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REPORT OF INVESTIGATIONS/1991

Testing of a Diesel-Powered Impact Cutting Head for Hard-Rock Mining

By P. D. Kovscek, C. D. Taylor, and H. Handewith

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	kHz	kilohertz
ft/s	foot per second	lb	pound
Gal	acceleration = 386 in/s^2	lb/ft^3	pound per cubic foot
hp	horsepower	psi	pound (force) per square inch
hp·h/st	horsepower hour per short ton	s	second
Hz	hertz	st/h	short ton per hour
in	inch	yd^3	cubic yard

TESTING OF A DIESEL-POWERED IMPACT CUTTING HEAD FOR HARD-ROCK MINING

By P. D. Kovscek,[1] C. D. Taylor,[2] and H. Handewith[3]

ABSTRACT

The performance of a novel prototype kerf-cutting impact mining machine was evaluated under a cooperative agreement between the U.S. Bureau of Mines and RAMEX Systems, Bellevue, WA, while operating under conditions typical of normal tunnel entry development. Selected operating parameters were monitored concurrently to determine baseline operating conditions and to study relationships between operating parameters. Using the data obtained, the specific energy requirements of the impact mining machine were calculated and compared to specific energy requirements of tunnel boring machines cutting in rock having similar hardness. Tests results indicate that the kerf-cutting impact mining machine can provide a mechanical means for mining very hard rock that cannot be effectively mined using commercially available mechanical excavators.

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INTRODUCTION

To increase productivity, the mining industry must sometimes try innovative types of mechanized mining systems. In the past, much of this technology has been based on the use of mining machines, such as the roadheader, that use rotary cutting heads with drag bits. However, the effectiveness of these machines is limited by rock hardness. If the rock is too hard to be cut by a mining machine, then explosives may be used. Mining with explosives is a labor-intensive operation, and the fracturing and weakening of surrounding rock strata are difficult to control.

Other types of mining machines that can cut in some harder rock use disk cutting bits. However, most of these machines, such as the tunnel borer, are large, difficult to maneuver and limited to cutting entries having a uniform diameter.

A new type of mechanized mining machine has been developed to fill the gap in technology between mechanical cutting machines and explosives or tunnel boring machines. Energy is delivered to an impact cutting head, eight to nine times per second, by a single free-floating piston. With an impact velocity of 10 ft/s, the cutting head is capable of fracturing and creating kerfs in rock too hard for most mechanical machines to cut. The machine can be designed for easy maneuvering in an underground mine, and its articulated boom allows the cutting of entries of varying size.

The prototype kerf-cutting impact mining machine was built by RAMEX Systems of Bellevue, WA.[4] For the initial tests, the impact mining boom of the machine was mounted on the body of a diesel-powered excavator (fig. 1). The mining boom can be mounted on a conventional backhoe undercarriage for some demolition, secondary breaking, and tunneling operations (fig. 2). For underground use, the boom can be adapted to various types of undercarriages. Some underground mining operations require an undercarriage that can gather, convey, and load the rock that is removed. The mining machine can be made small enough so that it can be easily maneuvered in underground entries and taken in and out of the mine.

RAMEX Systems and the U.S. Bureau of Mines entered into a cooperative agreement to evaluate the performance of this mining machine. RAMEX Systems operated the prototype machine in a rock quarry, and the Bureau provided equipment and personnel for monitoring machine operating parameters.

[4]Handewith, H. J., W. D. Coski, and E. D. Thimons. Development of a Prototype Hard Rock Excavating Machine. Paper in Proceeding of 1989 Rapid Excavation and Tunneling Conference Los Angeles, CA, June 11-14, 1989, SME, 1989, pp. 769-787.

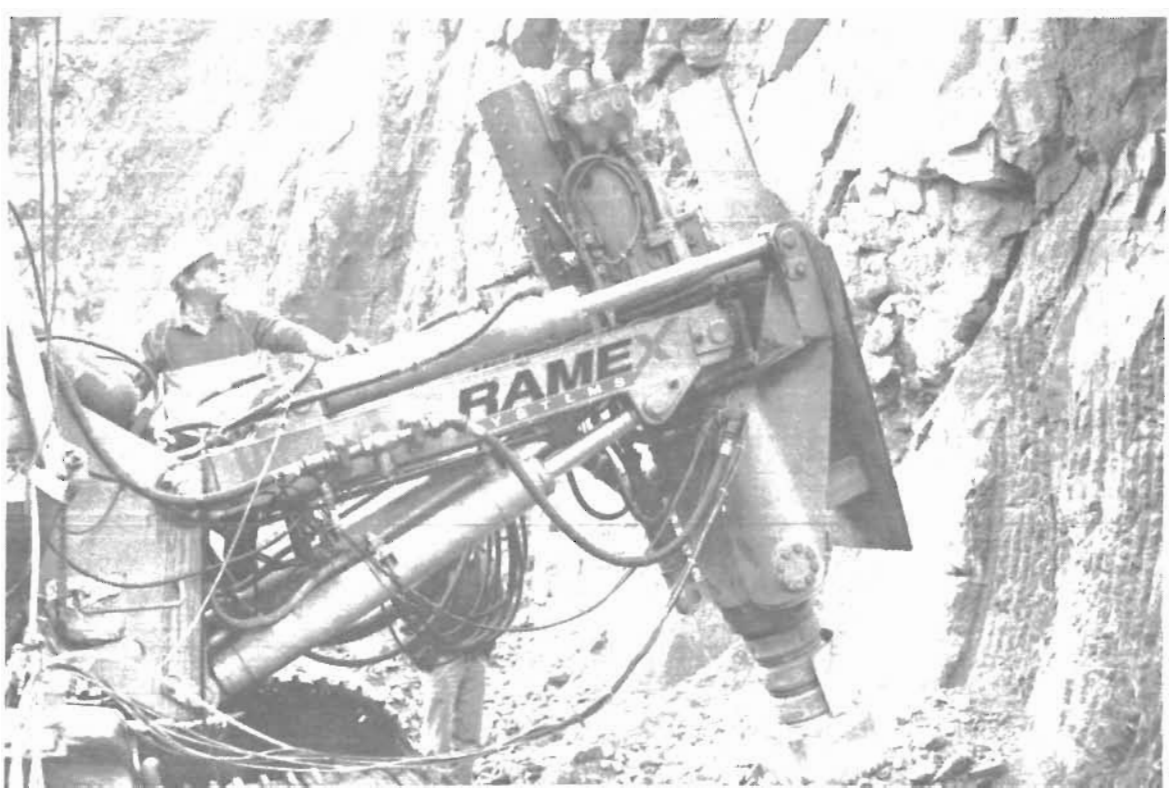

Figure 1.—Impact mining machine.

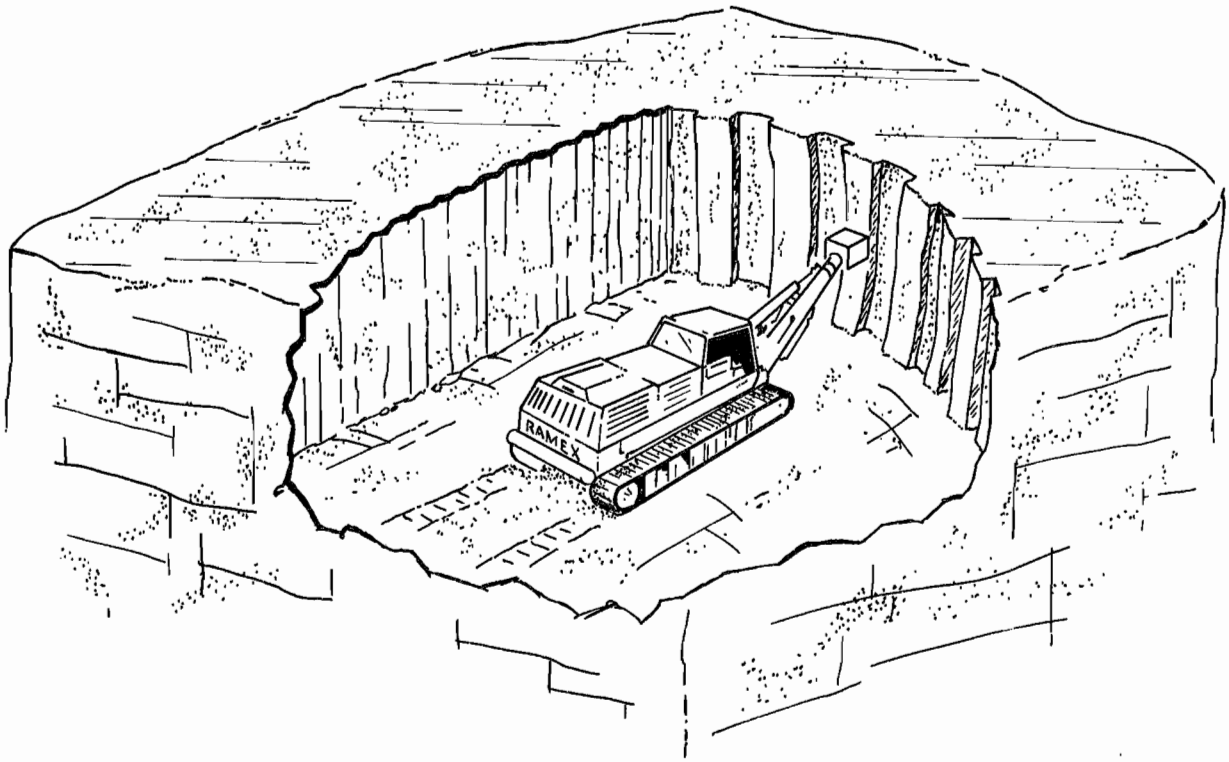

Figure 2.—Impact breaker performing tunneling operation.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of the following RAMEX Systems personnel who aided in operating the machine and setting up the monitoring equipment: Bill Coski, director and chief engineer; Richard Hunt, master mechanic; and Zepu Liang, test engineer. Allen Constantine, electronics technician, Schneider Services, Pittsburgh, PA assisted in the preparation and operation of the data collection system.

DESCRIPTION OF MACHINE DESIGN AND FUNCTION

Figure 3 shows the main internal components of the mining boom, which is called the Ram. A two-stroke, single-cylinder diesel engine moves a 700-lb piston inside the cylinder. The piston is free floating. To initially compress the air and attain fuel ignition, compressed air is released suddenly through a valve in the cylinder bounce chamber. Just before the piston reaches the combustion head, a linear cam shaft attached to the piston opens the fuel line valve, allowing fuel to pass through the diesel injector. The hot compressed air ignites the fuel. The combustion pressure stops the piston and causes it to move back toward the bounce chamber.

Compressed air in the bounce chamber stops the piston before it reaches the end of the cylinder. Without metal-to-metal contact, energy is transferred through the cushion of air to the cutting head. This cushion of compressed air also returns the piston to the combustion end of the cylinder where the cycle is repeated.

The cutting head (fig. 4) is specially designed to take advantage of the energy transferred from the piston. The 16- by 16-in head, which is bolted to the forward end of the Ram, has seven rows of 3/4 in tungsten carbide buttons that are spaced 2 in apart. Upon impact, with this spacing design, rock breaks out between the rows of buttons and creates a kerf or slot (fig. 5).

To develop a tunnel entry, several kerfs must be cut in the face. The cutter starts by sumping in about an inch deep at the crown and then trams down the tunnel face. Tramming the boom up and down produces a deep slot with five kerf-cut mounds on the bottom. The slot is deepened to about 1 ft by repeated tramming. The number of passes and depth of slot are determined by the

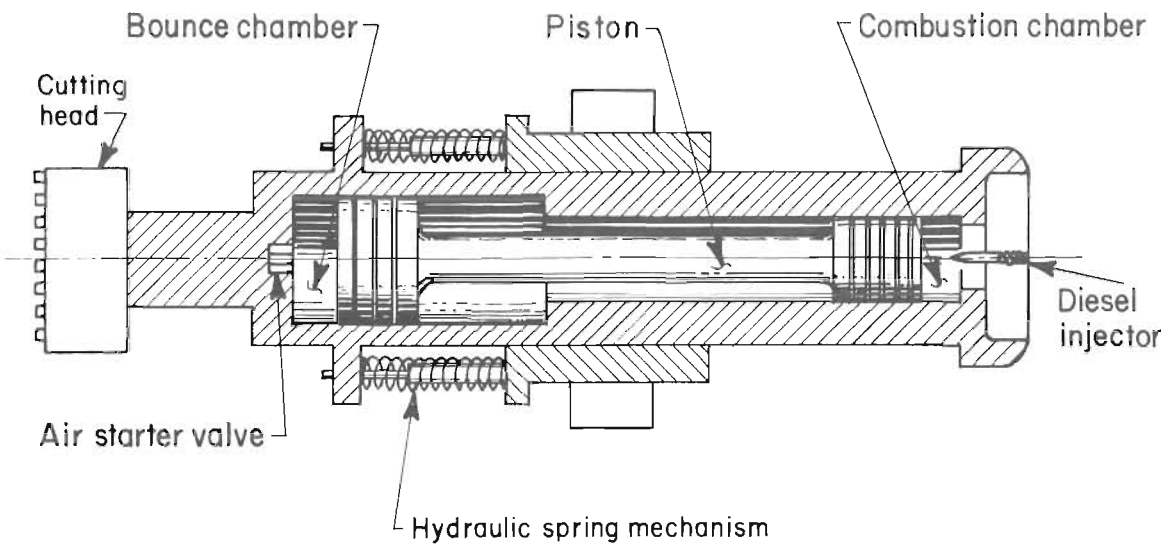

Figure 3.—Main components of Ram.

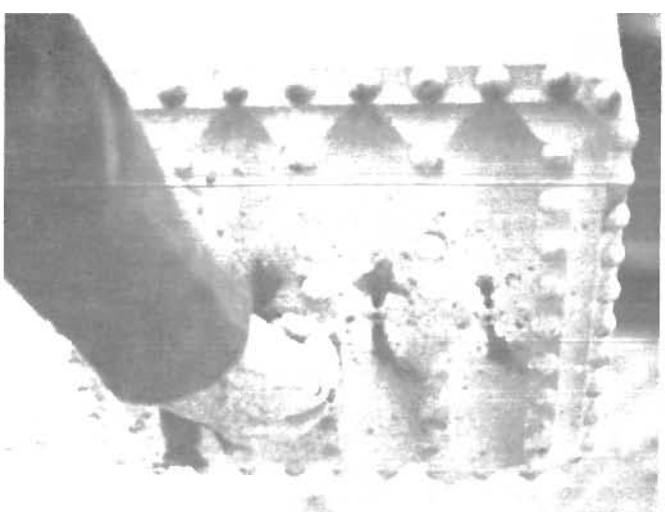

Figure 4.—Ram cutting head.

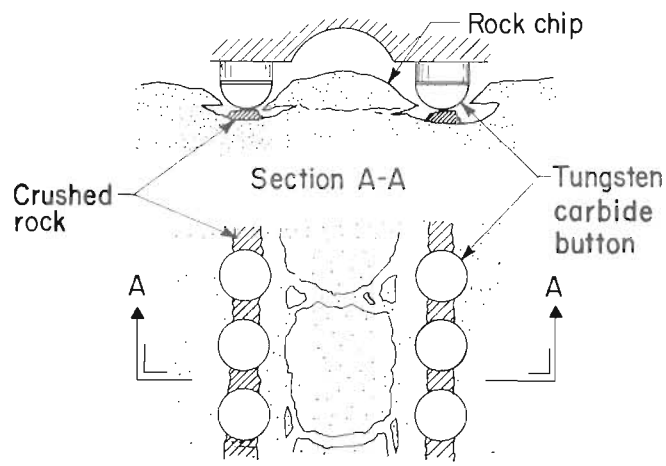

Figure 5.—Rock fracture pattern with Ram cutting head.

hardness of the rock formation being excavated. The tunnel gage is outlined with slots cut in this manner. Additional slots are then cut at convenient spacing across the tunnel face. The core or mound left between the slots, being unconfined on three sides, is broken out by the impacts of the cutting head.

As a new rock surface is exposed, subsequent impacts create new kerfs, and the depth of cut increases incrementally with each impact. The ability to control the shape and depth of the excavation is one of the primary advantages of using an impact mining machine with a kerf-cutting head.

Thrust force and Ram position are manually controlled by the operator. A steady thrust force is applied to the reciprocating Ram through a hydraulically actuated spring mechanism (fig. 3). The hydraulic mechanism senses thrust pressure and is used to automatically regulate engine throttle setting according to the power demand. This system also prevents operation of the engine when there is no power demand. Without this feature, destructive internal forces could occur.

EXPERIMENTAL PROCEDURES

Field-testing was conducted at a pit quarry site near Monroe, WA. The test rock was a massively jointed felsitic andesite that occurred at the quarry in a flow about 40 ft thick. The volcanic intrusive rock has a compressive strength of about 40,000 psi.

The machine was located at the base of a vertical 45-ft highwall. A wire mesh was bolted to the top of the bench and stretched above the test site to prevent rockfalls. During testing, the machine began developing a 10- by 10-ft simulated mine entry. For each test, the cutting boom was moved so that an 8-ft vertical slot was cut. Width of the slot was the same as the cutting head (16 in). The cutting boom, which was usually positioned horizontally to begin a test, was trammed up and down so that the same slot depth was maintained for the full length of cut.

Instrumentation for monitoring operating parameters was situated in a trailer located adjacent to the test site. Signal cables were extended from the trailer to the transducers, which monitored operating parameters on the mining machine and ground surface near the test site.

A block diagram of the data collection system is shown in figure 6. The type of transducers used and the parameters measured are discussed in the following section.

MACHINE PARAMETERS MONITORED

Piston and Ram Displacement

A pinion gear, attached to the shaft of a rotary potentiometer (0 to 500 ohm), was turned by a rack that was connected to the piston. A constant voltage was supplied to the potentiometer. The potentiometer was calibrated so that the voltage drop across the potentiometer was related to the piston displacement in the cylinder.

Ram movement, relative to the machine support structure, was monitored using a 12-in linear potentiometer. The upper end of the potentiometer was attached to the upper end of the Ram; the lower end of the transducer was attached to the machine support structure (fig. 7). A constant voltage was supplied to the potentiometer, which was calibrated so that the voltage drop across the potentiometer could be related to the Ram displacement relative to the machine support structure.

Combustion Pressure

A 0- to 5,000-psi, quartz-type pressure transducer was placed in the combustion chamber to monitor combustion pressure during each engine cycle.

Cutter Head Acceleration

A 0- to 200-Gal strain gauge accelerometer was installed on the top surface of the cutter head (fig. 8) to monitor the force delivered to the head in a direction parallel to the axis of the Ram (i.e., perpendicular to the rock surface).

Machine Body Force Measurements

Quartz-type accelerometers (0 to 50 Gal) were installed on the machine chassis beneath the operator's station and adjacent to the attachment point of the mining boom (fig. 9). Forces on the machine chassis were measured in three orthogonal directions (x = horizontal plane, y = vertical plane, and z = right or left, perpendicular to the axis of the Ram).

Rock Motion

High-output, low-distortion, 10-Hz geophones were installed approximately 25 ft from the cutter head at locations on the quarry highwall face and bench. Ground motion in the vertical direction was monitored at both locations.

Two quartz-type accelerometers (0 to 50 Gal) were installed on the highwall. One accelerometer, located 12 ft from the cutter head, measured rock motion in the horizontal direction. The second accelerometer, which was positioned adjacent to the highwall geophone, measured rock motion in the vertical direction.

Signal Conditioning and Recording

Charge amplifiers were used to power and condition the sensor signals from the combustion pressure transducer. Signals from the linear transducer were conditioned by instrumentation amplifiers. A full-bridge amplifier was used to power the sensor and condition the signal from the cutter head transducer. Battery-powered amplifiers were used to supply power and condition the sensor signals from the machine- and ground-mounted accelerometers. The geophone output required no signal conditioning and was connected directly to the magnetic tape recorder.

A 14-channel Racal[5] frequency modulated (FM) magnetic tape recorder, configured for a 10-kHz frequency

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

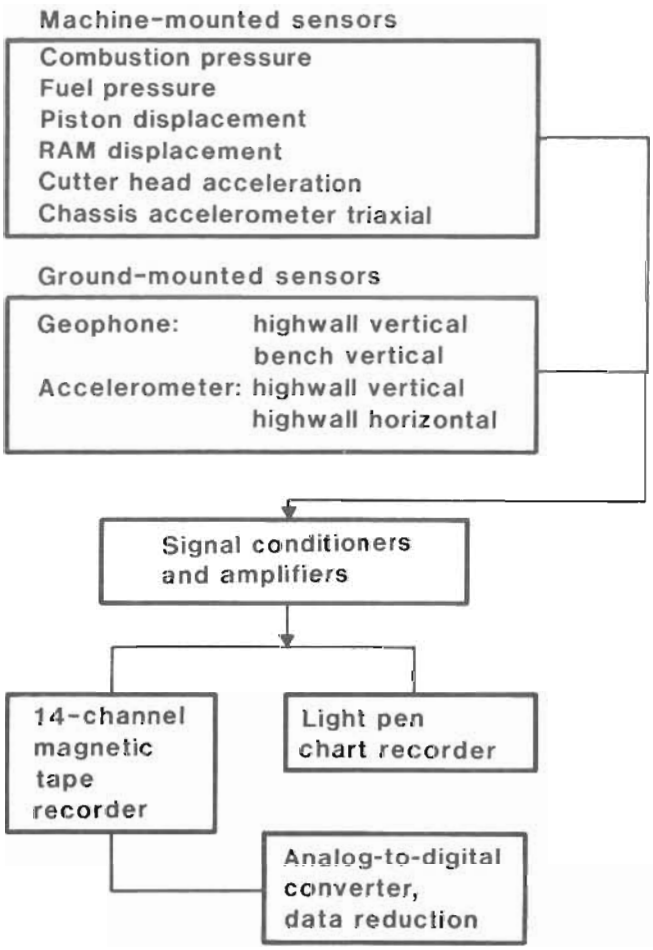

Figure 6.—Data collection system.

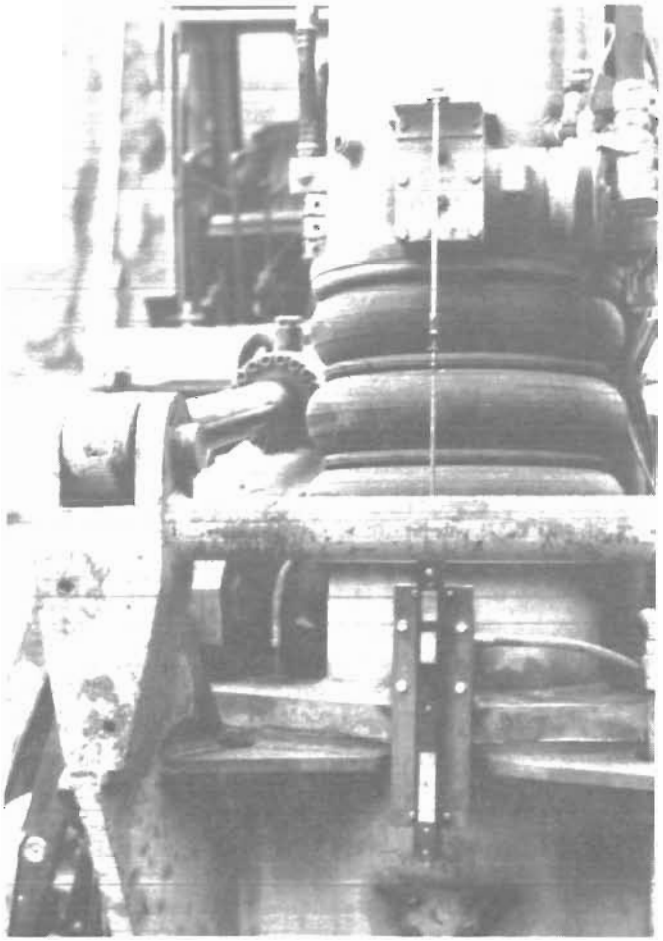

Figure 7.—Linear potentiometer for Ram displacement.

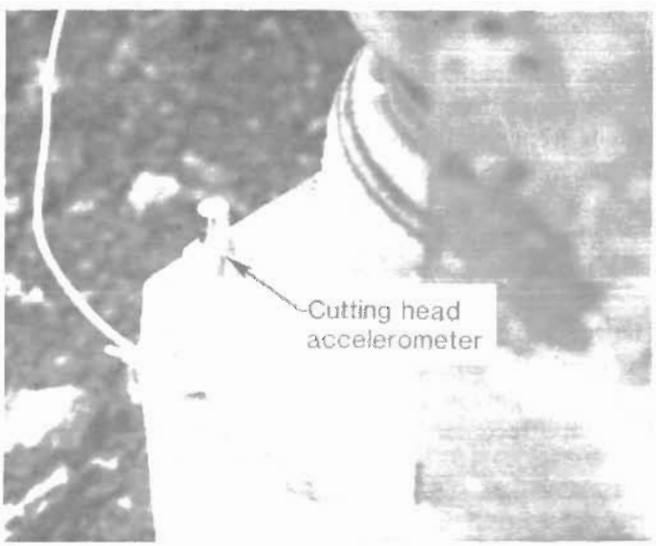

Figure 8.—Cutting head accelerometer.

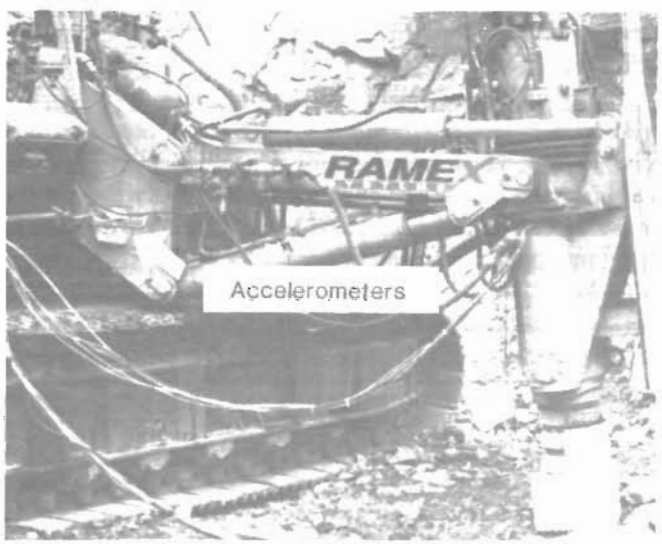

Figure 9.—Machine body accelerometers.

response, was used to record the machine and motion data. The magnetic tape enabled high-speed concurrent recording of data collected by the 14 sensors. Subsequent analysis of the data was performed by playing back the information through the recorder.

An oscilloscope was used at the test site to monitor and verify the tape recorder signals (fig. 10). Hard copies of the data were plotted at the test site using a fiber optics chart recorder.

DATA ANALYSIS

Plots Of Operating Parameters

Plots made with the fiber optics recorder were used to make a cursory inspection of all the data obtained. Approximately 5 s of data from one test segment was selected for a more detailed analysis. These data were replayed into an analog-to-digital converter (using Honeywell H-TMS 3000 instrumentation). Each channel was sampled at a rate of 2,400 samples per second. The analog-to-digital sample rate was selected to obtain accurate reproduction of the recorded information in both amplitude and frequency.

Figure 10.—Data instrumentation.

The digitized data were stored as American National Standard Code for Information Interchange (ASCII) files and plotted using the Lotus 1-2-3 software program. The type of plot obtained for each of the parameters monitored is shown in figures 11 through 16. Data included in each plot were obtained during the same period and represent about 0.2 s of testing time. This corresponds to approximately one complete engine cycle.

The plot in figure 11 illustrates how the piston moves between the combustion and bounce chambers. The total distance of piston movement is about 10 in. Fuel ignition occurs once during each cycle of piston movement. The height of the spike (fig. 12) resulting from each ignition shows the combustion pressure produced.

Following combustion, the Ram moves in a direction away from the cutting surface (fig. 13). For the engine cycle plotted, the Ram moved approximately 0.6 in before the constant thrust of the hydraulically actuated springs reversed the direction of motion. After impact, the Ram cutting head penetrated approximately 0.1 in of the rock. After initial impact, the cutting head rebounded from the rock and bounced several more times. No significant additional rock penetration occurred.

Force levels measured by the accelerometers placed on the cutting head, machine body, and ground are seen in figures 14, 15, and 16. As expected, the highest force level was recorded by the cutting head accelerometer after the initial rock impact (fig. 14).

Force levels on the machine body are shown for the x-direction (fig. 15). Although smaller in magnitude than the force levels measured on the cutting head, a significant amount of energy was transmitted back through the machine body.

A plot of ground force is given for the accelerometer position on the highwall, approximately 25 ft from the test cutting location (fig. 16). Force levels measured at all the ground sensing locations were less than on the cutting head or machine body. All ground sensing locations recorded force levels corresponding to the initial and secondary impacts.

The information in figures 11 through 16 represents data that were collected at the same time; therefore, the plots can be easily combined on the coinciding time bases (x-axis) to better show the relationship between the operating parameters. For example, figure 17 includes information for piston position and combustion pressure. Fuel ignition occurred just before the piston reached the combustion end of the cylinder.

The correlation between Ram movement and transfer of energy to the cutting head is shown in figure 18. The highest force level is related to the initial contact between

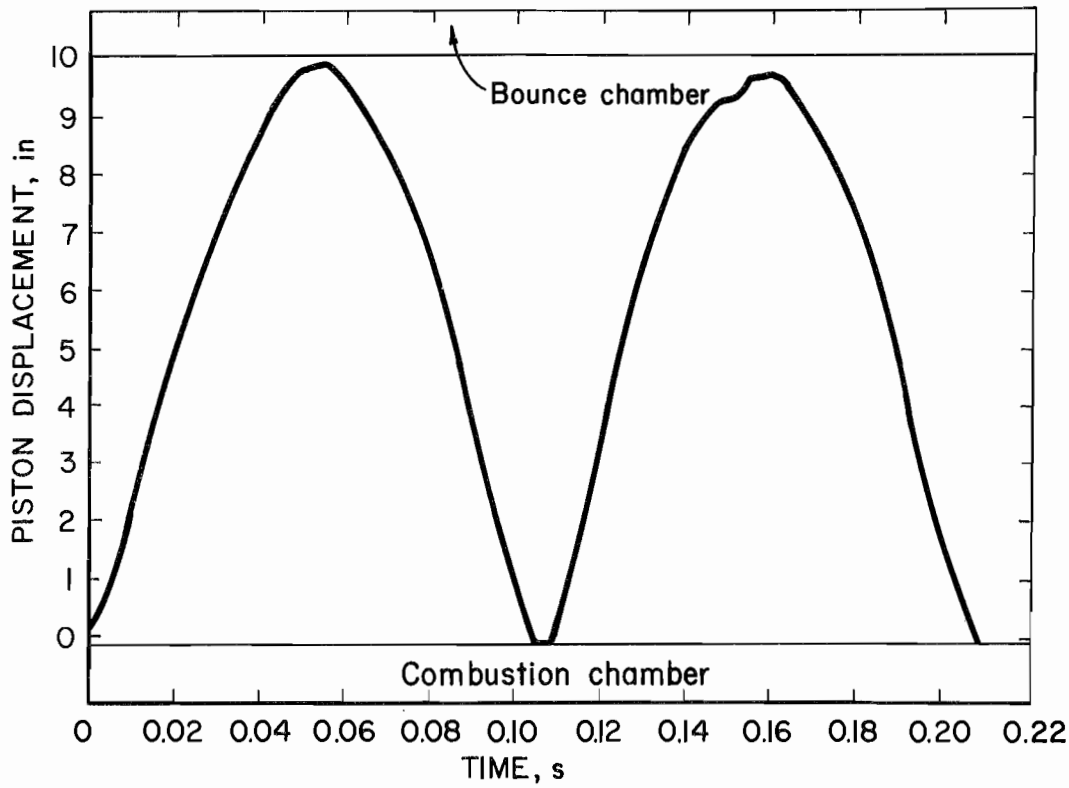

Figure 11.—Piston movement.

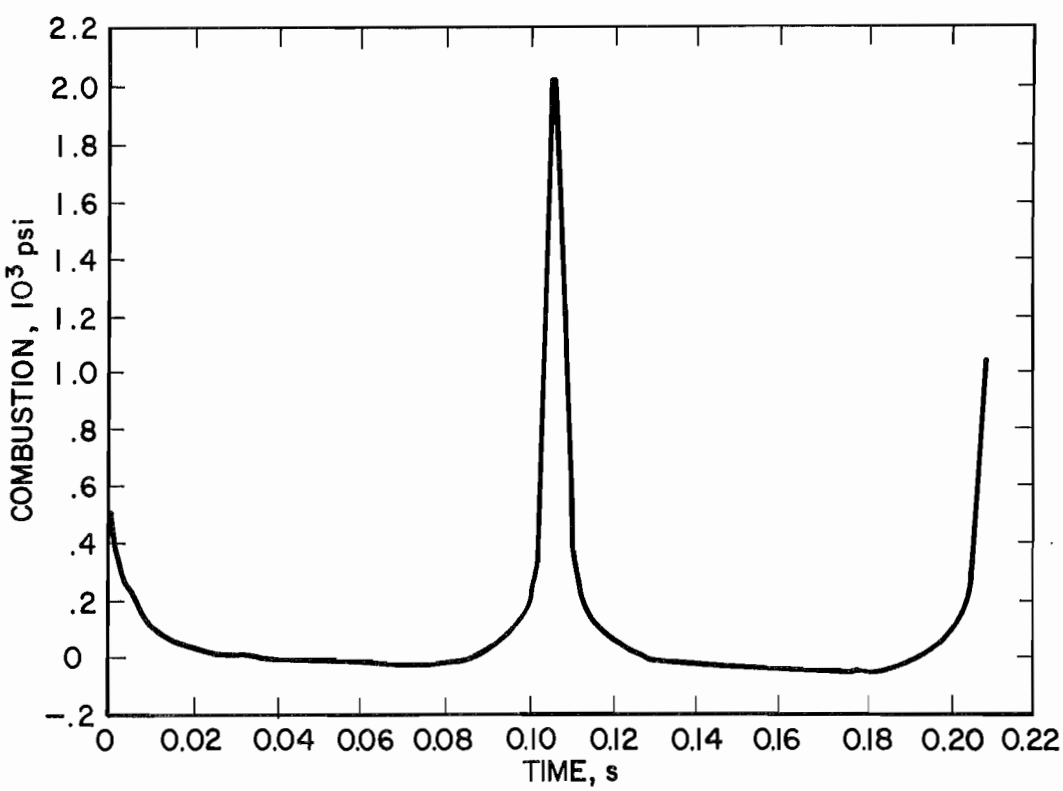

Figure 12.—Combustion pressure.

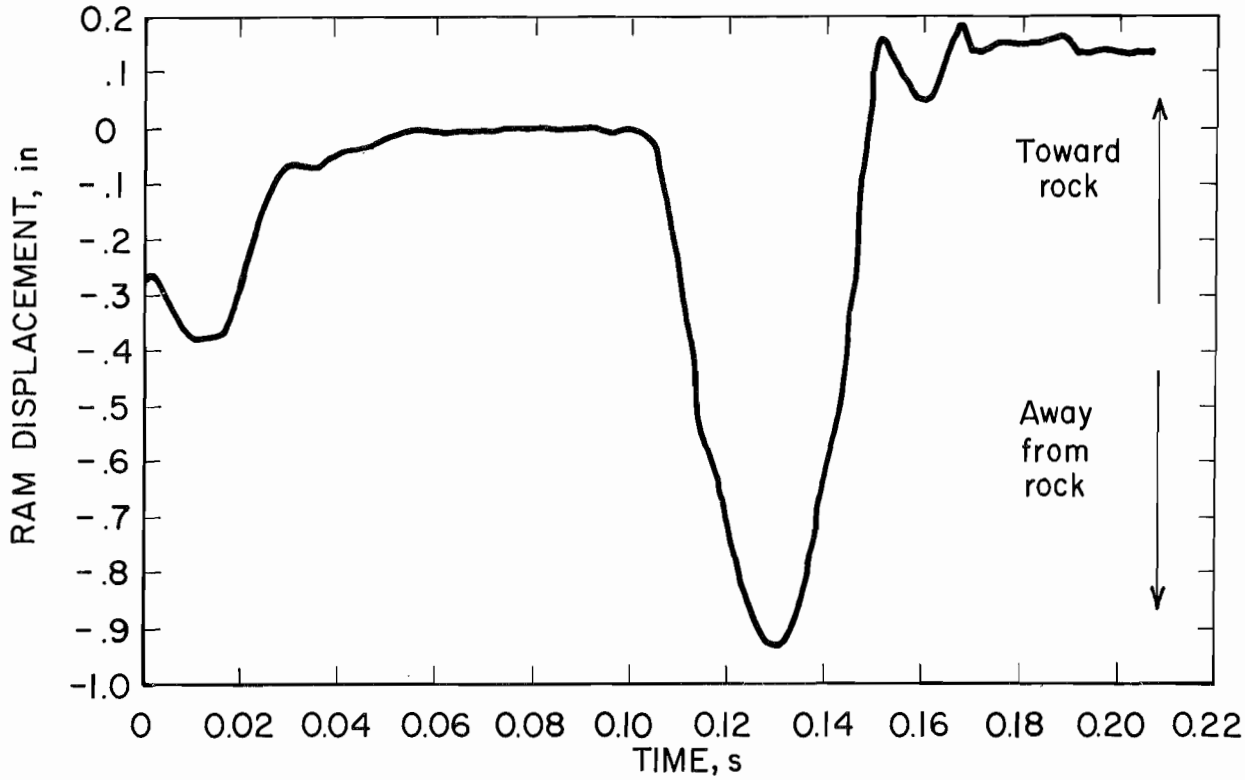

Figure 13.—Ram displacement.

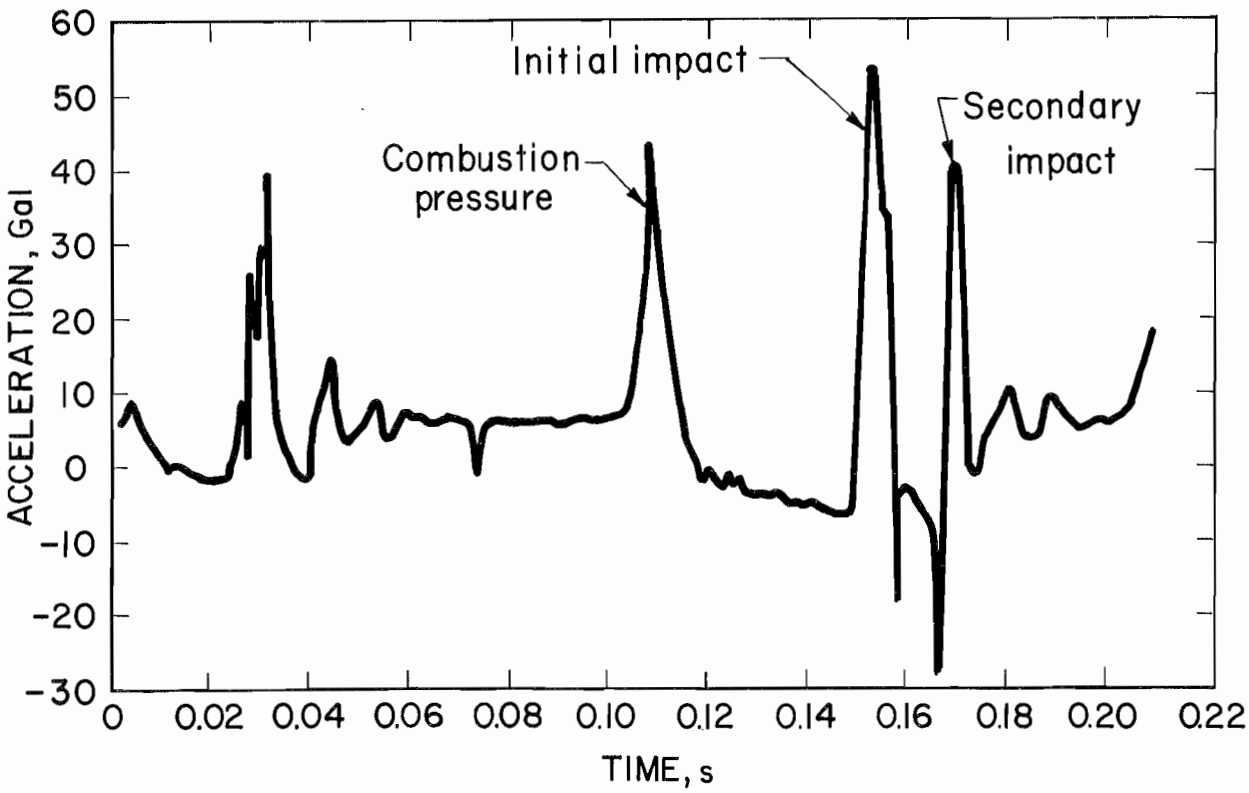

Figure 14.—Force levels measured on cutting head.

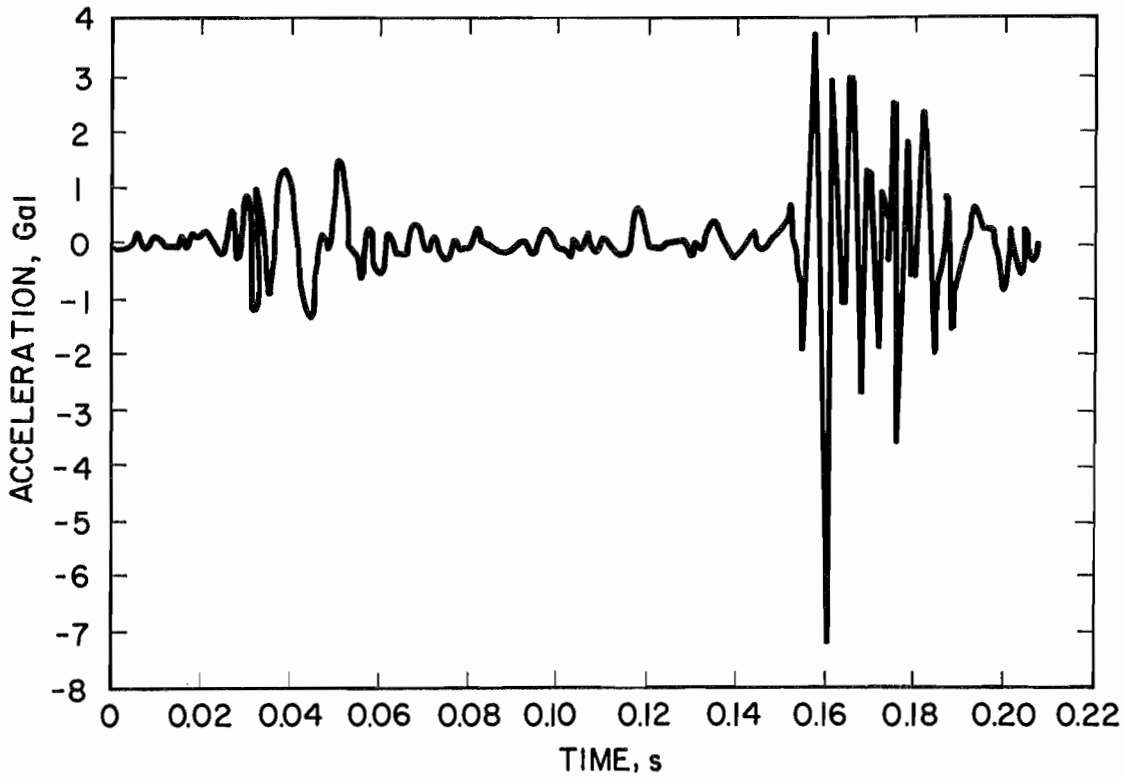

Figure 15.—Force levels measured on machine body.

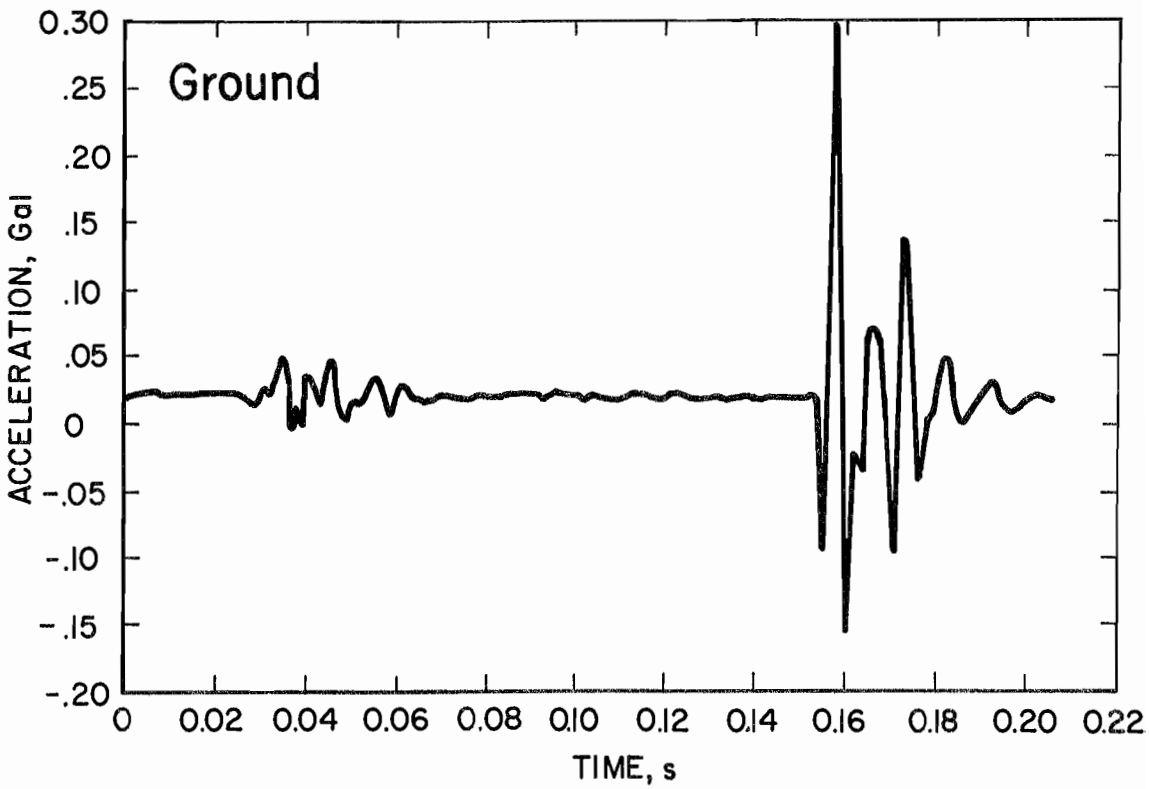

Figure 16.—Force levels measured on ground.

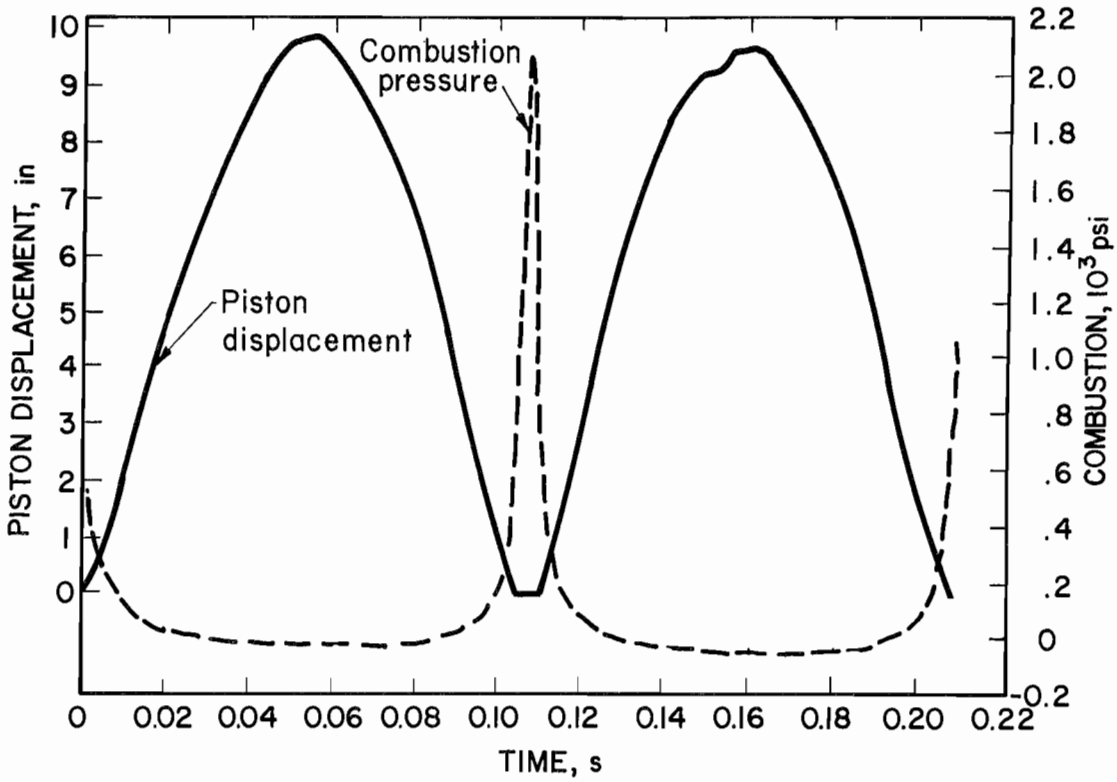

Figure 17.—Piston displacement and combustion pressure.

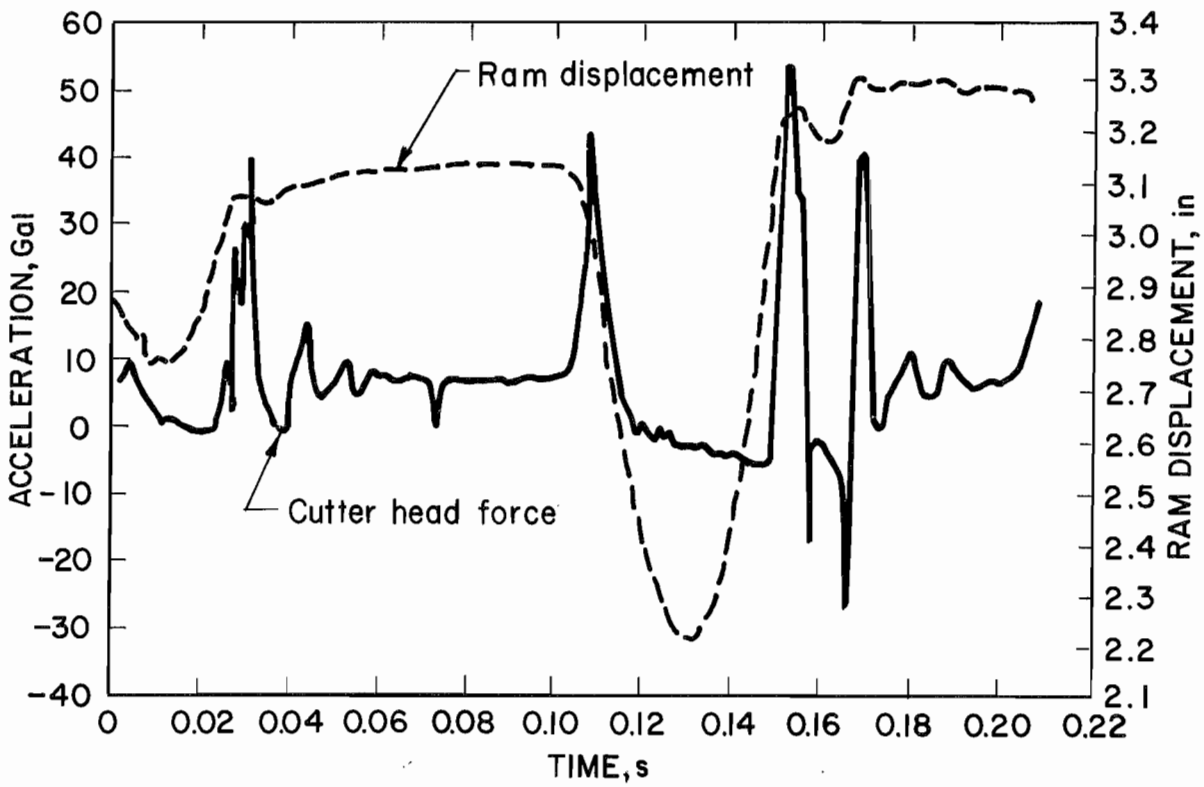

Figure 18.—Ram displacement and cutter head force.

the cutting head and rock. The head rebounded from the rock and subsequently struck it several more times. The additional strikes transferred small amounts of energy to the rock, but as previously noted, no significant additional rock penetration resulted.

Calculation Of Specific Energy

The specific energy of a mining machine is the energy required to remove a given volume of material. It is a function of many factors including cutting tool force and geometry, and rock strength. The cutting efficiencies of mining machines may be compared by calculating specific energies for machines operating under similar conditions. To calculate specific energy, the energy supplied by the mining machine and the volume removal rate must be known.

Calculation Of Energy Input

Operating power level of the diesel engine, rather than the rated horsepower, represents the energy that is actually delivered to the cutter head. The operating power level for the kerf-cutting impact mining machine was calculated using the combustion pressure and the piston location measurements. Summing the integrals:

$$\text{Impact energy} = \int_{TDC}^{BDC} F(x)Ddx + \int_{BDC}^{TDC} F(x)Ddx,$$

where F(x) = combustion pressure at piston location x,

D = bore diameter,

BDC = bottom dead center,

X = piston location,

and TDC = Top dead center

gives a calculation of the energy delivered to the rock with each impact. The shaded area in figure 19, which shows combustion pressure versus piston location, is the energy for one cycle. The power output was then calculated as the change in energy with respect to time. The average power delivered to the cutter head was between 35 and 40 hp.

The average energy supplied for several consecutive engine cycles can also be calculated. Figure 20 shows the energy for six cycles during a 0.7-s period. The average power supplied during these cycles was 36 hp.

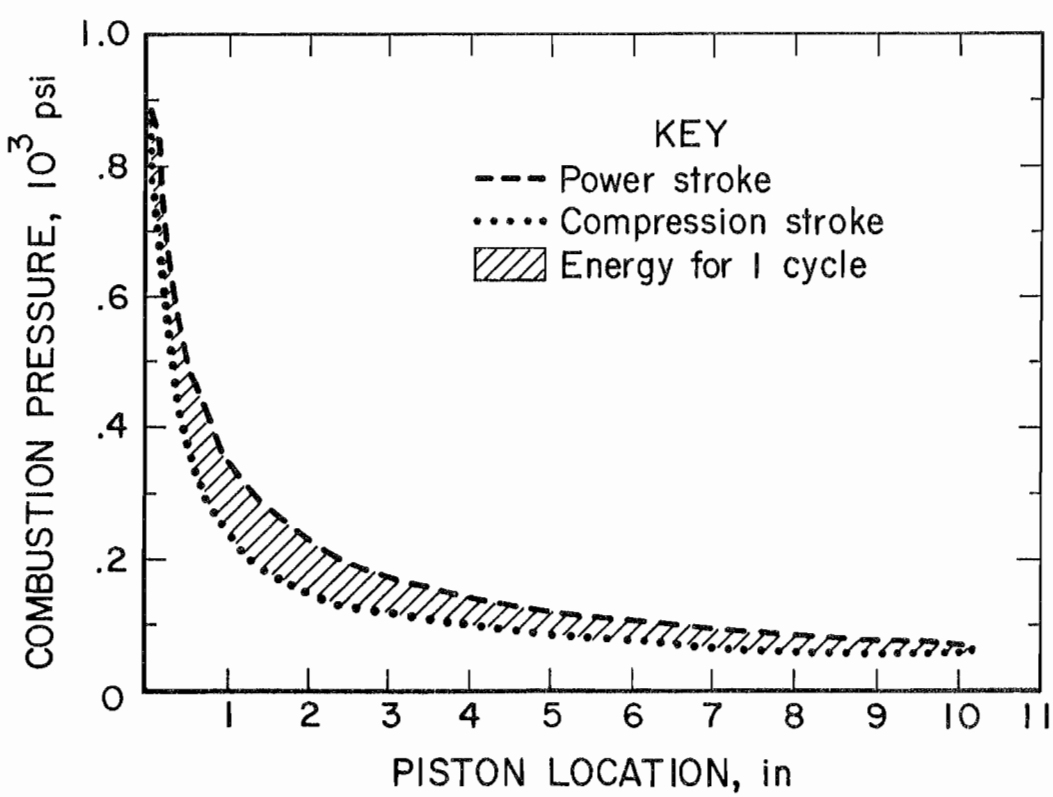

Figure 19.—Combustion pressure versus piston location.

Calculation Of Material Removal Rate

The specific energy (horsepower hour per short ton) is determined by dividing the operating power level (horsepower) by the rate of mining (short tons per hour). Normally, material removal rate is determined by weighing the material removed in a given period or, if the material density is known, by measuring the volume of material removed in a given time. For the tests conducted, the operation time was not long enough for an accurate determination of material weight or volume.

For these tests, data collected to determine Ram displacement were used to calculate the depth of cut per impact. Total depth of cut for 45 impacts was about 1.8 in (fig. 21). Therefore, the average depth of cut per impact was 0.04 in.

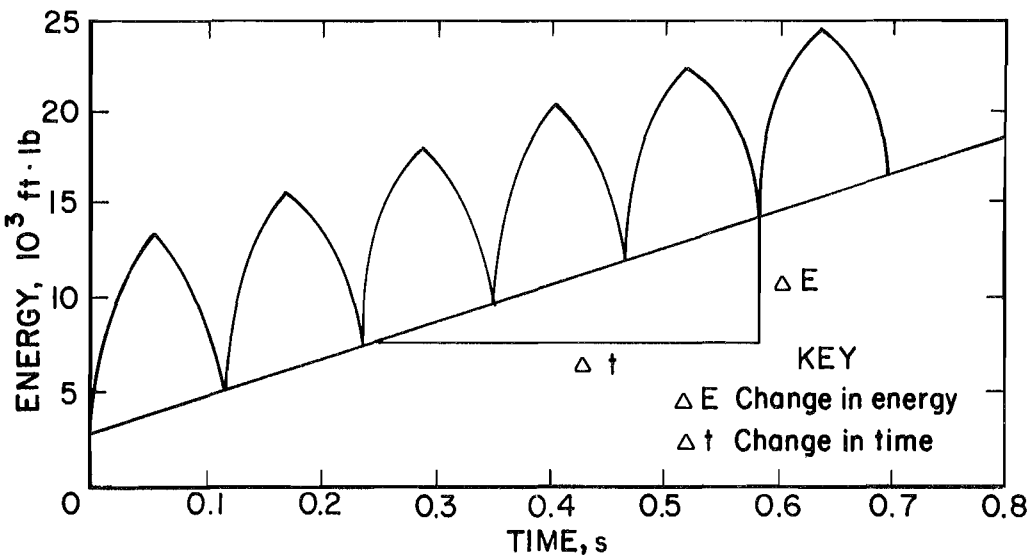

Figure 20.—Energy supplied during six engine cycles.

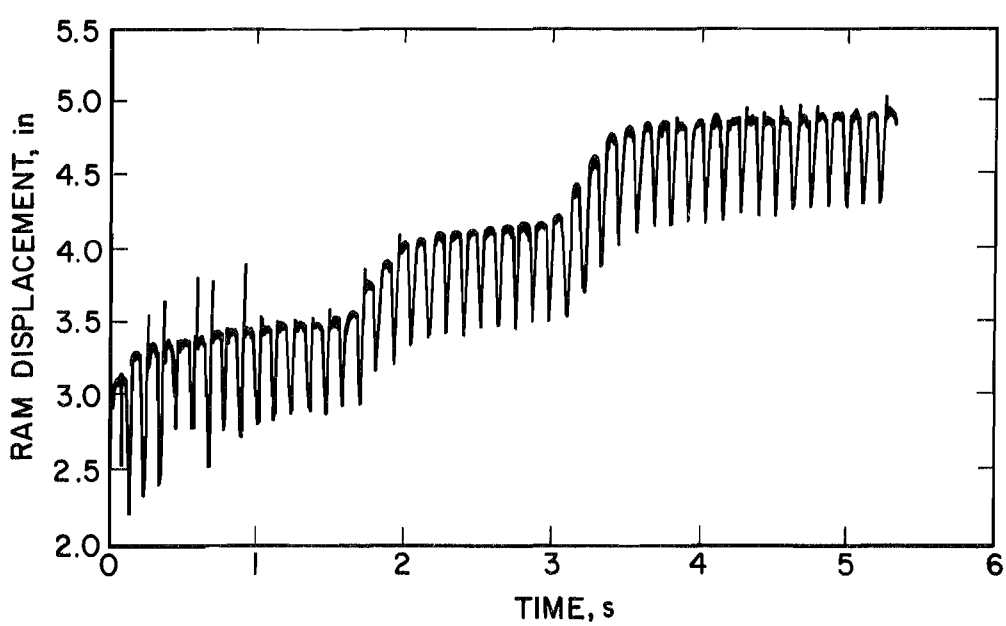

Figure 21.—Ram displacement during 20 impacts.

Volume removed with each impact was calculated by assuming equal penetration across the entire area of the cutting head (i.e., 16 by 16 in). Density of the quarry rock was taken to be 170 lb/ft³. During testing, the average material removal rate was 14.5 st/h. This accounts only for material removed from beneath the cutting head. During a typical mining operation, material will also break out from between the kerfs, and the mining rate will be higher. However, based on a removal rate of 14.5 st/h, the specific energy for the 36-hp engine is between 2 and 3 hp·h/st.

DISCUSSION AND CONCLUSIONS

SPECIFIC ENERGY

A key measure of cutting efficiency is the specific energy required for a given operation. The calculated specific energy for the kerf-cutting impact mining machine, mining in the test rock, was 2 to 3 hp·h/st.

It is difficult to relate the performance of this machine to other mining machines because most of those machines use either drag or disk bits that are attached to a rotating cutting head. Machines using drag bits require a specific energy of less than 1 hp·h/st to cut softer, less abrasive rocks, such as coal. Harder rocks, such as those cut by the impact mining machine, cannot be mined using drag bits.

Disk cutters on tunnel boring machines have been used to cut rock of comparable hardness (e.g., greenstone, quartzite, and granite). With the tunnel boring type of machine, calculated specific energies vary from 10 to 18 hp·h/st. Comparing the specific energy requirements for the kerf-cutting impact miner (i.e., 2-3 hp·h/st) and tunnel boring machines, the impact mining machine appears to provide an efficient means for mining very hard rock.

Theoretical specific energy curves (fig. 22) were drawn for 100, 40, and 36 hp engines. For the 36 hp engine, it can be seen that when the depth of cut is about 0.04 in, the specific energy is between 2 and 3 hp·h/st. For the same horsepower engine, specific energy decreases as the depth of cut increases. A larger engine may be required to increase the depth of cut. To maintain the same cutting efficiency (i.e., specific energy), a 100-hp engine would have to have a penetration rate of greater than 0.1 in per impact.

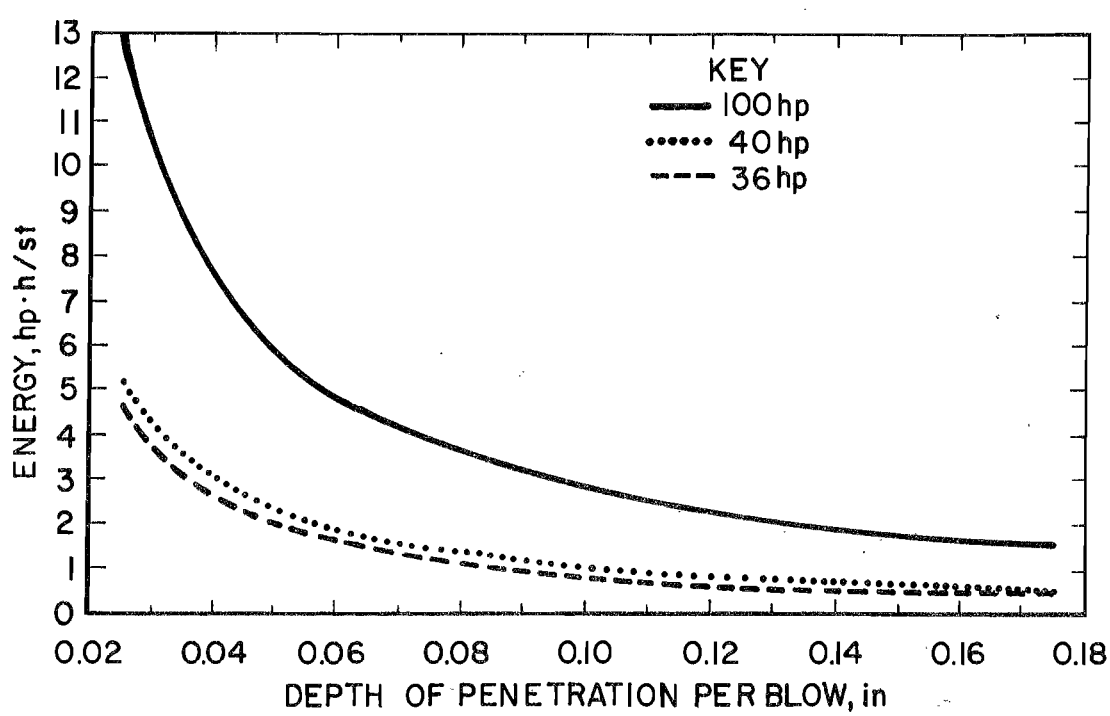

Figure 22.—Theoretical specific energy curves.

HORSEPOWER RATING OF DIESEL ENGINE

The diesel engine used for these tests was rated at 100 hp. The calculated power delivered to the cutting head was 36 hp. The primary reason the rated and delivered horsepower differed during the testing was that, due to a fuel injection system problem, the machine was not operating at full capacity. Since the testing, improvements have been made to the injection system and higher power outputs recorded.

EFFICIENCY OF CONVERSION—COMBUSTION TO RAM MOVEMENT

The data plotted in figures 11 and 13 show, qualitatively, how the energy from fuel combustion was converted to piston and Ram movement. The efficiency of this transfer was not calculated. However, unlike a hydraulic breaker, there are no hydraulic losses, and the bulk of the combustion energy is transferred into rock breaking. The only loss is heat transferred through the combustion chamber and sliding mechanical friction of the piston on the cylinder wall. Thus, the efficiency of the energy transfer is considered high.

ENERGY TRANSFERRED THROUGH MINING MACHINE

Not all of the energy generated by fuel combustion is transmitted through the cutting head. A part of the energy (fig. 15) is transmitted back through the machine body. This energy is wasted and potentially damaging to the mining machine body. Further study is needed to determine if the force levels measured can cause damage to the machine. Reducing the energy transferred through the machine body could increase machine life and, possibly, increase the energy transferred through the cutting head.

ENERGY TRANSFERRED THROUGH ROCK

With the Ram, rock fracture results when energy is transferred from the cutting head to the rock. During the cutting tests, ground motion was monitored in an attempt to determine how the energy directed to the rock affects the amount of rock fracture.

It was not possible to measure the force delivered to the rock at the location of cutting head impact. Rather, the geophones and accelerometers were attached to the rock, at locations near where the head struck the rock, but far enough away so that they were not damaged by the impacts.

At the sensor locations, the force levels measured were much less than force levels on the cutting head (figs. 14 and 16). The force-induced vibrations decreased as they traveled through the rock to the sensor locations due to several factors, including

1. Distance and direction between the location of impact and point of measurement: The ground accelerometer, which monitored acceleration in the vertical direction, was placed about 25 ft from the location of impact.
2. Material composition and discontinuities in rock material: The quarry rock was composed of nonhomogeneous rock that in many locations was fractured or contained thin veins of unconsolidated material.

During the testing, it was not possible to interpret how much the force levels had been reduced due to the distance between the sensors and location of impact, and the material composition. Further work is needed to evaluate how the magnitude of the force levels delivered to the rock surface are related to amount of rock fracturing that results.

ENERGY TRANSFER—ROCK FRACTURE AND PRODUCT SIZE

One way to determine how efficiently energy is transferred from the cutting head of the mining machine to the rock is to look at the size of the fractured material. The mining operation and machine are designed to produce a certain-sized product. Producing a product smaller than the desired size wastes energy.

The cutting head of the impact mining machine was designed to "break out" oyster-shell-sized rock chips when the head impacts the rock. To prevent additional fracturing of these chips, they must immediately be removed from under the cutting head before the next impact. A chip that does not fall out immediately will be crushed by the next impact, and part of the energy will be wasted by the additional fracturing. In addition, the fractured material will form a cushion between the tungsten carbide buttons and the solid rock, thus making additional chip formation more difficult. Removal of the chips allows the tungsten buttons to come in direct contact with the solid rock.

The rock cuttings produced during these tests varied in size from plus 10 in down to dust. Techniques for more efficiently removing the rock chips from beneath the cutting head have been investigated. During the test program, compressed air was directed through four holes that were drilled through the bottom of the cutting head. The

holes were placed so that the air passed between the tungsten carbide buttons. Part of the material removed by the compressed air was finely crushed rock. This resulted in increased concentrations of airborne dust near the cutting boom.

Future testing of the impact mining machine will include use of high-pressure jets of water that will be directed between the tungsten carbide bits. Operating at a pressure of about 10,000 psi, the water jets should "force out" the rock chips and reduce dust resulting from secondary crushing.

The test program conducted has shown that the kerf-cutting impact mining machine has the potential to mine rock materials that are too hard to be cut efficiently with currently available mechanized mining machines. Moreover, the impact mining energy requirements are less than for other commercially available mechanical excavators cutting in rock of similar hardness.

OPERATING COSTS

Operating costs are dependent on the life of the cutting bits, muck gathering and conveying, and other wear components. A computer program was developed to compare operating costs of the RAMEX mining boom, drill-blast techniques, and other mining methods.[6] Results of this program indicated that a mining machine with a 400-hp RAMEX boom could be cost and performance competitive with explosive excavations in many of the same rock formations.

During the test program described in this report, only about 80 st (35.9 yd^3) of material were mined. This amount of mining resulted in little noticeable wear on the cutting bits. A longer test period with a full-scale mining machine is needed to evaluate the costs associated with the wear of cutting bits and other machine components.

[6]Work cited in footnote 4.

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