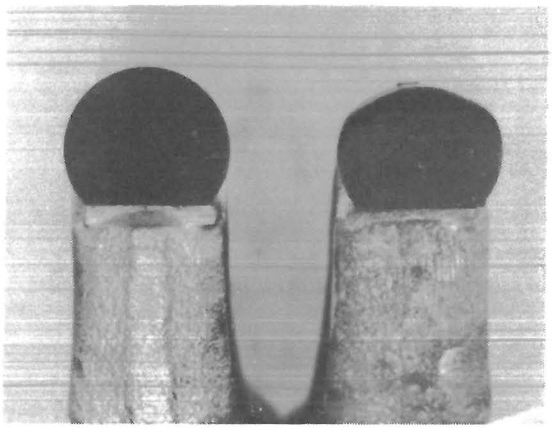
Figure C-4.–The 0° PDC bit at various cutting distances. *A*, Front view (note slight scuffing of cutting edge); *B*, front view; *C*, top view (note wear has extended into tungsten carbide backing); *D*, front view; *E*, top view.



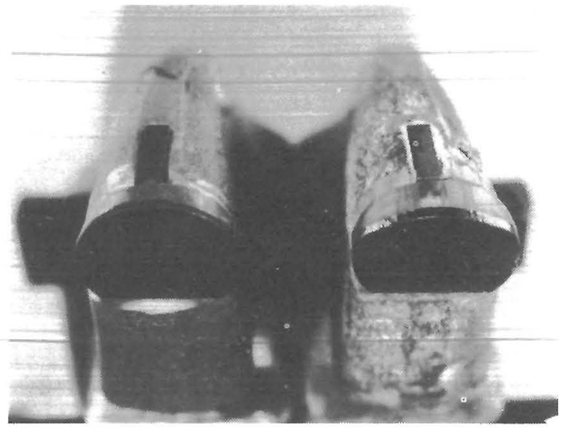
F, 80,136 ft



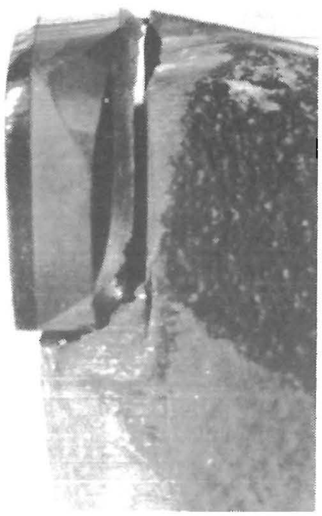
G, 80,136 ft



H, 98,664 ft

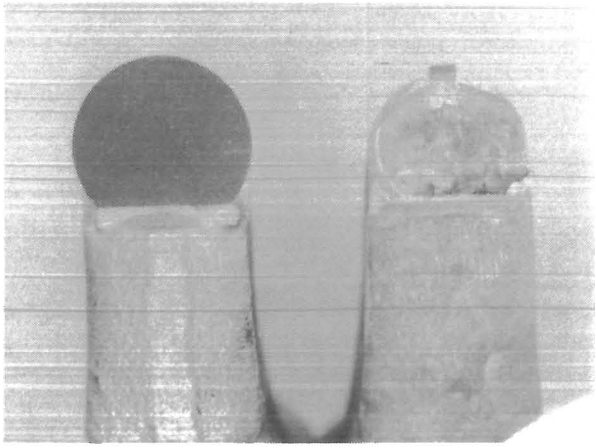


I 98,664 ft



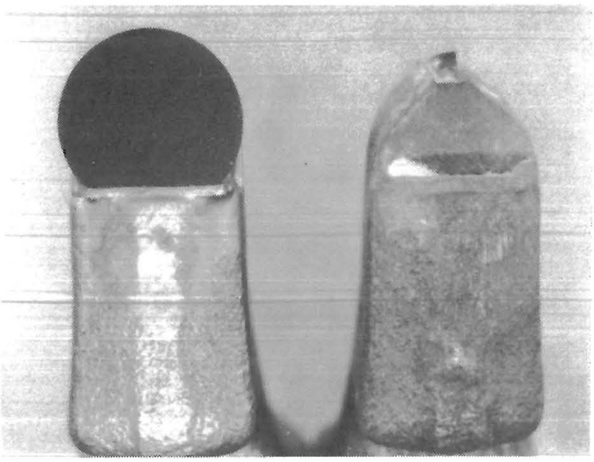
J, 98,664 ft

Figure C-4.—The 0° PDC bit at various cutting distances—Con. *F*, **Front view;** *G*, **top view;** *H*, **front view;** *I*, **top view (note main insert is actually detached but positioned in place for photo, although clearance PDC insert remains intact);** *J*, **side view (note separation of insert from bit body at tool steel-braze interface and large wear angle of PDC material relative to tungsten carbide).**

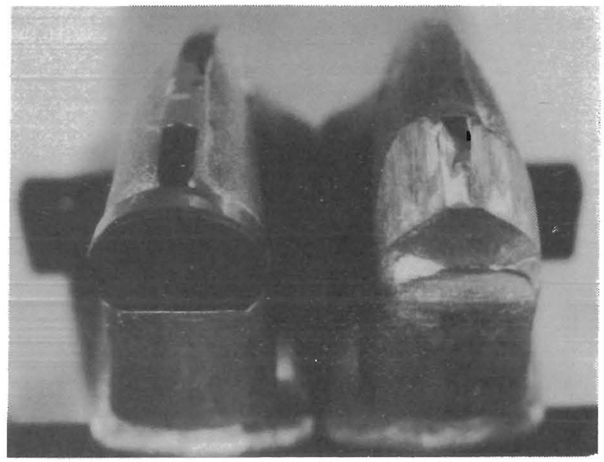


K, 98,664 ft

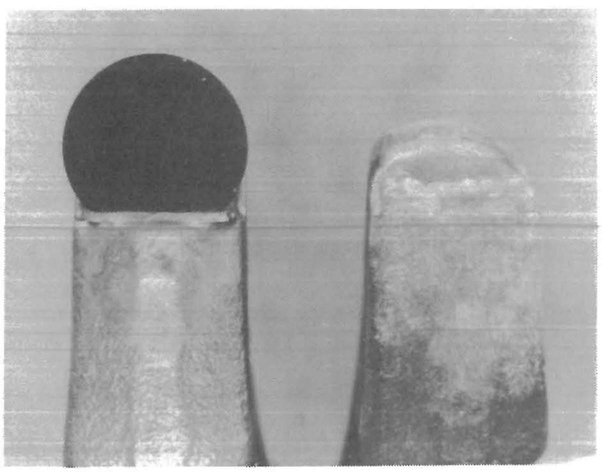
L, 98,664 ft



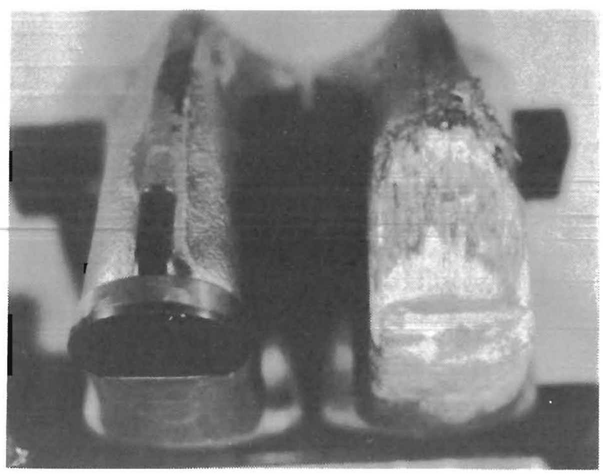
M, 100,440 ft



N, 100,440 ft



O, 101,520 ft



P, 101,520 ft

Figure C-4.–The 0° PDC bit at various cutting distances. *K*, Front view; *L*, top view; *M*, front view; *N*, top view; *O*, front view; *P*, top view (note melting of tool steel and presence of melted and recompacted quartz).

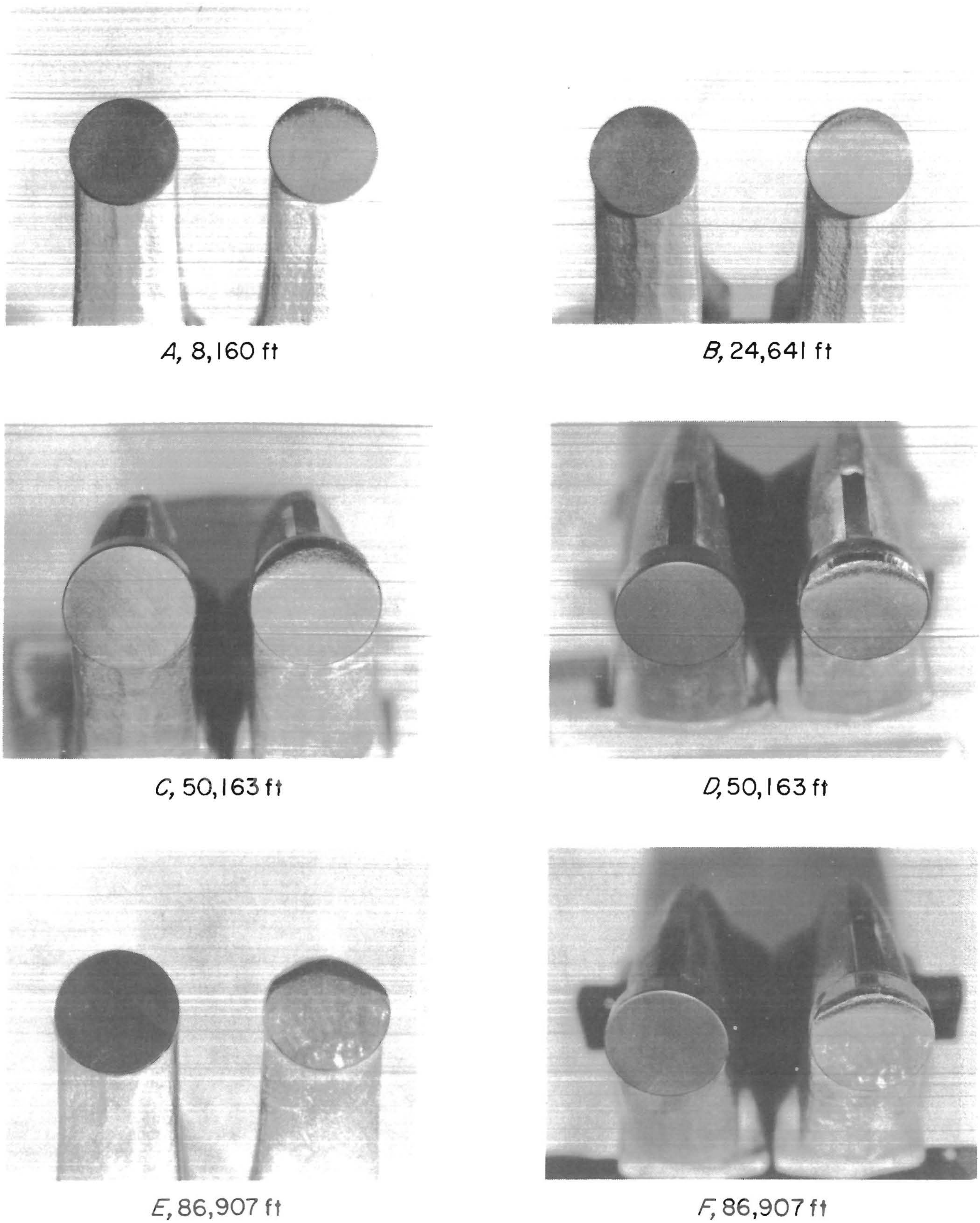


Figure C-5.–The -20° PDC bit at various cutting distances. *A*, Front view (note slight scuffing of cutting edge); *B*, front view; *C*, front view; *D*, top view (note wear beginning to extend into tungsten carbide backing); *E*, front view; *F*, top view.

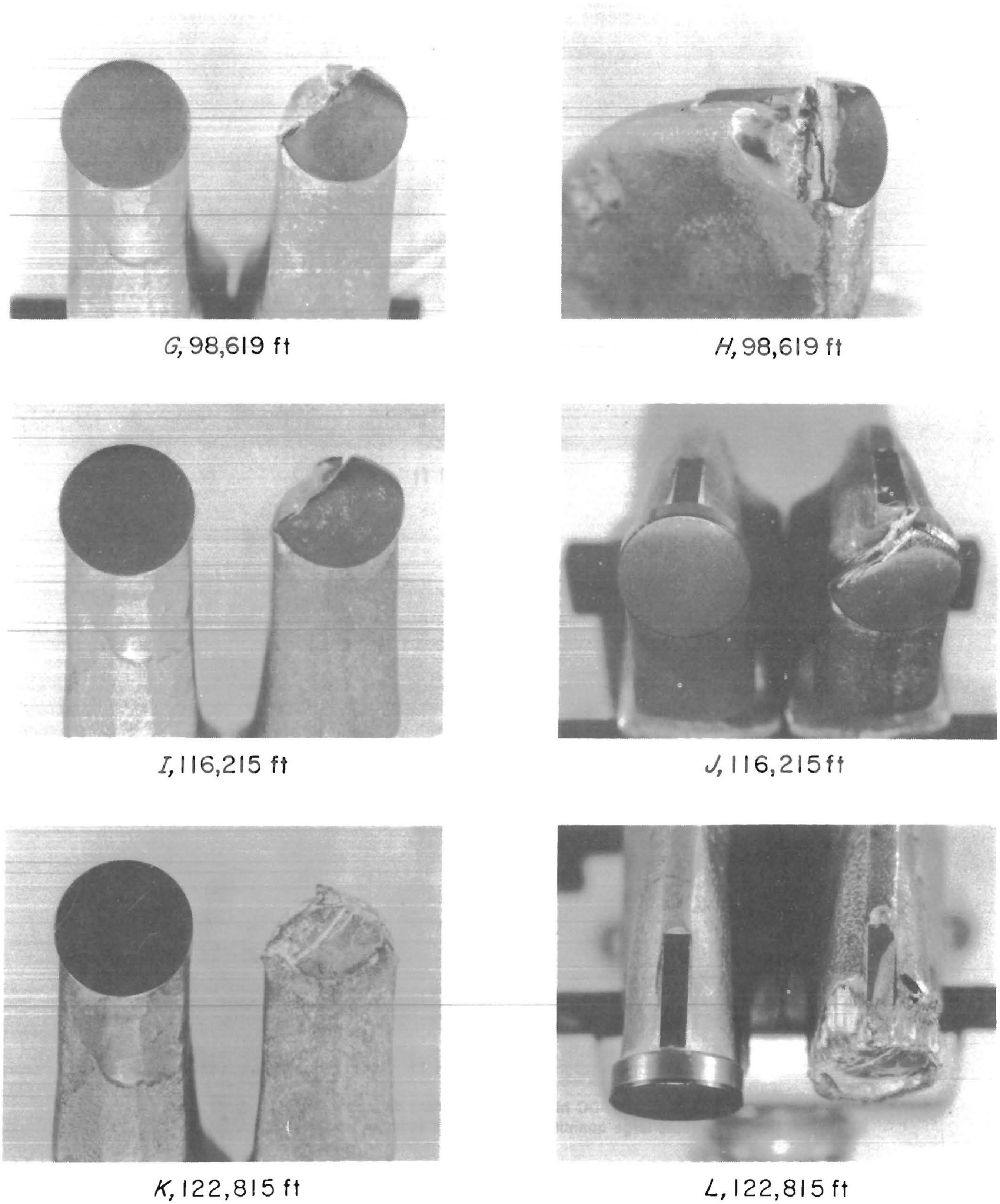
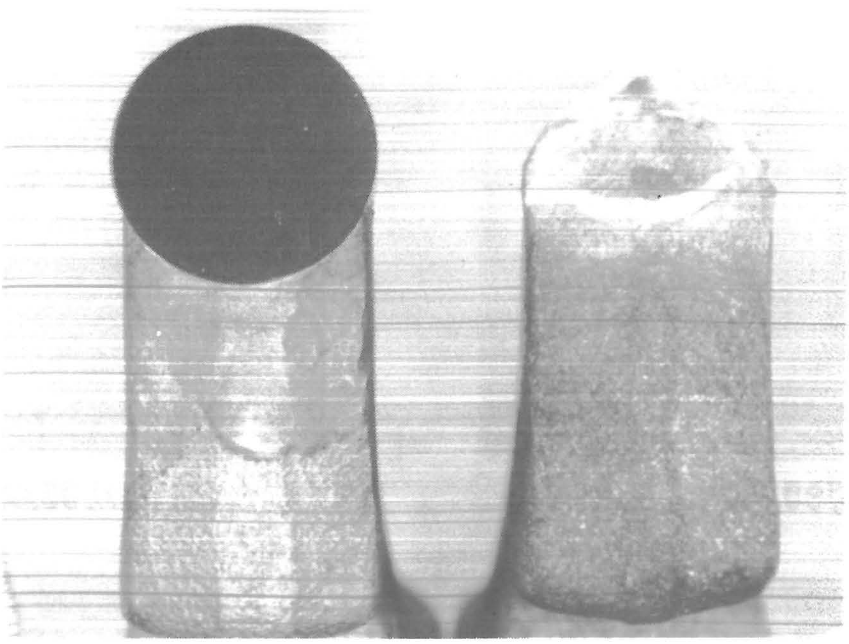
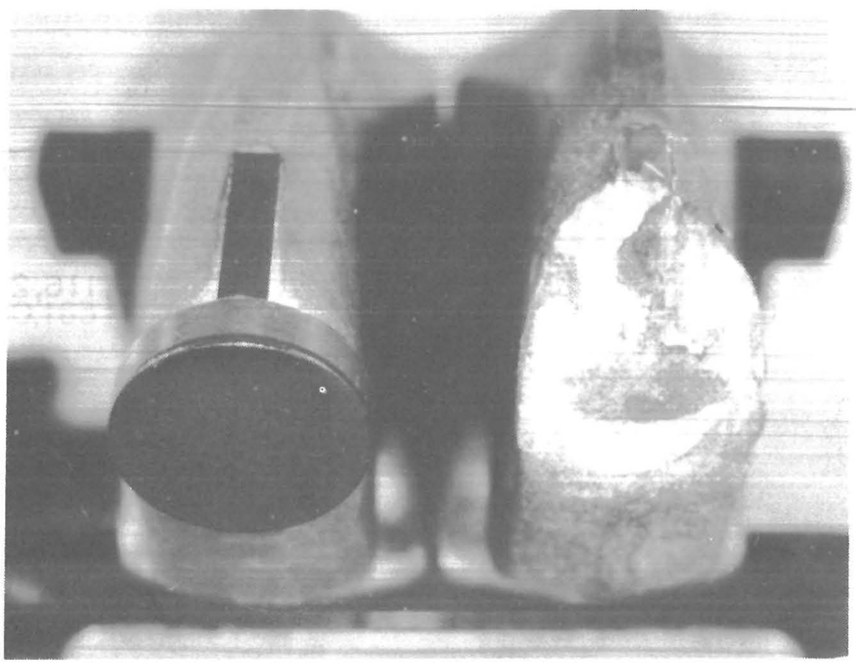


Figure C-5.–The -20° PDC bit at various cutting distances–Con. *G*, **Front view;** *H*, **side view (note that insert was broken accidentally, not by normal cutting conditions);** *I*, **front view;** *J*, **top view;** *K*, **front view;** *L*, **top view (note missing main, and broken clearance inserts, and melting of tool steel).**



M, 125,071 ft



N, 125,071 ft

Figure C-5.–The -20° PDC bit at various cutting distances–Con. *M*, Front view; *N*, top view (note large quantity of melted and recompacted quartz).

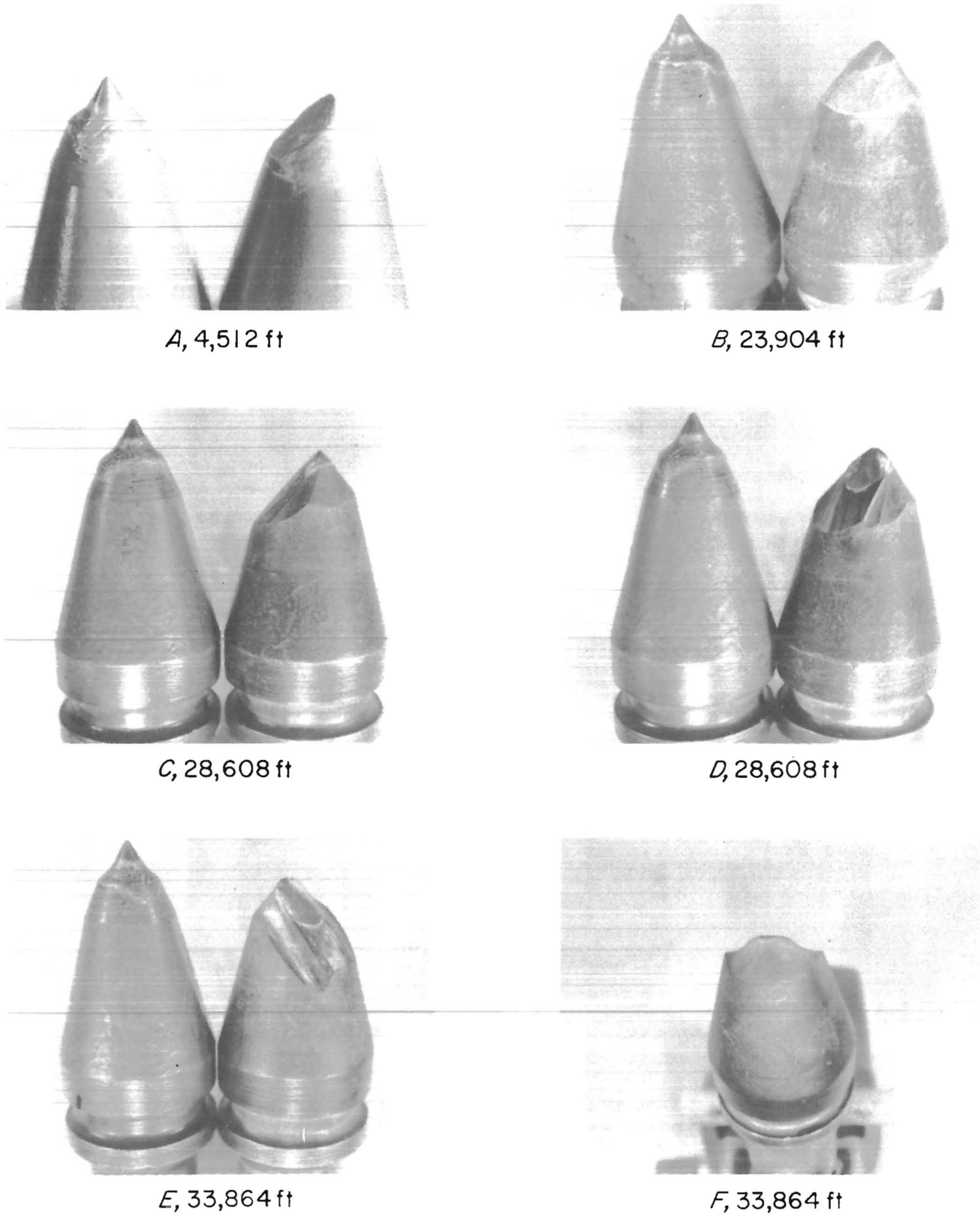
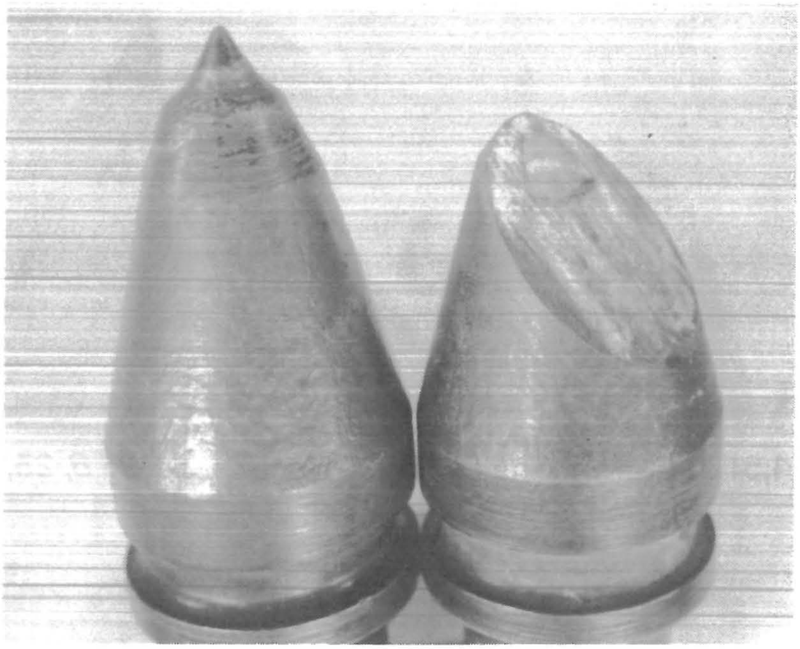
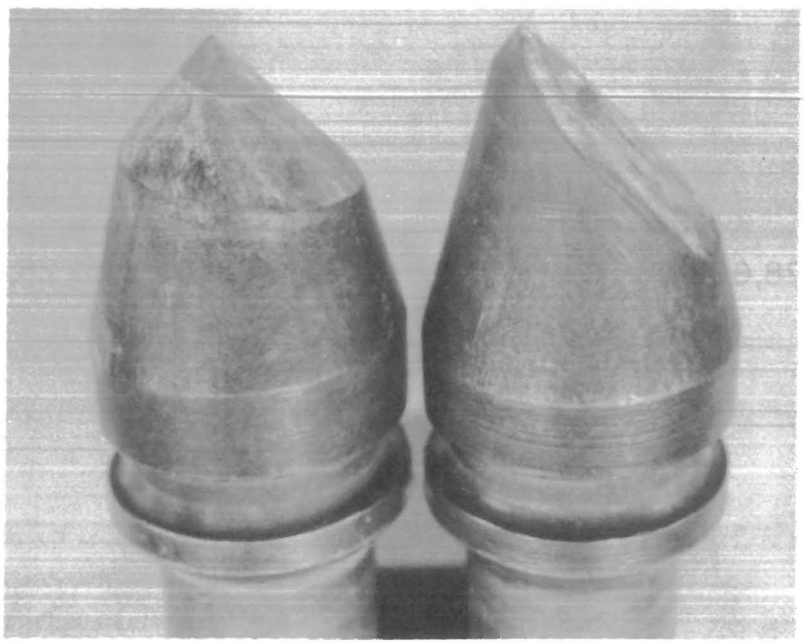


Figure C-6.—The 60° conical bit at various cutting distances. *A*, Front view; *B*, front view (note that bit was locked in its holder to prevent rotation after this point); *C*, front view; *D*, side view (note formation of a large wear flat); *E*, side view (note that tool steel is wearing more quickly than tungsten carbide and large quantity of melted and recompacted quartz); *F*, top view.

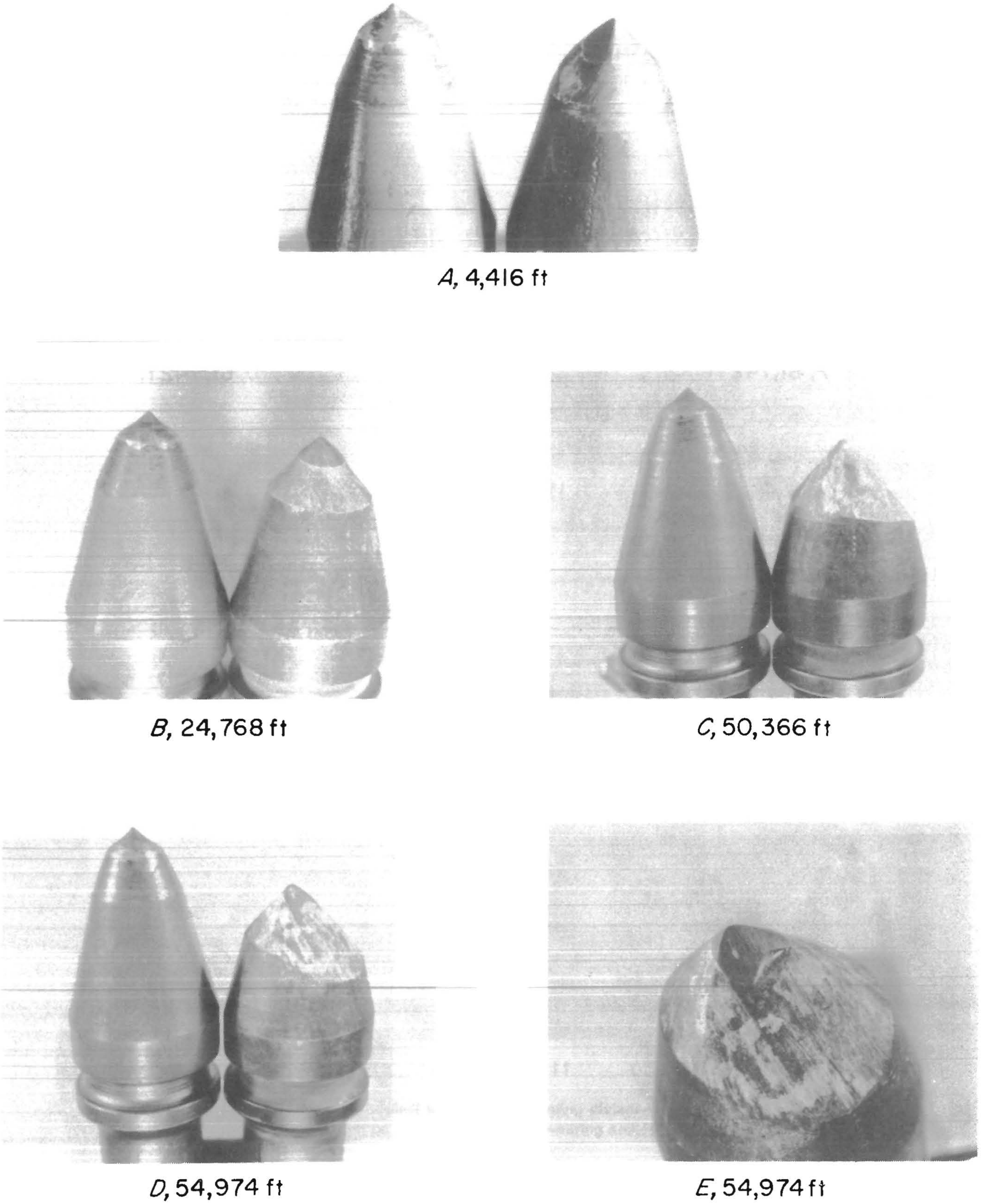


G, 38,520 ft



H, 38,520 ft

Figure C–6.–The 60° conical bit at various cutting distances–Con. *G*, **Side view (note missing tungsten carbide insert);** *H*, **left: 90° conical, 41,928 ft; right: 60° conical, 38,520 ft.**



A, 4,416 ft

B, 24,768 ft

C, 50,366 ft

D, 54,974 ft

E, 54,974 ft

Figure C–7.–The 90° conical bit at various cutting distances. *A*, **Front view;** *B*, **front view;** *C*, **front view;** *D*, **side view;** *E*, **top view (note chipped insert, presence of melted and recompacted quartz, and evidence that the bit is only occasionally rotating symmetrically).**

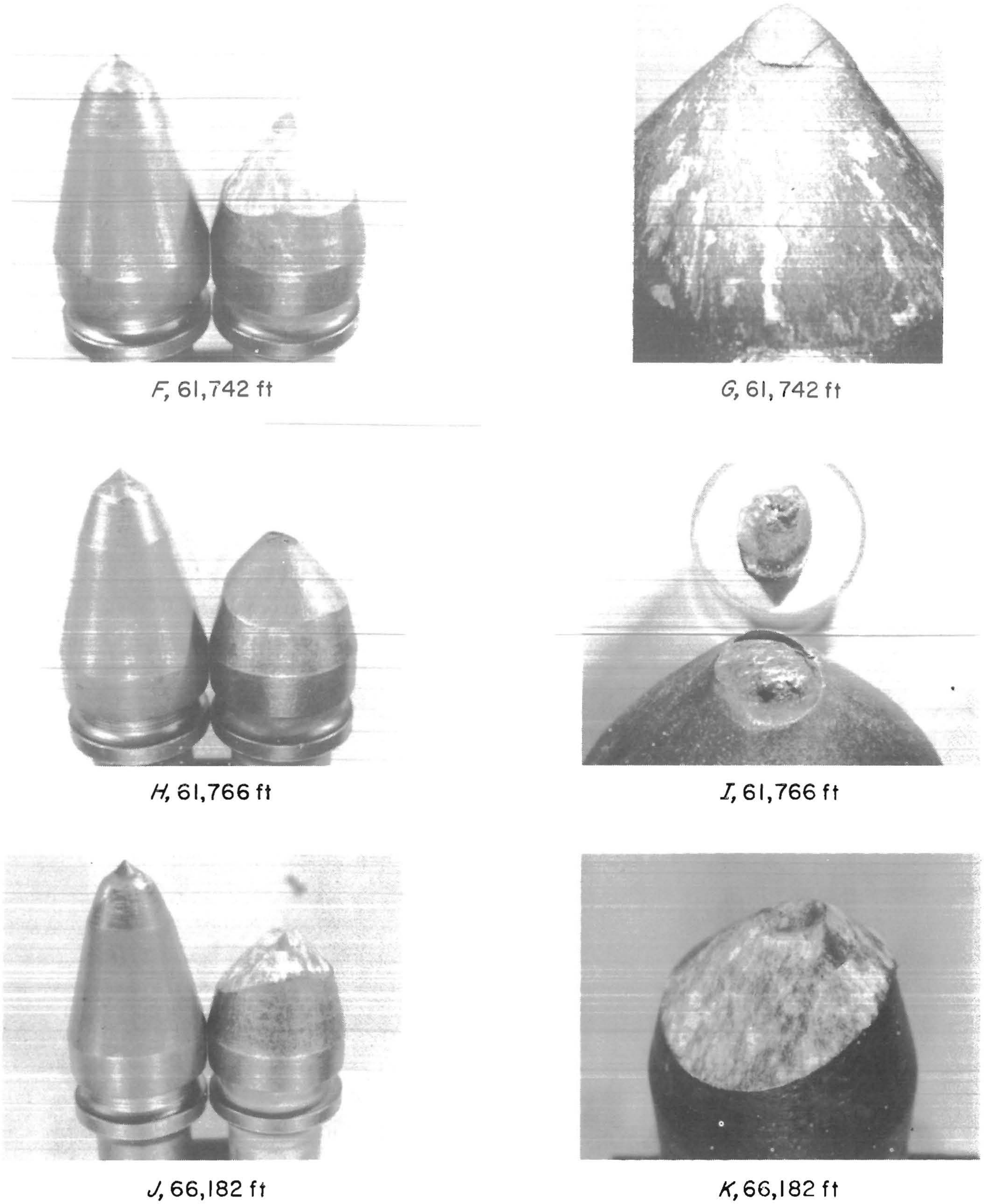


Figure C-7.–The 90° conical bit at various cutting distances–Con. *F*, **Front view;** *G*, **close view of bit tip (note cracked insert);** *H*, **front view (note that tungsten carbide insert has separated from tool steel body);** *I*, **close view of bit tip (note separated insert above bit);** *J*, **front view;** *K*, **close view.**

L, 73,910 ft

M, 83,150 ft

Figure C–7.–The 90° conical bit at various cutting distances–Con. *L*, Front view; *M*, front view (note that bit is still rotating and wearing somewhat asymmetrically).

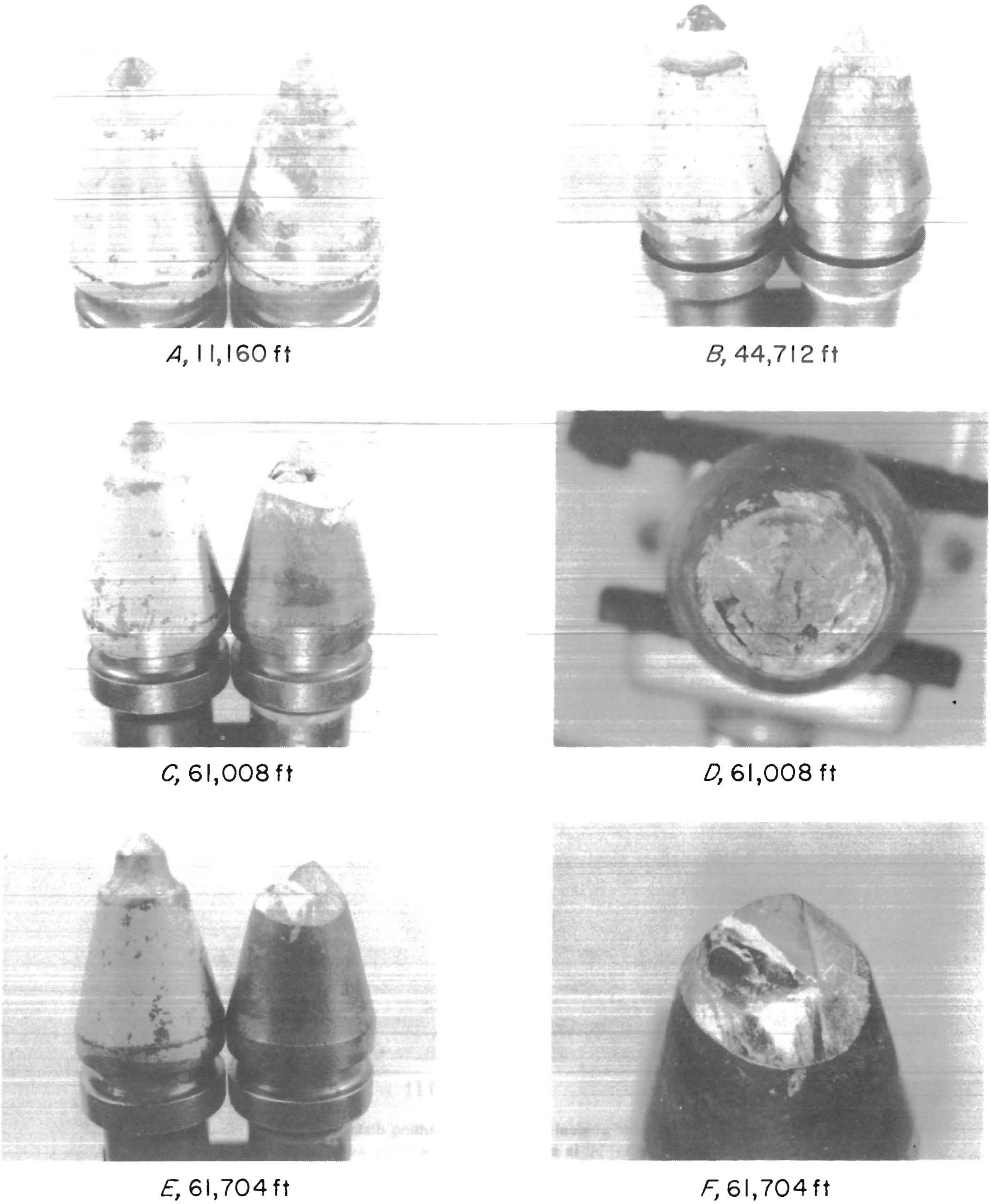


Figure C–8.–The 90ET bit at various cutting distances. *A*, **front view;** *B*, **front view (note that bit is wearing somewhat asymmetrically);** *C*, **front view;** *D*, **top view (note extensively cracked insert and melted compacted quartz);** *E*, **front view;** *F*, **close view of bit tip (note missing half of insert).**

G, 70,776 ft

Figure C-8.–The 90ET bit at various cutting distances–Con. *G*, Front view.

APPENDIX D.–QUALITATIVE VISUAL AND AUDITORY OBSERVATIONS OF BIT WEAR TESTS

Round-nose radial bit

3,744 ft	Small flat worn on the bit.
7,056 ft	Large amount of sparking observed periodically. Cuttings contain a large amount of chips compared with the cuttings produced by -20° bit cuttings.
9,264 ft	Moderate sparking observed between 7,056 ft and 9,264 ft – sometimes severe. Bit was hot enough to burn a finger shortly after testing stopped.
11,472 ft	Occasional minimal amount of sparking observed. Sometimes a few large, bright sparks are seen.
13,632 ft	Moderate to heavy sparking.
15,744 ft	Testing discontinued because bit was worn out.

Parrot PDC bit

4,344 ft	Seeing a few tiny sparks as the bit makes its initial contact with the block. Produces many large chips in the cuttings instead of the relatively fine cuttings generated by the other PDC's (Note: Spacing versus depth ratio was effectively greater and more optimal than it was for the other bits).
8,856 ft	Occasional minor sparking observed.
26,256 ft	No sparking observed.
28,632 ft	No sparking.
31,008 ft	No sparking.
33,336 ft	No sparking.
57,120 ft	Heavy sparking, so stopped test to check bit; found that the PDC had been worn off and only the WC remained as a cutting surface.
59,040 ft	Heavy sparking and much vibration in the system.
61,440 ft	Generally heavy sparking with intermittent periods of light to moderate sparking. Vibrational levels correspond to sparking intensity. Test discontinued because the bit had worn out.

Three-insert PDC bit

2,280 ft	This bit is unusually quiet and vibration-free.
4,320 ft	This bit produces perhaps the most uniformly coarse cuttings of any yet tested. There is a large quantity of >1/4-in material on both sides of the drum, and even the fine material under the drum is relatively coarser than that produced by the other PDC bits.
62,616 ft	Minor sparking.
73,752 ft	Occasional minor sparking. Found that the inner one-third of one side of the PDC inserts had broken away allowing abrasion of the WC backing to proceed.
85,752 ft	Noticed that chipping had started on the previously intact side insert, with the other showing significant wear.
88,056 ft	Light vibration and very minor sparking. Much quieter than the 90ET bit at 70,000 ft or the 90° conical at 80,000 ft, and the cuttings are much more uniform in size and distribution.
91,536 ft	One of the side inserts has fallen out.
92,328 ft	Light vibration and very minor sparking.
95,736 ft	The other side insert has fallen out.
96,504 ft	Light vibration and very minor sparking.
101,184 ft	Noticing a little more sparking now. Light vibration and minor sparking overall. Noticing a squeaking noise from the bit during cutting that sounds somewhat like a fingernail on a chalkboard. Decided to discontinue testing because additional data can be extrapolated from results of work with the parrot PDC bit. (Note: PDC insert fell out during a force test after wear testing had been discontinued.) The wear rate should increase from this point in a manner similar to that exhibited by the parrot PDC bit after its insert fell out.

0° PDC bit

8,808 ft	This bit appears to impart much less momentum to the sandstone block; the cutting is much quieter and the block barely vibrates with the initial contact of the bit compared with the others. No sparking observed.
18,840 ft	The bit again appears to impart much less momentum to the sandstone, and the sound level is much lower than with the -20° PDC bit. There is also less of an explosive action to the cuttings with the 0° bit; nearly all cuttings are found directly underneath the drum, while the -20° bit throws a relatively greater amount away from the drum.
28,968 ft	The 0° PDC bit appears to produce a relatively greater amount of fines than the -20° PDC, but these fines appear to be relatively coarser than those produced by the -20° bit.
77,736 ft	Minor sparking observed.
98,664 ft	PDC insert fell out; clearance insert remains.
100,080 ft	Minor sparking and vibration. Sparking is observed only when the bit strikes the very edge of the block. Apparently, the clearance insert is protecting the bit during normal cutting. Spacing versus depth ratio is greater than optimum, since the bit now has such a narrow profile; the cuts are not interactive.
100,440 ft	The front two-thirds of the clearance insert has broken off, and inspection of the block showed that about 50 pct of the cuts are now interactive. Possible explanations for this change are that the tool width effectively increased or the geometry of the bit changed in some way that increased the lateral force of the bit upon the sandstone.
101,520 ft	Moderate to heavy sparking and vibration. Testing discontinued because the bit had worn out.

-20° PDC bit

2,016 ft	No sparking observed; produced relatively fine cuttings.
4,032 ft	Bit face only slightly polished.
8,160 ft	PDC surface only polished on upper edge of bit.
9,168 ft	This bit generates a sound similar to that produced by sandpaper during its use, as opposed to the harsh scraping sound of carbide insert bits. No sparking observed.
17,856 ft	No sparking observed.
63,267 ft	Lots of vibration induced in the system while cutting with this bit.
71,835 ft	Back part of sandstone block literally exploded, apparently owing to the force of the initial impact of the bit upon the rock. Decided to discontinue testing until force test data are analyzed.
94,059 ft	Block disintegrated under impact.
98,619 ft	The initial impact force was very high with this bit, so much so that it was causing the back of the sandstone blocks to fracture along the bedding planes, and sometimes causing the blocks to fail explosively. Decided to install a side brace for the block in an attempt to further stabilize the block and minimize the induced fracturing. A corner of the brace protruded into the bit path, which was not noticed until it was hit by the bit. One-half of the bit fractured off and was not recovered.
100,971 ft	Decided to run the broken -20° bit to see what would happen. There is much less noise and vibration while cutting with the broken bit than when it was in "good" shape. Also, there are many more >1/8-in chips in the cuttings with the broken bit, compared with the "good" bit. (Note: The spacing versus depth ratio effectively increased when the bit broke, more closely approaching optimum conditions, and the area of the bit actually in contact with the rock during cutting decreased.) Most of those chips were found in a pile off to the side of the bit that had broken away.
122,815 ft	Bit broke as a result of the sandstone block breaking, falling forward, and jamming between the bit and table. Main PDC insert fell out, clearance insert damaged but in place. Brazing material still adheres to the steel body.
124,000 ft	Heavy vibration, minor to moderate sparking. Enough of the clearance insert remains so that it may play a part in inhibiting sparking.
124,543 ft	Heavy sparking. The front two-thirds of the clearance insert was found to have broken away. The bit appears to have friction heated to a relatively high temperature after the clearance insert fell out; the metal near the bit tip is now fairly discolored.

60° conical bit

4,512 ft	Bit was free to rotate, although a wear flat had formed. Large amount of sparking.
6,672 ft	Very little sparking observed. Bit was free to rotate. Cuttings contained many large (>1/2-in maximum dimension) chips.
11,016 ft	Minimal sparking observed.
13,200 ft	Occasional minor sparking.
23,928 ft	Decided to lock the bit in its holder to prevent rotation. Bit geometry now essentially identical to the 90° conical at similar footage, so want to compare rotating and nonrotating bits.
26,256 ft	Occasional light to moderate sparking observed. A small wear flat has begun to form.
29,472 ft	Moderate to heavy sparking.
31,656 ft	Occasional periods of moderate to heavy sparking.
33,864 ft	Occasional periods of moderate to heavy sparking, during which there is a lot of vibration induced in the system.
36,288 ft	Occasional periods of moderate to heavy sparking with light sparking common.
38,520 ft	Carbide insert broken, so testing discontinued.

90° conical bit

4,416 ft	Clearance flat developed on one side even though the bit was free to rotate. Large amount of sparking.
6,624 ft	Only a small amount of sparking was observed.
11,064 ft	Moderate sparking observed between approximately 6,880 ft and 7,800 ft, minimal thereafter.
13,248 ft	Occasional minor sparking observed.
15,408 ft	Minor sparking.
43,704 ft	Back of the sandstone block disintegrated under impact of the bit. Lots of vibration in the test stand with this bit.
52,646 ft	Cuttings are much coarser than those produced by a relatively new bit. Occasional periods of heavy sparking.
61,766 ft	Carbide insert fell out.
64,166 ft	Only moderate vibration and very minor sparking. This points to a proportional relationship between clearance angle and sparking, and contact area and forces. Spacing versus depth ratio is, in effect, low here, owing to the relatively large bit width. Visually there seemed to be a large amount of dust produced while cutting; cuttings were relatively small in size.
66,182 ft	Heavier vibration, but still only minor sparking. Heavy vibration and sparking started at about 65,100 ft and lasted for 100 ft until the bit rotated back to moderate vibration and minor sparking.
67,574 ft	Moderate to heavy vibration, but only very minor sparking. Periods of relatively light vibration. Bit is wearing asymmetrically and is obviously rotating.
69,518 ft	Still only minor sparking.
71,678 ft	Light to heavy vibration and still only very minor sparking.
73,910 ft	Starting to get occasional periods of moderate sparking–mostlyvery minor sparking, though. Light to moderately heavy vibration as the bit rotates.
76,262 ft	Moderate to heavy vibration, but still only relatively light sparking.
83,150 ft	Moderate to heavy vibration, but still only relatively light sparking. Testing discontinued because bit is worn out.

90ET

0 ft	This particular bit has its carbide insert set at about 1.5° off the axis of the bit – it's skewed enough to be very noticeable to the eye. It may or may not have an effect on the rate or pattern of wear compared with a bit with a properly centered insert.
2,016 ft	Minor sparking, but little vibration while cutting.
13,584 ft	Moderate sparking and vibration. This bit produces cuttings similar in size and distribution to the three-insert PDC bit, but with much more sparking and vibration.
15,960 ft	Minor vibration and sparking. Apparently, the bit is wearing asymmetrically, so that the clearance angle, and consequently sparking and vibration, changes as the bit rotates.
24,696 ft	The bit is wearing asymmetrically so that as it rotates, spacing and depth of cut change continuously. Sparking intensity, noise, and vibration increase in relative proportion to depth of cut (and consequent negative clearance angle). Wear of the tool steel bit body has begun.
31,656 ft	Light to moderate sparking.

38,328 ft	The bit is wearing asymmetrically and, as it wears, the difference in vibration, depth of cut, noise, and sparking is very dramatic between the opposite sides having maximum positive and negative clearance angles.
49,200 ft	Periods of heavy sparking and vibration. Sandstone block shattered after nearly continuous heavy vibration.
51,648 ft	Heavy sparking and vibration.
53,952 ft	Relatively light sparking and vibration on greater part of block – dramatic difference from previous block.
56,448 ft	Light to heavy sparking and vibration.
61,008 ft	Stopped test, as sandstone block shattered. Carbide tip is extensively cracked and probably will fail soon.
61,704 ft	Noticed that sparking and vibration had become unusually light, and upon examining the bit found that a large part of the carbide had broken away.
63,744 ft	Light to heavy sparking and vibration. Generally lighter than normal overall.
66,096 ft	Remaining half of carbide still relatively intact.
70,776 ft	Moderate vibration and sparking. Testing discontinued.

INT.-BU.OF MINES,PGH.,PA. 28785

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