DESIGN CONSIDERATIONS OF MECHANICAL FRAGMENTATION SYSTEMS FOR ENTRY DEVELOPMENT IN OIL SHALE

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Abstract

The Underground Mining Division, Twin Cities Mining Research Center, U.S. Bureau of Mines has conducted research to evaluate bits and cutters of continuous fragmentation machines for oil shale. Laboratory experiments were performed to (1) define fundamental differences in performance of the various bits and cutters and (2) relate inherent advantages of the different cutting tools to entry development in oil shale. In addition, mechanical excavation machines that have potential in oil shale mining are presented.

The bit and cutter experiments were performed on oil shale samples from the Mahogany Zone, Parachute Creek Member of the Green River Formation, in the Piceance Creek Basin (Colo.). A linear cutting apparatus was used to load and traverse a bit or cutter across a smooth shale surface; a rotary drill was used for tests with drag bit cutterheads. Graphs of specific energy, chip weight, groove width, and cutting coefficient versus depth; cutting force and depth of cut versus normal force; and specific energy versus penetration rate of drag bit cutterheads are presented.

The experiments demonstrated that (1) specific energy decreases with increasing depth of penetration, rapidly at first, then approaching a constant; (2) drag bits are more efficient, and (3) the specific energy for steady fragmentation is about 40 percent of that required for independent groove fragmentation. The benefit of drag bit fragmentation efficiency was demonstrated by comparison calculations for drag bit and disk cutter machines. These comparisons were made using a disk cutter tunnel boring machine, a drag bit tunnel boring machine, and a continuous drum miner. At the same production rate, the drag bit tunnel boring machine required only 12 percent of the thrust and 43 percent of the torque needed by the disk cutter machine. Even though the production rate of the drum miner was 60 percent of that of the other machines, it required only 10 percent of the torque and 20 percent of the thrust needed by the disk cutter tunnel boring machines.

Introduction

The use of tunnel and raise boring machines; shaft drills; drum, boom-type and boring-type miners for mechanically excavating shafts, raises, and tunnels has increased significantly in the last 25 years. The many advantages of continuous mechanical excavation, such as, increased advance rates, opening stability, safety, and minimum overbreak, have led to its use in many civil and mining applications (Morrell and Larson 1974). Before these machines are used for oil shale, basic fragmentation studies of the bit and cutter are required to determine the best machine type.

This paper summarizes the application of these machines to entry development in oil shale. The Bureau's Twin Cities Mining Research Center initiated a research program as the first step in scientifically predicting future machine performance in oil shale. This bit and cutter evaluation examined the fragmentation efficiencies of various bit and cutters. This work is an extension of research started several years ago on diamond and percussive drilling characteristics and tunneling machine research. Some publications that apply directly to mechanical fragmentation of oil shale, although not cited in the text, are included under references: Bruce 1969; Rad, Rad and Olson 1974.

The bit and cutter evaluation study for oil shale used a Bureau-designed linear cutting apparatus and a horizontal rotary drill. Several types of drag bits and disk cutters were used in the experiments. This report includes the results obtained from a 60-degree disk cutter, large and small point attack drag bits, and cutter-type drag bits, and includes relative comparisons for 90-degree and gear-type disk cutters and finger-type drag bits. At least 30 tons (27 metric tons) of oil shale were obtained from the Colony Development Operation near Rifle, Colo. Test block sizes ranged from 3 x 3 x 1-1/2 ft (0.9 x 0.9 x 0.5 m) to 4 ft (1.2 m) cubes and had compressive strength range of 6,000 to 18,000 psi (41 to 126 MN/m^2) and grade range of 21 to 67 gallons (0.095-0.301 m^3) per ton.

Bit and Cutter Evaluation Study for Oil Shale

The Bureau's Twin Cities Mining Research Center initiated a research program to define preliminary machine requirements and the technical feasibility of fragmenting oil shale with various bits and cutters. The objective of this research was to develop bit and cutter design requirements for tunnel boring and continuous mining machines and to estimate their overall performance.

Experimental Equipment and Test Procedures - Bits and cutters were evaluated on two experimental test fixtures: a linear cutting apparatus, named the rock cutting device (RCD) and a large rotary drill, named a horizontal underground borer (HUB). The RCD was used for independent cutting tests with disk cutter and drag bits, as shown in figure 1.

From left to right, the top row shows a disk and gear tooth cutter; the bottom row shows a small point attack drag bit, a large point attack drag bit, and a cutter-type drag bit. The disk cutters used were 1 in. (2.5 cm) thick and 7 in. (18 cm) in diameter with a cutting edge of 90^o and 60^o. The gear tooth cutter was constructed with 60^o cutting tips. The small point attack drag bit was 5 in. (13 cm) long and 1 in. (2.5 cm) diameter with a tip angle of 75^o. The large point attack drag bit was 5.5 in. (14 cm) long and 1.5 in. (3.8 cm) diameter with a tip angle of 75^o. The cutter drag bit was 3 in. (7.6 cm) long and 0.5 in. (1.3 cm) thick with a negative 10^o rake.

Single bits and cutters were tested on the Bureau-designed RCD (fig. 2). This apparatus is designed to load and traverse a bit or cutter across rock surface and to measure the forces, speed, and depth of cut

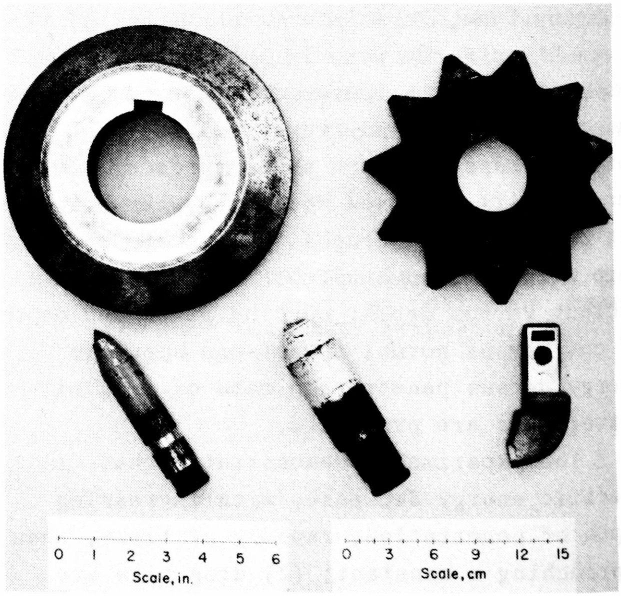

Figure 1. - Bits and cutters used in the linear cutting tests.

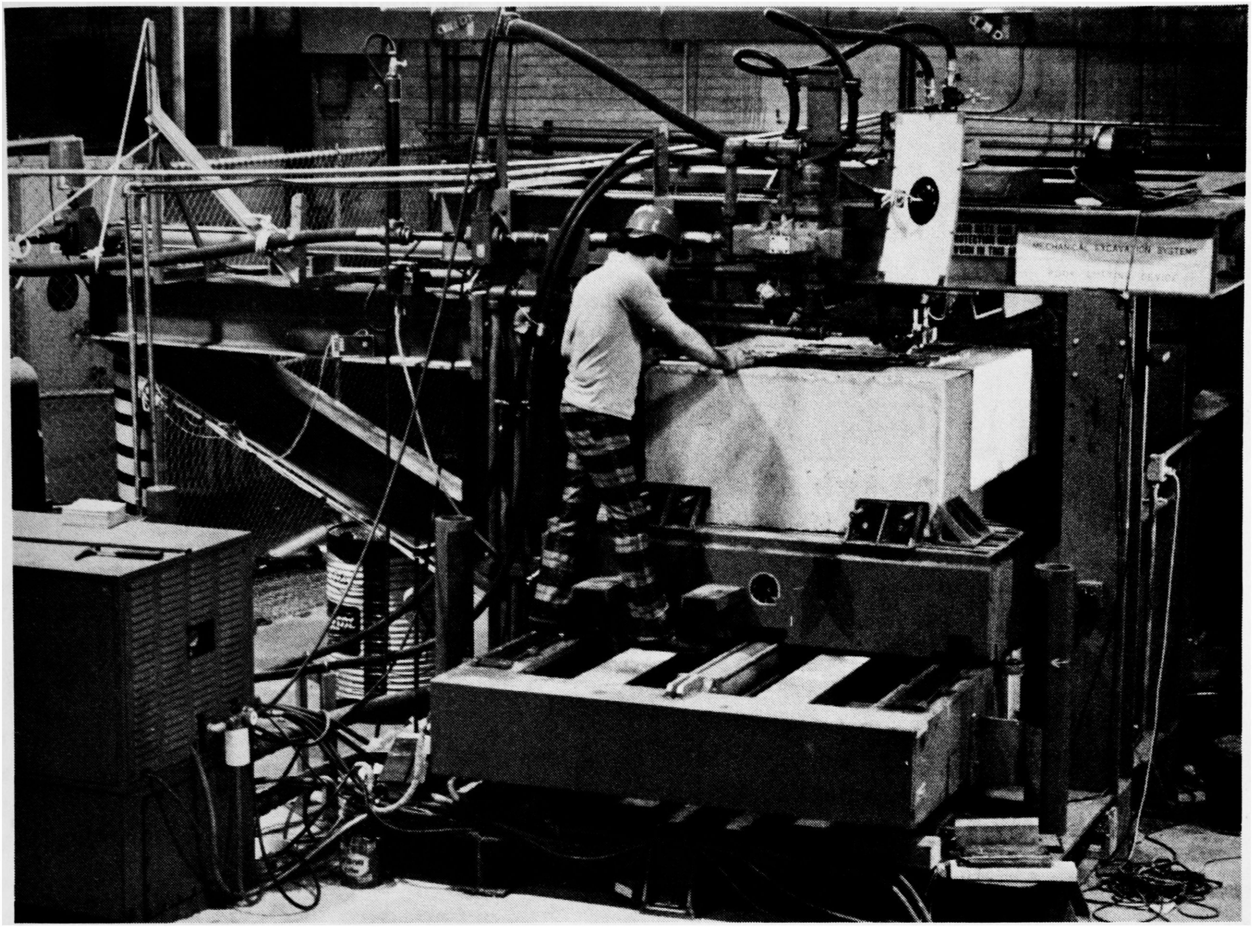

Figure 2. - Rock cutting device.

(Rad and Schmidt 1973). Normal load and horizontal motion for the bits and cutters are provided by two hydraulic cylinders. Hydraulic systems are designed to provide a maximum of 30,000 lb (135,000 N) normal force; 15,000 lb (68,000 N) horizontal force, and cutting speed up to 70 in./sec (177 cm/sec). The linear cutting experiments reported were primarily designed to define the fundamental differences of the bits and cutters in fragmenting oil shale. They were performed under a narrow range of experimental conditions, including, linear motion, single groove studies, absence of indexing effects, and smooth rock surfaces. The samples were oriented to simulate a vertical direction of cut within horizontally bedded oil shale deposits. Data for each bit and cutter were developed through several tests on a few oil shale samples.

Since linear cutting does not duplicate the field conditions of the continuous fragmentation machines, a large drill was modified to test steady-state conditions with various cutterheads like the one shown in figure 3. This cutterhead is 2 ft (0.6 m) in diameter and uses the large point attack drag bit shown in figure 1. The bit spacing can be varied from 1 to 3 in. (2.5 to 7.6 cm). The test fixture is shown in figure 4. The HUB, a small raise borer mounted horizontally, is designed to provide a maximum rpm of 80, thrust of 162,000 lb (721,000 N) and torque of 31,000 ft-lb (43,000 Nm) (Schmidt and others 1975). Rpm, thrust, and torque were recorded during tests. Cutter-

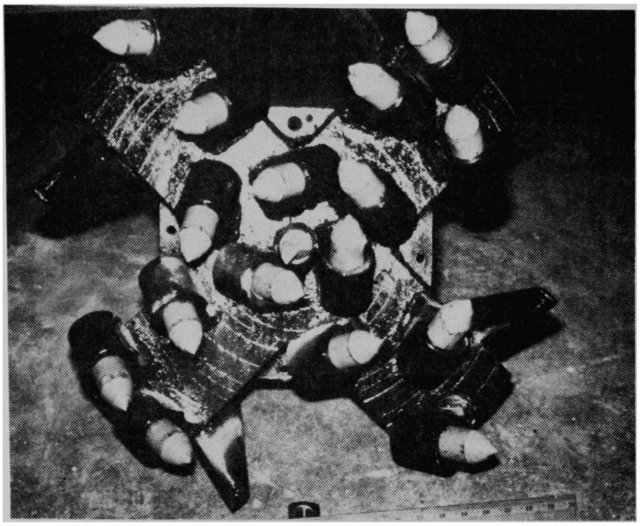

Figure 3. - Two-foot rotary cutterhead used for steady-state tests.

head advance was parallel to the bedding to simulate horizontal entry development.

Experimental Results - Specific Energy. Relative efficiency of a fragmentation process can be measured by the energy (cutting force times length of cut) required to break out a unit volume of rock; i.e., specific energy. Fragmentation efficiency increases as specific energy decreases (Morrell and Larson 1974; Gaye 1972). As found in previous mechanical fragmentation experiments with disk cutters (Morrell and Larson 1974; Rad 1974), figure 5 shows that as groove depth increases, specific energy decreases; rapidly at first, then approaching a constant value.

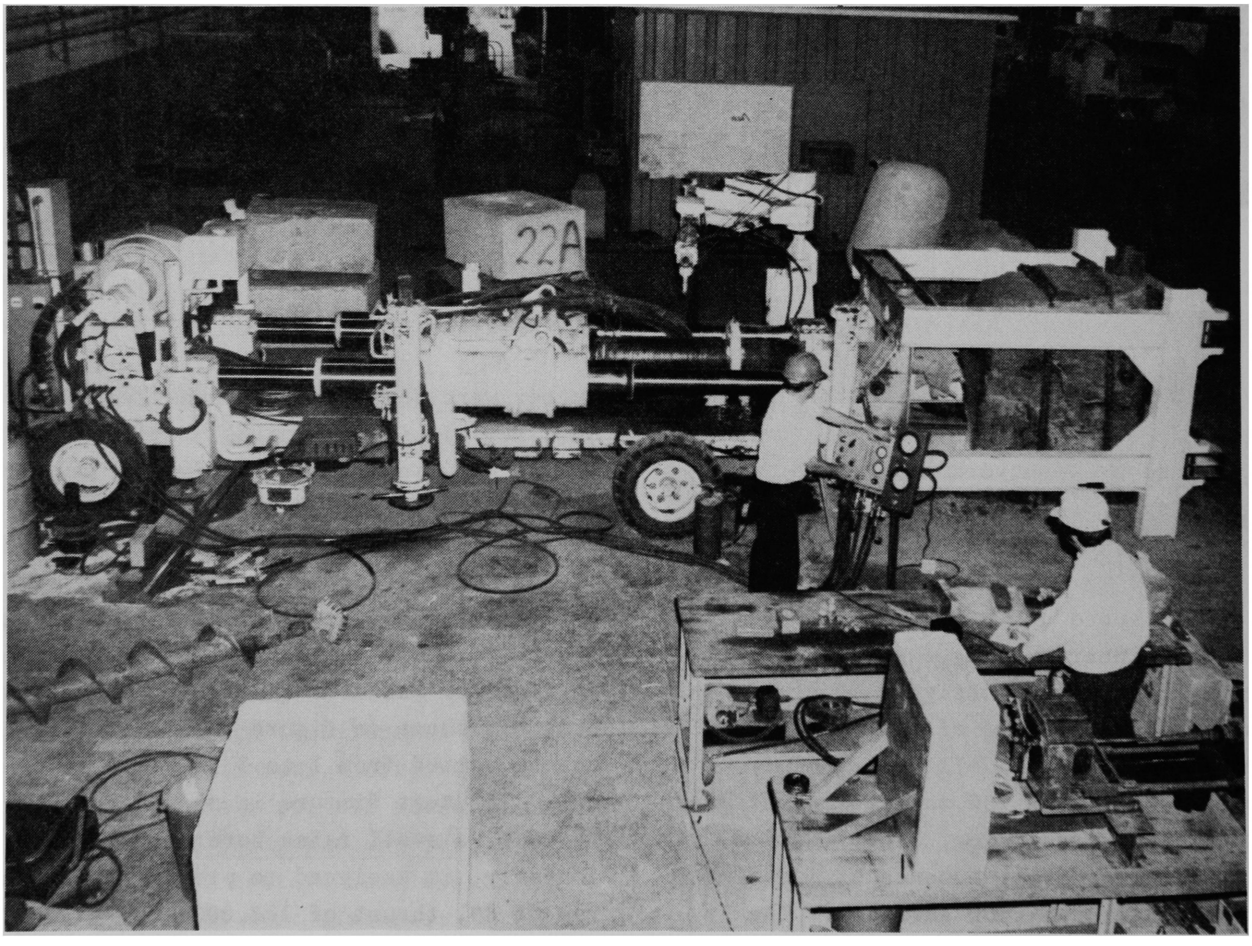

Figure 4. - Horizontal underground borer.

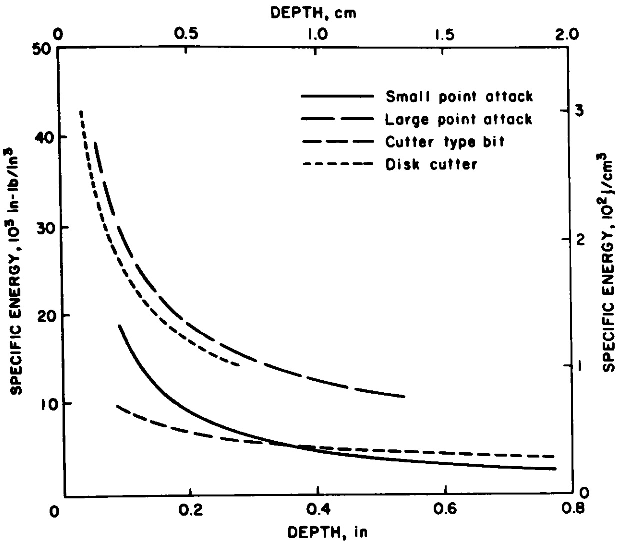

Figure 5. - Specific energy as a function of groove depth in oil shale for independent linear grooves.

The curves in figure 5 represent the results of independent linear cutting tests with a 60° disk cutter, cutter drag bit, and large and small point attack drag bits. The figure shows the relative fragmentation efficiency of the different tools. Specific energy differences, at any depth, demonstrate that the overall efficiency of the small point attack and cutter type drag bits is better than the disk cutter and the large point attack drag bit.

Tests also indicated that as the depth of groove increases, the magnitude of the lateral forces and vibrations increased. In designing an ideal machine for oil shale, specific energy, and magnitude of the lateral forces and vibration should be minimized. From the standpoint of fragmentation efficiency, the depth of cut need not exceed 0.3 to 0.4 in. (0.8 to 1 cm) because specific energy does not decrease significantly. In addition, 90° disk and gear tooth cutters were also tested. The 90° disk induced very little damage to the rock and the gear tooth did not improve the fragmentation efficiency of the disk cutter.

Cutting Forces. Figure 6 shows an inherent disadvantage of the disk cutter. The curves represent the results of linear, independent cutting tests. The thrust, or normal force, required to penetrate the oil shale is six times greater for the disk than the drag bits. At the same normal force, drag bits are able to penetrate at least eight times deeper than the disk cutter. The figure illustrates why drag bit machines can react to the thrust forces with their weight, while tunnel boring machines require large-capacity rib jacks.

Figure 7 shows how cutting force is related to normal force in linear, independent cutting tests. Cutting force is the force required to pull the tool through the shale and is the force that determines the torque required to rotate a cutterhead. The figure shows that the drag bit cutting force is much greater than that required for the disk. This cutting force difference is caused by the plowing action of drag bits through rock versus the rolling action of disk cutters.

The ratio of cutting force to normal force, cutting coefficient, when plotted against groove depth, allows comparison of the force applications necessary to fragment shale. This comparison can be used to illustrate the advantages and disadvantages of various continuous fragmentation machines. Cutting force, normal force, and depth are proportional to the respective torque, thrust, and rate of penetration of these machines. As shown in figure 8, for independent linear cutting tests, the coefficient increases linearly with depth, with the drag bits having a higher coefficient (as much as four times higher) than that of the disk cutters. Any increase in this ratio indicates that cutting force increases more than normal force. This, in turn, increases fragmentation energy input but decreases specific energy (see fig. 5). However, in a mining situation, both forces have to be realistically reacted. The force reactions are provided through the machine's thrust and rotary system, weight, and auxiliary hold-downs. In the case where cutter forces can be easily reacted and wear is not a problem, drag bits are advisable; however,

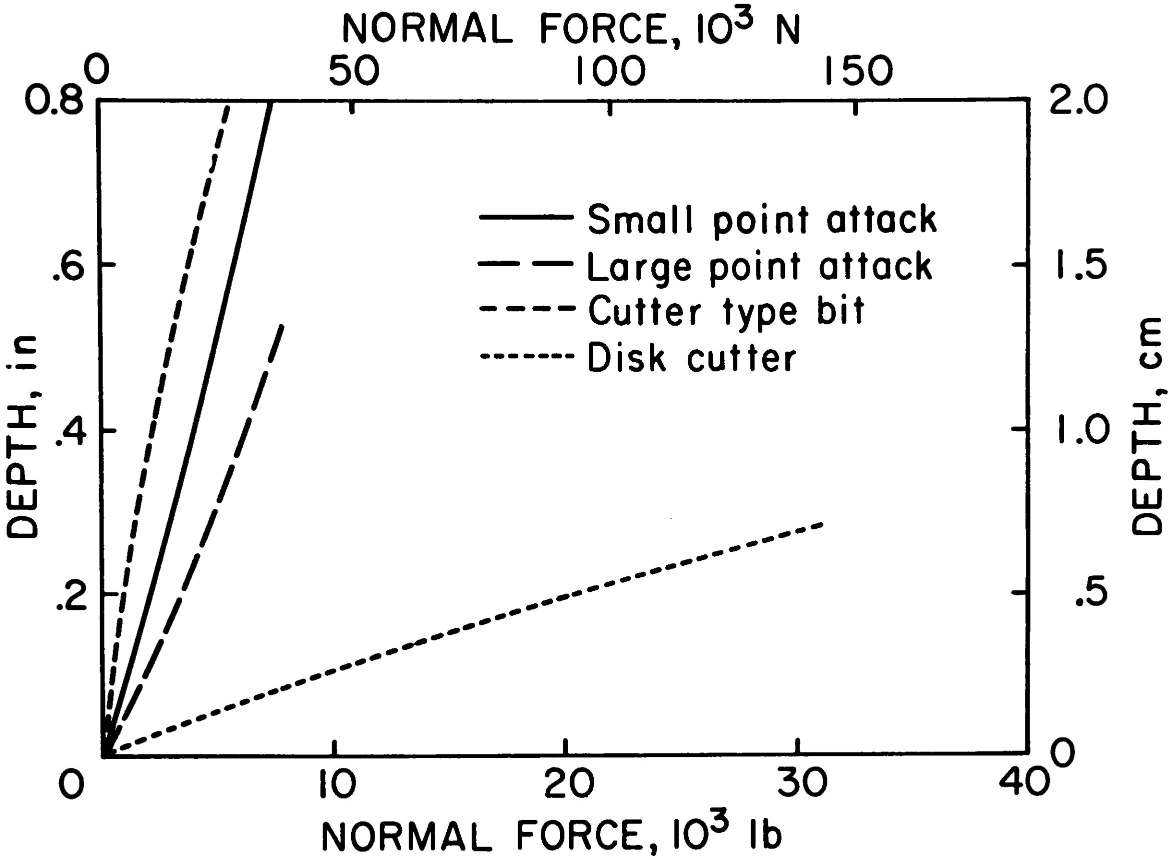

Figure 6. - Depth of groove as a function of normal force in oil shale for independent linear grooves.

when high drag bit forces cannot be reacted, or wear is excessive, disk cutters are used.

Groove Characteristics. Weight of chips per unit length was chosen as a measure of groove size since it is proportional to volume and normalizes the length of different grooves. Figure 9 shows chip weight per unit length as a function of the groove depth for independent linear cutting tests. In practical terms, the curves indicate fragmentation is increased by depth. The figure indicates that disk cutters fragment the shale easily, but they are limited to shallow depths because of the normal force requirements. The cutter and small point attack bit fragmented the most shale for any given depth.

Groove width can serve as a first approximation for optimum tool spacing. In figure 10, width is plotted as a function of groove depth. For oil shale, width to depth ratio is about 9 for the disk cutter, and ranges from 5 to 7 for drag bits. The ratio indicates that disks would have a greater optimum spacing than the drag bits at the same depth of cut. However, the large normal force requirements of disks limit their penetration to shallow depths.

Steady State Testing. Unfortunately, well-controlled, independent linear cutting tests do not duplicate the fragmentation process of boring or mining machines. Therefore, steady-state conditions were evaluated with a disk cutter and drag bit to

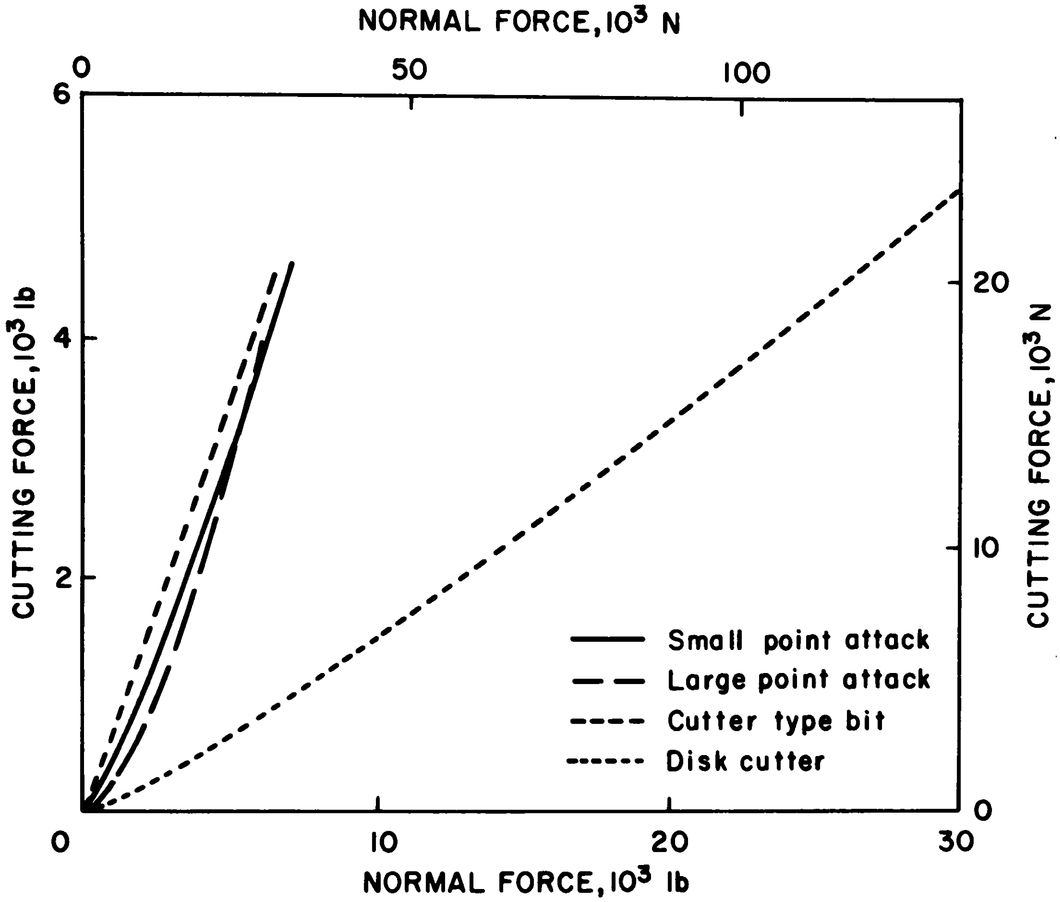

Figure 7. - Cutting force as a function of normal force in oil shale for independent linear grooves.

better understand this fragmentation process. The steady-state condition is reached when fragmentation efficiency is not increased by removing more layers of rock. A rotary drill (fig. 4) was used for the drag bit steady-state tests. One of the cutterheads (fig. 3) was mounted with large point attack drag bits. Since the capability of the rotary drill test fixture and sample size was limited, the steady-state disk cutter test was performed on the RCD (fig. 2). The test involved removing six layers of oil shale with interacting groove tests. Interacting grooves means the oil shale was broken out between the grooves and a layer is the average groove depth.

Figure 11 compares steady-state drag bit drilling with independent linear cutting drag bit tests, where specific energy is plotted as a function of drilling rate. The figure shows specific energy decreases, with depth, for both linear cutting and rotary drilling. The large point attack drag bit was used for the linear cutting and 2-ft-diam (0.6-m) rotary tests. The difference between the 2-ft (0.6-m) rotary and the linear cutting shows the benefit of steady-state fragmentation by the reduction of

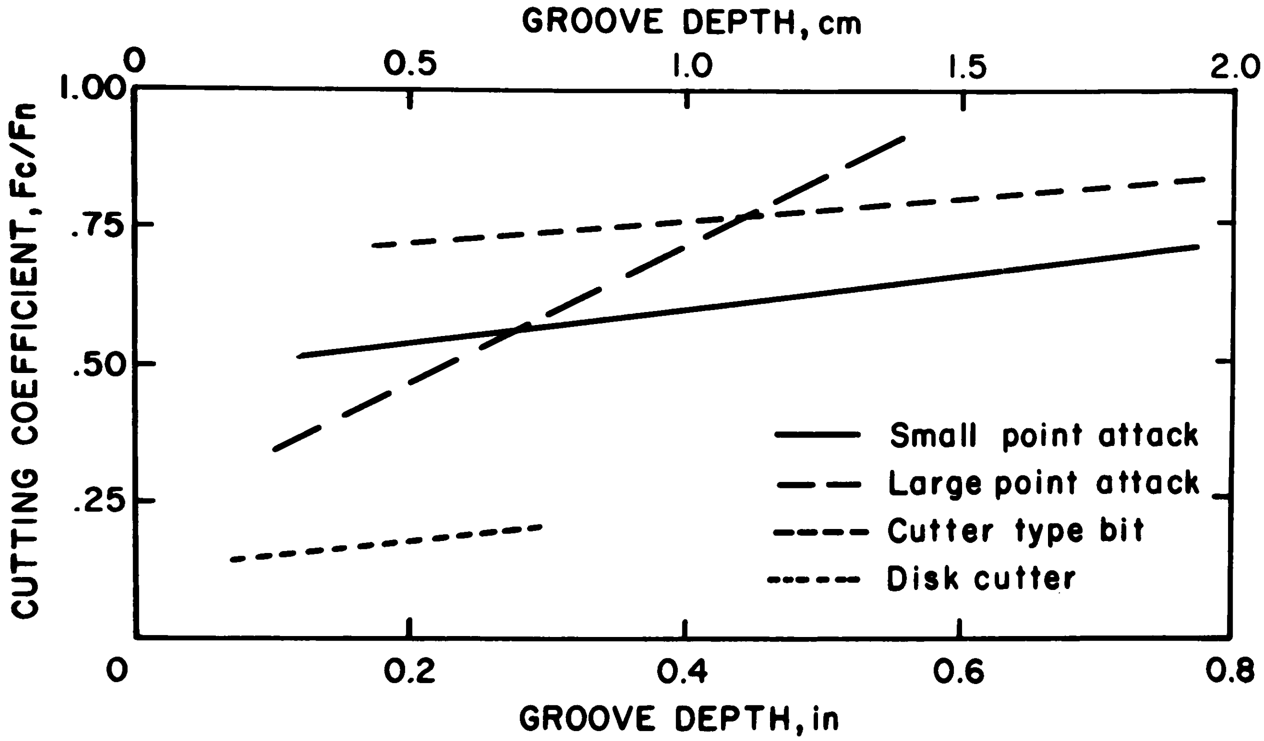

Figure 8. - Cutting coefficient as a function of groove depth in oil shale for independent linear grooves.

specific energy between the two curves. At the minimum specific energy level, the steady-state condition required only 30 percent of the specific energy requirements of independent linear cutting tests. The other curve on the figure is the test result from a 1-ft (0.3-m) cutterhead, using small finger cutter bits. With this type of bit, fragmentation efficiency, lowest specific energy, was best; however, it easily deviated from the hole axis and was not capable of high drilling rates.

The steady-state disk cutter test only represents one data point and can only be compared to an independent linear cutting test on the same oil shale sample. Making this comparison at the same depth of groove, the steady state required only 45 percent of the specific energy required by independent groove tests.

The rotary tests also emphasized the importance of optimizing the specific energy, considering the lateral loading and vibrations. An increase in depth increased the shock loads to the drill. From the standpoint of fragmentation efficiency, figure 11 shows there is very little gained by increasing the drilling rate more than 0.4 in. (1 cm) per revolution for the 2-ft (0.6-m) cutterhead.

Application of Results - Even though the bit and cutter experiments were performed under a narrow range of experimental conditions, the results can be used to approximate mechanical fragmentation machine performance. Disk cutter and drag bit machine requirements can be directly compared, assuming their use on a large rotary cutterhead, such as a tunnel-boring machine. For simplicity, this comparison was made, using linear cutting test results at lower specific energy levels. The calculation was

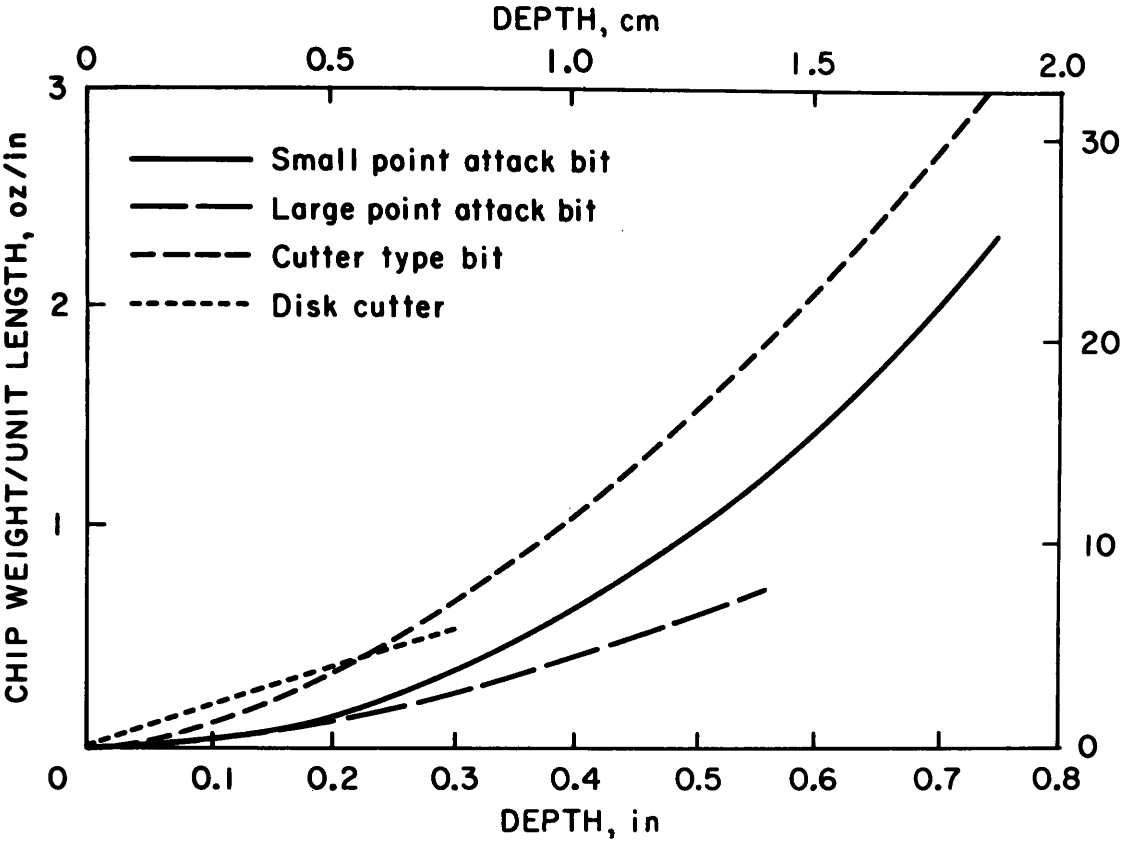

Figure 9. - Chip weight per unit length as a function of depth in oil shale for independent linear grooves.

restricted to fragmentation characteristic of the 7-in. (18-cm) 60° disk cutter and the small point attack bit. For equal tunnel sizes (11.3-ft-diam [3.4-m]), it was assumed that both cutterheads rotated at 5 rpm and penetrated 0.28 in. (0.71 cm) per revolution. This yields a production rate of 37 tons (33 metric tons) per hour, at an advance rate of 6 ft (1.8 m) per hour, considering cycle time. The experiment data dictated a 2.5-in. (6.4-cm) disk cutter spacing and a 2-in. (5-cm) drag bit spacing. Comparison calculations, using 33 disk cutters and 40 drag bits, showed that the disk cutter machine would require a thrust of 990,000 lb (4.4 MN) and a torque of 560,000 ft-lb (760,000 Nm). The drag bit machine would require a thrust of 120,000 lb (530,000 N) and a torque of 240,000 ft-lb (320,000 Nm). Calculations also indicated that the torque requirement for the disk cutter machine could not be significantly reduced by decreasing cutter spacing.

Another interesting comparison is the capability of a continuous drum miner. In this case, production rate is limited by the specifications of one of the most powerful miners manufactured. Its capabilities are limited by 120,000-ft-lb (160,000-Nm) torque; 83,000-lb (370,000-N) forward thrust; and 60,000-lb (270,000-N) shearing force. The assumptions were as follows: 10- by 10-ft (3.1 by 3.1 m) face (the same face area as the tunnel boring examples); 1-in (2.5-cm) bit spacing, for a total of 132 small point attack drag bits; 44.5-in. (113-cm) drum diameter; 25 rpm, and 6-in. (15-cm) sumping depth.

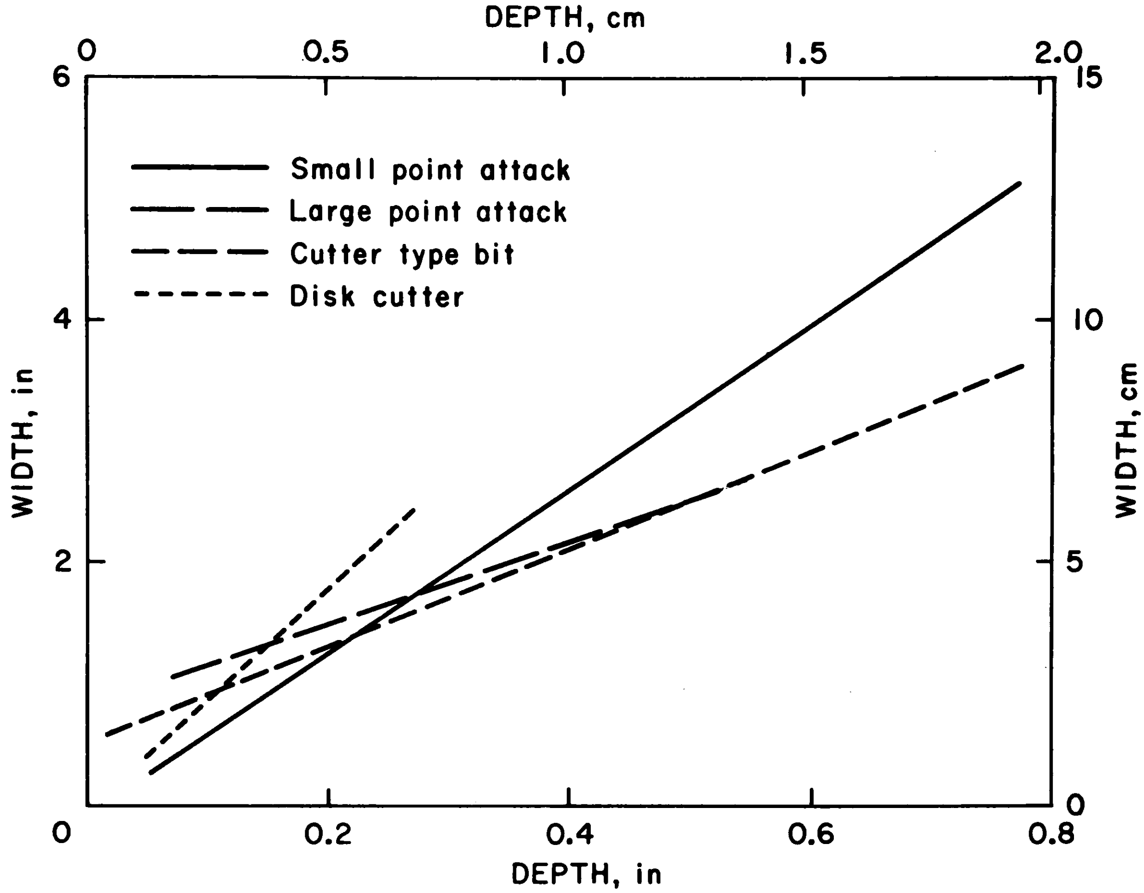

Figure 10. - Groove width as a function of groove depth in oil shale for independent linear grooves.

From experimental results of the small point attack drag bit, equations were defined for torque, thrust, and shearing force, as a function of depth, for the sumping and shearing cycle. Depth of cut per revolution and time delays determine cycle time. Calculated depth of penetration per revolution was 0.2 and 0.7 in. (0.5 and 1.5 cm) for the sump and shear, respectively. Therefore, one cycle produces 3.4 tons (3.06 metric tons) in 8.3 min. This yields a production rate of 24 tons (21.6 metric tons) per hour and an advance rate of 3.6 ft (1.0 m) per hour. Production rate could be increased with auxiliary jacks.

These examples are used only to illustrate the difference between a drag bit and disk cutter machines; production rates should only be considered as first approximations. For example, predictions could have been improved, using the steady-state test results and the 7-in. (18 cm) disk cutter which is approximately one-half the size used on the tunnel boring machines. However, at the same production rate, the drag bit tunnel boring machine required only 12 percent of the thrust and 43 percent of the torque needed by the disk cutter machine. Even though production rate of the drum miner was 60 percent of that of the

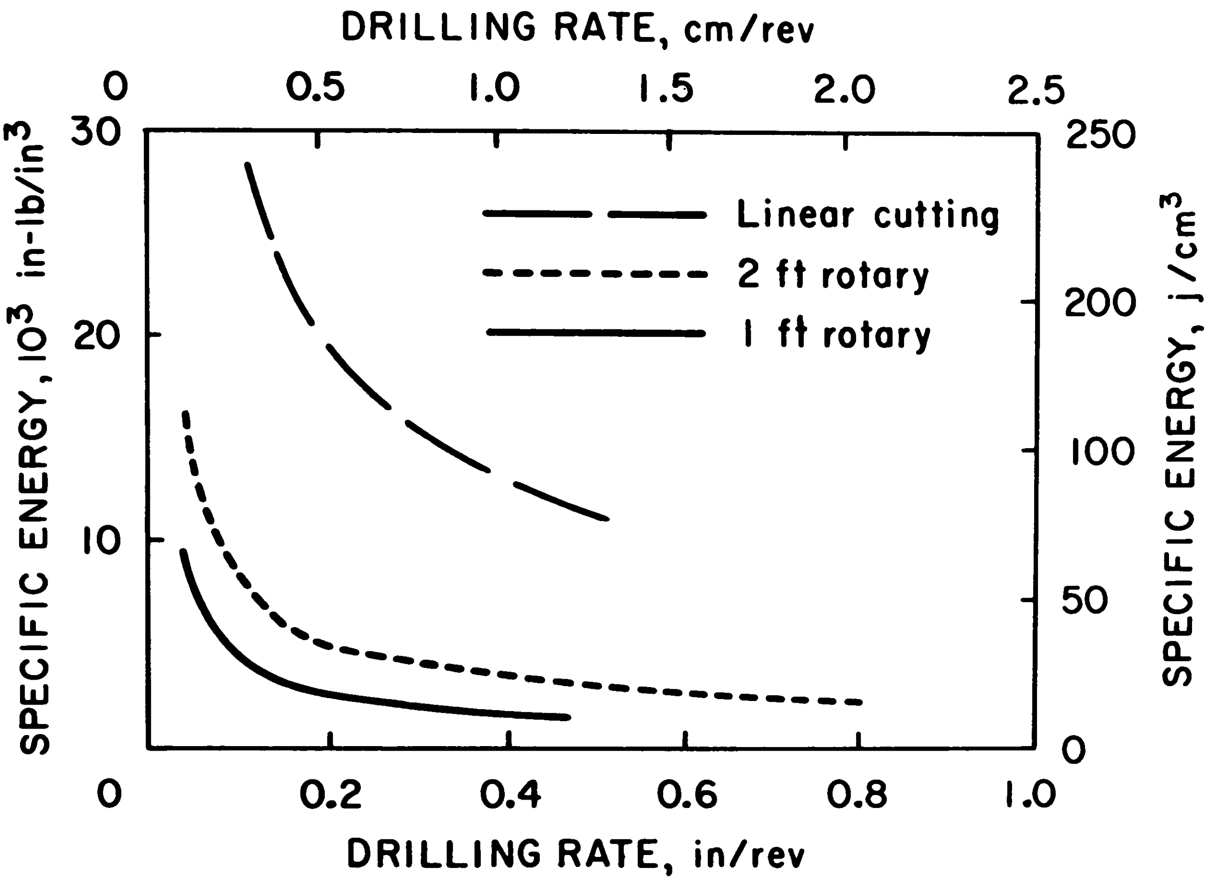

Figure 11. - Specific energy as a function of drilling rate in oil shale for both independent and steady-state conditions.

other machines, it required only 10 percent of the torque and 20 percent of the thrust needed by the disk cutter tunnel boring machine.

Summary

The important results of the bit and cutter evaluation are as follows:

(1) Fragmentation efficiency - Specific energy varies inversely with groove depth. As depth approaches zero, specific energy increases rapidly; and, as depth increases, specific energy decreases and approaches a constant value. Drag bits are more efficient than disk cutters. Specific energy for steady-state fragmentation is about 30 percent for drag bits and 45 percent for disk cutters of that required for independent groove fragmentation. Future improvements in mechanical fragmentation, such as water jet assisted bits (Morrell and others 1970) show some promise for increasing the fragmentation efficiency.

(2) Cutting forces - Depth of penetration is approximately a linear function of normal force for any bit or cutter. Drag bits required only one-sixth the normal force needed for disk cutters for the same depth of penetration. Drag bit cutting force is nearly four times greater than that required for the disk cutter at the same normal force. However, at equal depths of penetration, drag bits require a smaller cutting force than the disk cutter.

(3) Groove characteristics - Width varies directly with groove depth for all

cutting tools. The results demonstrate that optimum spacing for the disk could be as much as 1.7 times the optimum spacing for drag bits.

(4) Machine requirements - The machine requirements for drag bits are less than for disk cutters. This was illustrated by the comparison of two tunnel boring machines. The drag bit machine required only 12 percent of the thrust and 43 percent of the torque required by the disk cutter machine to obtain the same production rate.

Candidate Mechanical Driving Systems for Oil Shale

To determine the best machine for entry development in oil shale, machine experience must be considered. Basically, entry driving requires successful completion of three principal activities:

(1) Break the rock free from the face.

(2) Muck and transport the broken rock.

(3) Support the surrounding rock mass (Schenck 1974).

Explosives can excavate tunnels in all rock types with daily advance rates of 40 to 60 ft (12 to 18 m). Although versatile, the conventional drill-and-blast system has the disadvantage of accomplishing the three basic activities cyclically. This precludes any dramatic increases in excavation rates. Furthermore, excavation costs increase when tunnel diameter is below 11 ft (3.4 m) because of restricted working space (Muirhead and Gossop 1968).

By contrast, today's fully mechanized miners, roadheaders, and boring machines execute the first two principal activities simultaneously and continuously. The main advantages of continuous entry systems are:

- Break the rock continuously.
- Muck and transport continuously, at the rate material is produced.
- Provide a roof and/or wall requiring less support than the fractured rock left by blasting. The amount of overbreak rarely exceeds 5 percent, whereas, it often exceeds 25 percent in conventionally driven openings.
- Provide an inherently safer working environment since the excessive noise, fumes, and vibration of blasting are eliminated (Schenck 1974; Bruner 1974).

The disadvantages vary with machine type.

Continuous entry driving systems that could be used in oil shale can be divided into two categories:

(1) Continuous miners - Highly mobile machines, usually track mounted, which include the fixed drum miner, roadheader, and boring-type miner.

(2) Boring machines - These include tunnel and undercutting type boring machines.

Continuous Miners - Drum Miners. The first continuous mining machines were chain-type ripper miners, introduced in the late 1940s to the coal industry. These machines were replaced by drum-type continuous miners (fig. 12), such as the Jeffery Heliminer, Joy 11-CM and 14-CM, and the Marietta Drum Miner (Schenck 1974). Most are crawler mounted, with four basic structural components, consisting of main frame, gathering head, intermediate and discharge conveyor, and cutter drum.

The drum miner excavates a rectangular cross-section, the width of the cutter drum, cyclically. The cycle starts with the sump, where the bits are forced into the face at the roof line, then forced to the floor by hydraulic cylinders during the shear down. Next, the cusp is removed during the cut out. Finally, the machine is repositioned for the next cutting cycle (Fife 1974).

Main advantages of drum-type continuous miners are:

- High production rates - Trevorrow (1975) cites an example of cutting hard bottom rock of a coal mine (compressive strength: 21,000 and 30,000 psi [140 and 210 MN/m^2]), at 2.1 and 1.4 tons (1.9 and 1.3 metric tons) per minute. This production converts to advance rates of 16 and 11 ft (4.9 and 3.4 m) per hour for a 10- by 10-ft (3.1 by 3.1 m) heading. At these

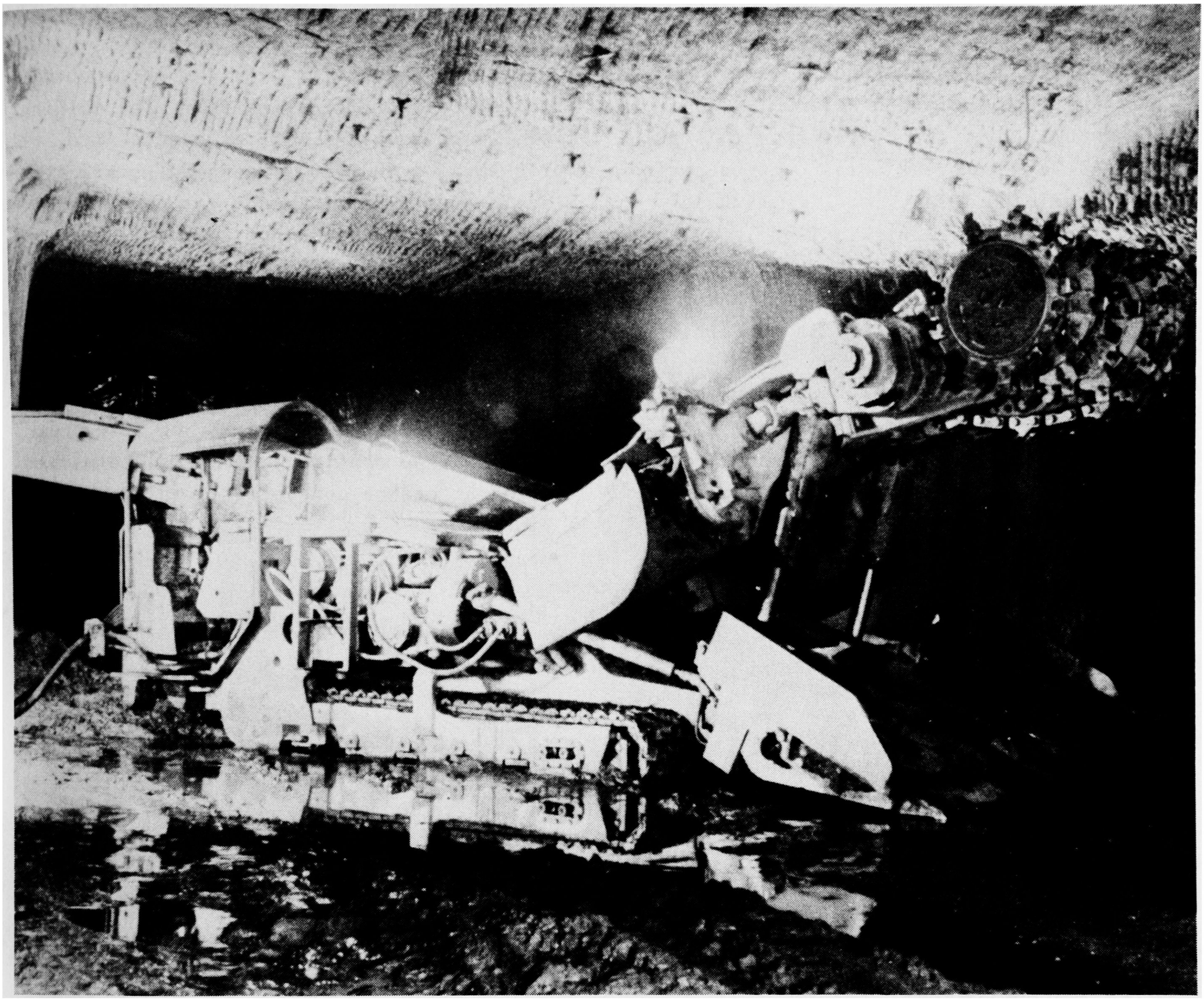

Figure 12. - Drum-type continuous miner in a French iron ore mine. (Courtesy, Jeffery Mining Machinery Div., Dresser Industries, Inc.).

high production rates, the continuous drum miner would require only a few hours of cutting time to outperform a conventional system.

- Relatively low investment cost.
- Crawler mounting gives the flexibility and maneuverability necessary for most mining systems, including 90° cross cuts.
- Easy bit changing and inspection - With these machines, the face is accessible.
- Roof support installation capability close to the face.
- Ready availability of spare parts.

The main disadvantages of the drum miner are:

- Lack of cutting force - Cutting forces are distributed over many bits and are solely reacted by the machine's weight since most machines are not braced against the roof or walls.
- High dust generation - Cutterheads, laced with many bits, create fines

and dust. This precludes their use where coarse muck is required and cost restricts the use of dust collectors, scrubbers, and additional fans (Schmidt and others 1975).

- Inability of the cutter boom to slew sideways to break cores between kerfs (Kogelmann 1974).
- Average machine utilization is only 20 to 30 percent. The rest of the time is for maintenance, bit changes, and waiting for materials handling equipment.
- Inability to excavate special cross-section shapes. To date, drum miners have been used in coal, gypsum, potash, salt, iron ore, and trona mines for entry driving and removing bottom rock.

Roadheaders. Roadheaders, or boom-type continuous miners, have been in use since the 1950s. The first one, an Alpine, ripper-type miner (fig. 13) was introduced into the United States in 1969. The milling type, Dosco Mark 2A, was introduced into North America in 1973. Roadheaders are similar to drum miners, except for the articulated boom. In addition, they are lighter and require less horsepower (Schenck 1974), and are capable of cutting harder rock (Kogelmann 1974).

The main advantages of the roadheader are:

- Ability to cut harder rock than drum or boring-type continuous miner since machine weight can be concentrated on one bit at a time.

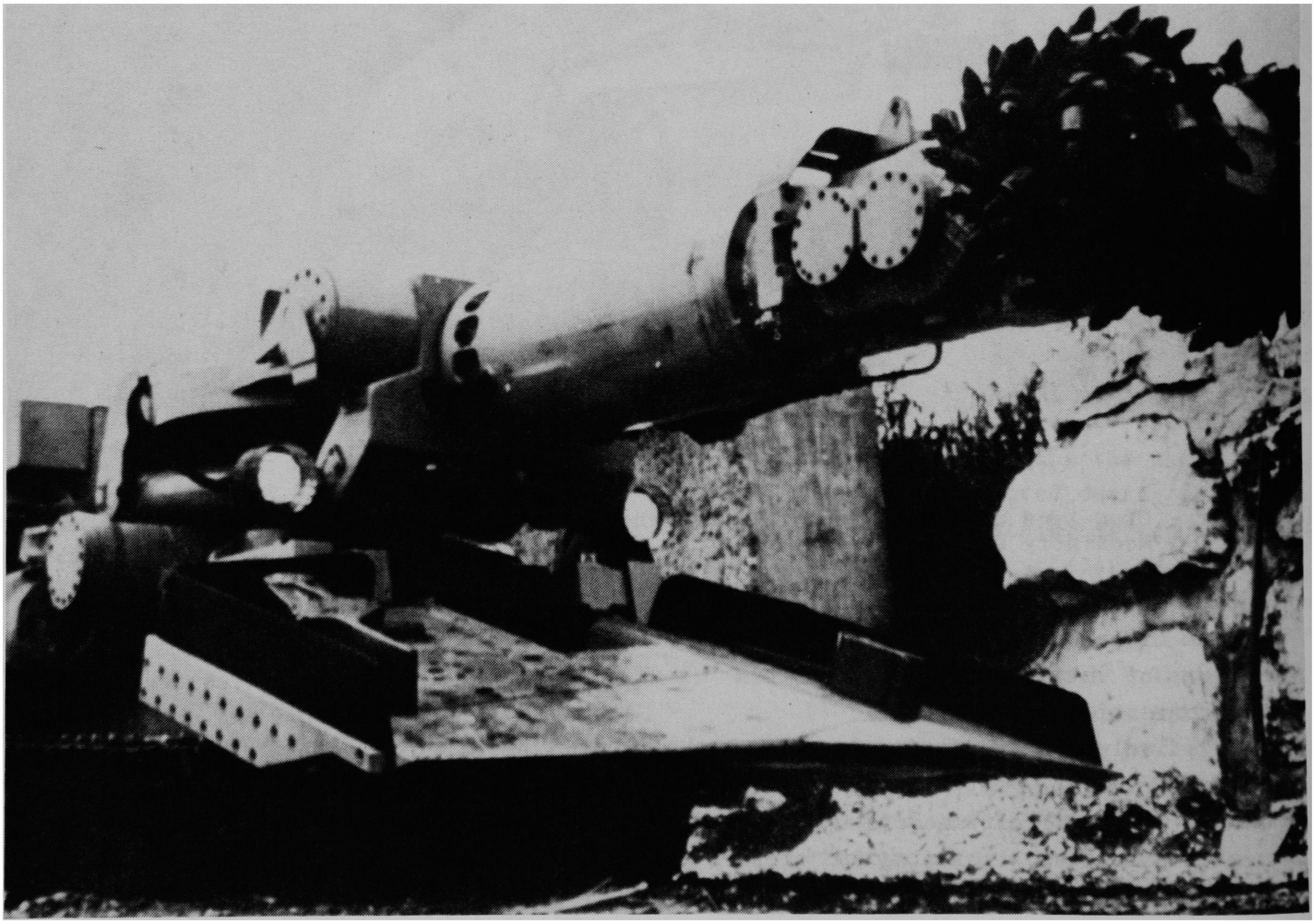

Figure 13. - Boom-type continuous miner. (Courtesy, Alpine Equipment Corporation.)

- Relatively low capital cost.
- Generates less dust than drum miner.
- Can negotiate steep grades and tight crosscuts (Schenck 1974).
- Ability to excavate various cross-section shapes.
- Roof support installation capability at the face.
- Greater utilization than a drum miner. Kogelman (1974) cites an example where a roadhead outperformed a drum miner in an iron ore mine. However, Schenck (1974) states that roadheaders have lower production rates.

The disadvantages of the roadheader are:

- Productivity generally lower than drum and boring type miner.
- Milling type cutterhead throws fragmented rock sideways and requires a separate mucking cycle.
- Careful maintenance required.

The ripper-type roadheader has been used to excavate rock up to 18,000 psi (120 MN/m^2).

Boring-Type Miners. Boring-type continuous miners (fig. 14), such as the Joy, Goodman, and Marietta, were first introduced for coal mining; however, they have obtained their greatest success in potash, salt, and trona mining. Such miners, equipped with two to four cutterheads and up to 1,500 hp, have achieved production rates up to 15 tons (13.5 metric tons) per minute (Schenck 1974). A kerf-core cutting principle produces larger cuttings than other continuous miners by cutting deep kerfs and breaking the core. The main advantages of the boring-type continuous miners are:

- High production rates.
- Crawler mounting gives flexibility and maneuverability necessary for curves and crosscuts.
- Easy inspection and replacement of bits.
- Ready availability of spare parts.

The disadvantages of the boring-type continuous miners are:

- Cutting reaction force is only the machine weight.
- Can only operate on moderate grade since they are heavy.
- Difficult to control dust on second pass.
- Limited excavation shapes.

Boring Machines - Tunnel Boring Machine. The tunnel boring machine or mole (fig. 15) evolved over the last century, beginning in England in 1856; however, the 1950s saw their first extensive use (Weber 1970; Bruce and Morrell 1970). During the past 15 years, techniques have improved enough to give this machine the economic edge over conventional methods for single entry development. Today's machines range in size from 6 to 40 ft (1.8 to 12 m) in diameter. The tunnel borer performs best on projects of several miles with few setups.

The machine can be visualized as a self-advancing, rotary drill, capable of cutting the circular face in a semicontinuous fashion. The machines are made up of an inner and outer frame. The inner frame carries the cutterhead that rotates and advances. The outer frame is held stationary by hydraulic rib jacks during the cutting cycle (Bruce and Morrell 1970). Thrust and torque capabilities are up to 2×10^6 lb (8.8 MN) and 1.5×10^6 ft-lb (2.1×10^6 Nm), respectively. All U.S. hard-rock machines use some type of rolling cutters. The most popular are single or multiple disks, or roller-shaped bits with carbide inserts. The single or multiple disk cutters yield the best penetration, if there is effective fragmentation between adjacent disks.

The main advantages of the tunnel boring machine are:

- Continuous fragmentation.
- Continuous mucking at cutting rate.
- Machine availability of about 50 percent (Hamilton 1972).
- Smooth roof with little overbreak, which allows less costly roof support.
- Easy dust control.
- High penetration rates in competent and uniform rock (Barendsen 1972).

The disadvantages of the tunnel boring machine are:

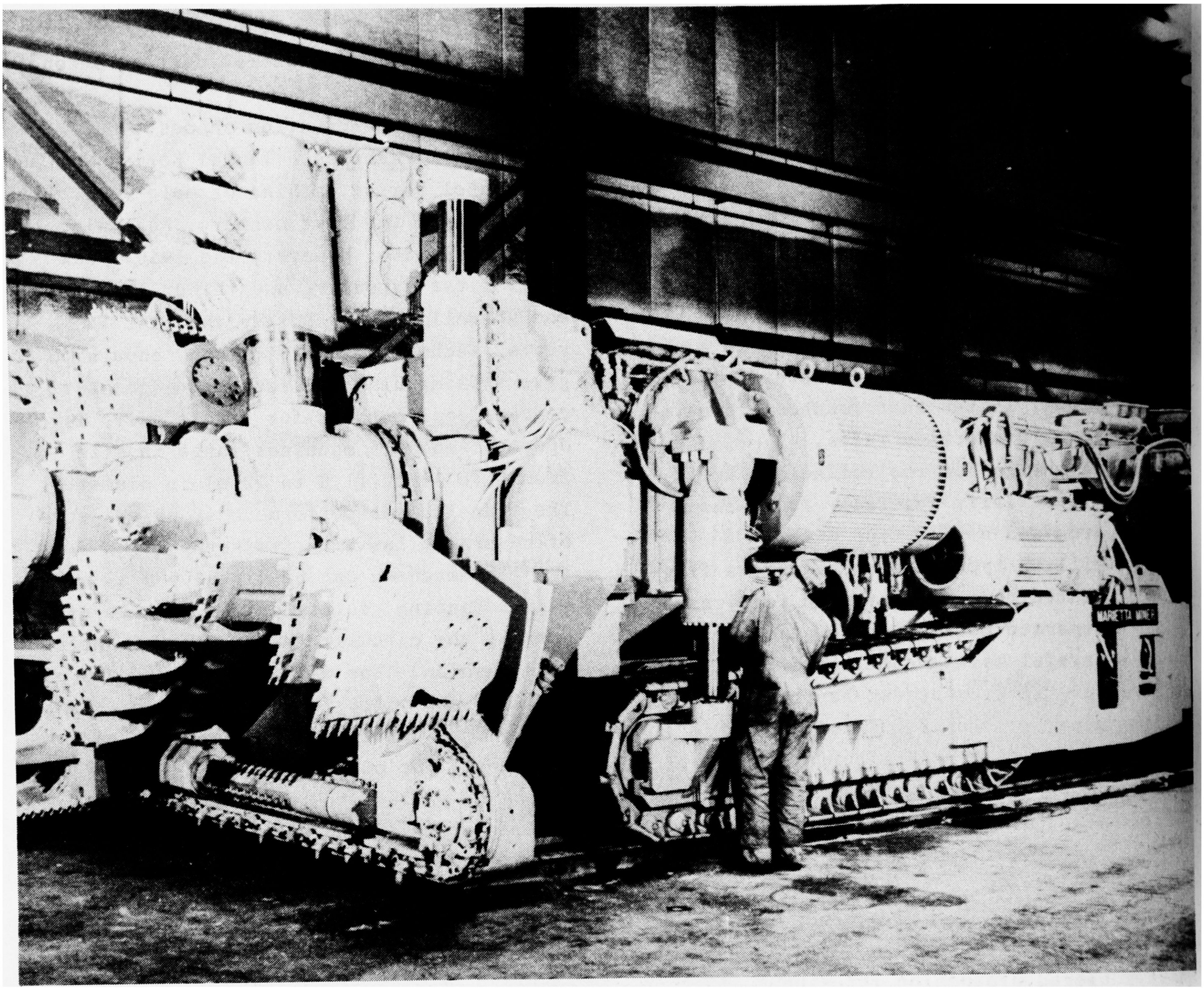

Figure 14. - Boring-type continuous miner. (Courtesy, National Mine Service Co.)

- High capital cost - To offset the \$1,300 per horsepower cost with power requirements up to 1,500 hp, the machine must be capable of boring 6 to 12 miles (10.8-21.6 km).
- High cutter costs - According to Weber (1970), they range from \$0.04 to \$0.70 per ft^3 (\$1.40 to \$25 per m^3).
- Much labor for setup and disassembly - This restricts the machine to developments of more than 1 mile.
- A large turning radius, generally 300 to 400 ft (91 to 120 m).
- Tunnel geometry only circular.

Undercutting Boring Machine. A new concept in tunnel boring, using the undercutting principle, was patented in 1951, originally tested in the early 1960s, and, since 1968, undercutting boring machines have been manufactured by Atlas Copco (fig. 16). The typical undercutting boring machine breaks the rock by inducing stresses that exceed its compressive/shear strength through a thrust force applied parallel to the tunnel axis.

The undercutting principle, as shown in figure 17, undercuts the rock with drag bits mounted on a rotating swinging cutterhead. The undercut ridge is easily broken and

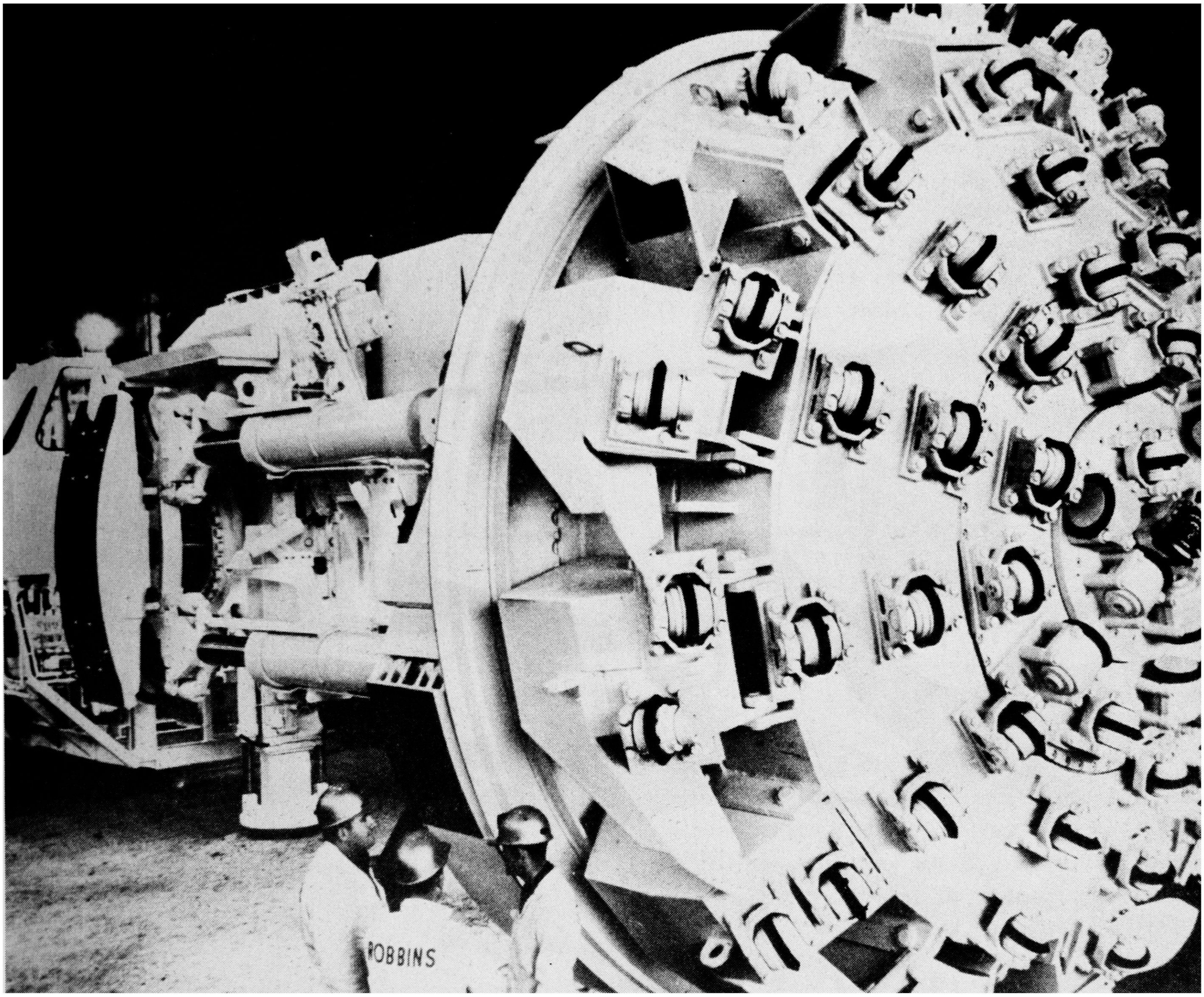

Figure 15. - Eighteen-foot-diameter tunnel boring machine (3). (Courtesy, The Robbins Co.)

creates 70 to 85 percent of the excavated volume. The forces required to oppose the cutting forces are provided by rib jacks. This undercutting method is adaptable to several different tunnel cross sections, as shown in figure 18. Figure 16 shows the smallest version, the minifullfacer, of the Atlas Copco machines.

Atlas Copco machines have driven tunnels through homogeneous rock with compressive strengths up to 30,000 psi (210 MN/m^2). Test tunnels have been driven in 55,000-psi (380-MN/m^2) rock. The minifullfacer has obtained advance rates up to 8.2 ft (2.5 m) per hour.

The advantages of the undercutting boring machine are:

- Low cutter cost since only part of the excavated volume is cut. Case histories list cutter costs from \$0.05 to 0.16 per ft^3 (\$1.80 to \$5.60 per m^3) for 15,000- to 28,000-psi (100- to 190-MN/m^2) shale.
- Undercutting boring machines require less than 30 percent of the thrust required by tunnel boring machines.
- Undercutting produces less fines. Less than 10 percent of muck is below

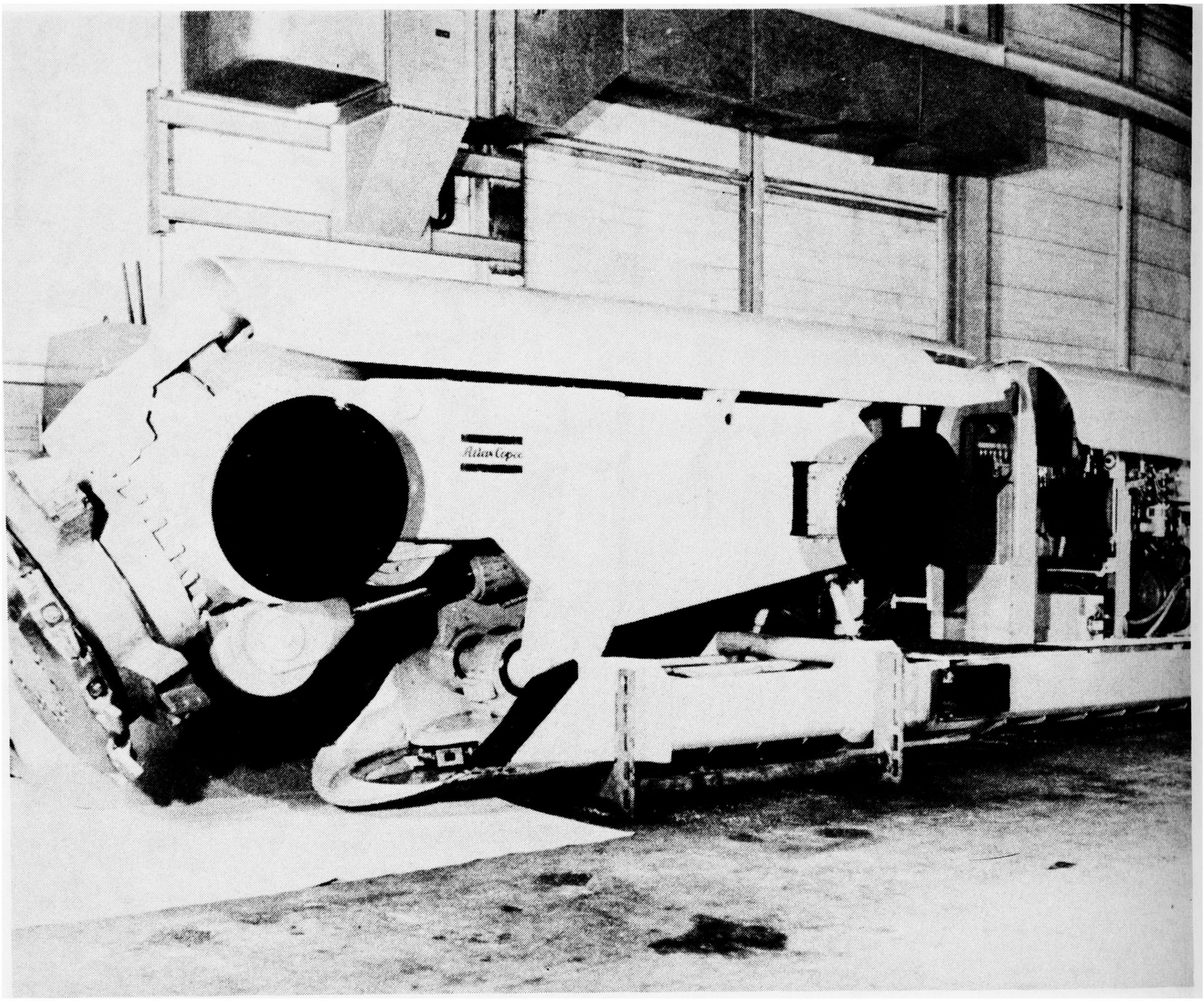

Figure 16. - Minifullfacer tunnel boring machine. (Courtesy, Atlas Copco, Inc.)

3/8-inch (9.53 mm) size.
- Easy bit changing.
- Variability of tunnel geometries with different machine designs.

The disadvantages of the undercutting boring machine are:
- Low maneuverability since the machines are propelled by rib jacks. However, the machines can be designed to turn in a 40-ft (12 m) radius which is better than that of the tunnel boring machines (Barendsen 1972; Brodbeck 1974; Talvensaari 1974).
- Less flexible than the continuous miners.

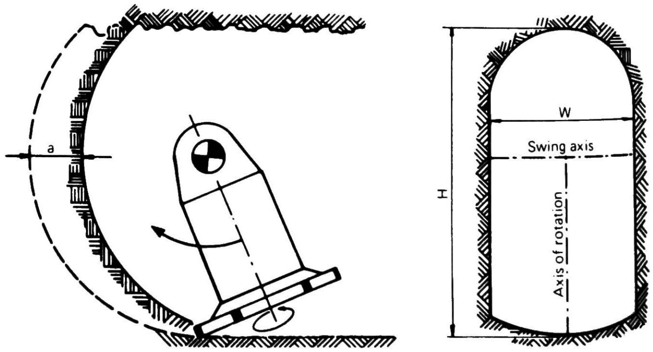

Figure 17. - Drag bit cutterhead used for undercutting principle. (Courtesy, Atlas Copco, Inc.)

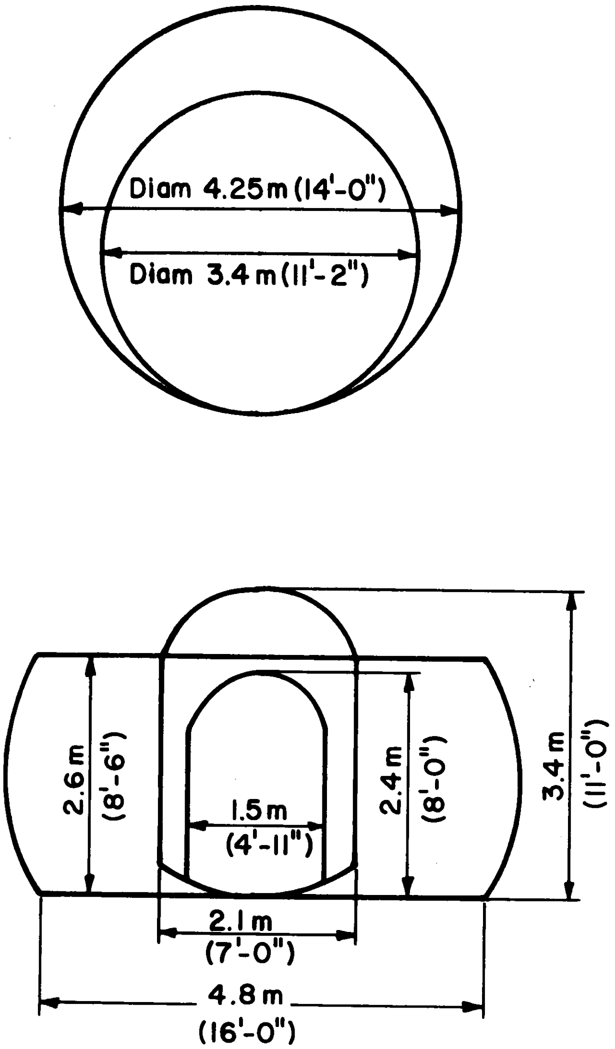

Figure 18. - Tunnel size and shape capabilities of the undercutting machines. (Courtesy, Atlas Copco Inc.)

Recommendations and Conclusions

The next step in introducing mechanical fragmentation systems to oil shale mining should be a field trial to develop some cost and performance data. In mechanical excavation, bit and cutter wear is an important cost consideration. Even though we did not examine wear qualitatively, none of the bits or cutters used in our experiments, showed any appreciable wear. In fact, the large point attack drag bits showed no wear after cutting up to 1,500 linear feet (460 m) for the steady-state tests. The experimental results cannot be applied directly to predict the performance of any of the candidate machines; however, they can be used to predict trends for the fragmentation efficiency of the various bit and cutters. The important criteria for choosing an entry development machine for a field trial should be: (1) the machine should require no, or slight, modification -- this dictates hard rock experience; (2) the fragmentation process should be as efficient as possible; (3) the systems should be as flexible as possible.

For vertical development, machine selection is limited to the shaft drill and the raise boring machine. The separation of cutterhead and machine, limits their performance to the capability of the drill steel to react the dynamic forces generated by the fragmentation process. Because of this system limitation, there are only minor variations of the roller cutter fragmentation process. However, our experiments indicated oil shale fragmented more efficiently when cut to simulate vertical entry development.

Several machines have been used in noncoal formation for horizontal development, making the choice of machine more difficult. One can, however, make up a decision matrix, emphasizing the important criteria for the future job. Using our test results and information we prepared a simplified matrix (table 1) to illustrate the possible selection process of a machine for a field trial. Table 1 is oversimplified and very subjective. Its primary purpose is to stimulate thought. Each category of machine characteristics was ranked, from 1 to 3, and category ranks for each machine were added. The undercutting boring machine received the highest ranking because it incorporates many of the advantages of both a disk cutter and drag bit machines. If there is a use for a small size entry, the minifullfacer or the midifullfacer would be a logical choice to develop cost and performance data on mechanical fragmentation systems for oil shale.

Table 1. - Simplified decision matrix to select a candidate machine for oil shale entry development.

Desirable machine characteristic for oil shale entry development	Fixed drum miner	Road-header	Boring-type miner	Tunnel boring machine	Undercutting boring machine
Low specific energy........	2	3	3	1	3
Low normal force...........	2	2	2	1	2
Large cutter spacing.......	2	2	3	3	[1]3
Stable machine structure...	2	1	2	[2]2	2
High maneuverability and low mobilization..............	3	3	3	1	2
Hard rock experience.......	2	2	1	3	3
Total............	13	13	14	11	15

[1]Space between undercuts.
[2]High lateral force generated by disk cutter.

Acknowledgments

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