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Toward Development of a Hard-Rock Mining Machine—Drag Cutter Experiments in Hard, Abrasive Rocks

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	in-lb	inch-pound
fps	foot per second	ipm	inch per minute
ft	foot	ips	inch per second
ft^3	cubic foot	kw	kilowatt
ft-lb	foot-pound	kwhr	kilowatt-hour
ft-lb/min	foot-pound per minute	lb	pound
g/cm^3	gram per cubic centimeter	pct	percent
hp	horsepower	psi	pound per square inch
hr	hour	yr	year
in	inch		

TOWARD DEVELOPMENT OF A HARD-ROCK MINING MACHINE—DRAG CUTTER EXPERIMENTS IN HARD, ABRASIVE ROCKS

By Roger J. Morrell[1] and Richard J. Wilson[2]

ABSTRACT

The Bureau of Mines conducted drag cutting experiments in hard, abrasive rock in an effort to extend the capabilities of an experimental kerf-core mining machine. The basic kerf-core mining machine cannot be used in hard, abrasive rocks because of the high wear experienced by the kerf cutters. These experiments were conducted in an effort to develop a method of preweakening the rock ahead of the kerf cutters in order to reduce the high cutting loads and hence the higher wear rates experienced by the cutters. The two "preweakening" techniques studied were indenting with mechanical wedges and single and double slotting with diamond saws. The best cutter force reduction achieved with mechanical indenting was 70 pct, whereas double slotting achieved force reductions of up to 99 pct.

Conceptual designs of preweakening systems that could be retrofitted onto the basic kerfing cutterhead were developed for both the indenting and the slotting techniques. A high-energy impactor with wedge bit was used for the indenting method, and high-pressure water jets were used for the slotting method. A preliminary technical and economic analysis was performed for both of these full-scale systems to illustrate the methodology and to point out the important technical and economic factors that must be considered.

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[2]Mining engineer.
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INTRODUCTION

The objective of this research is to develop a fragmentation technique that will allow the economical use of drag cutters in abrasive rocks of up to 30,000-psi compressive strength. This effort supports the Bureau's program to develop a kerf-core mining machine for hard rock. This machine is currently being developed under contract,[3] and the concept is shown in figure 1.

This kerf-core mining machine is being designed to replace conventional drill-blast excavation in small, confined headings which includes all development openings as well as small stoping operations such as room-and-pillar mining. It is not designed to compete with drill and blast techniques in large underground stoping operations or in surface operations. These machines are being designed to excavate and load out ore from the face at a cost and production rate competitive with drill and blast methods.

In addition, these machines must be able to excavate any reasonable size and shape of opening, cut 90° crosscuts, work on grades of up to 30°, and, in general, to operate without requiring a major change in existing mining methods.

The kerf-core mining machine is theoretically capable of meeting all of these performance goals in most soft-to-medium

[3]Testing of a Fragmentation System for a Hard Rock Mining Machine, BuMines Contract J0100081, Foster-Miller Associates, Inc.

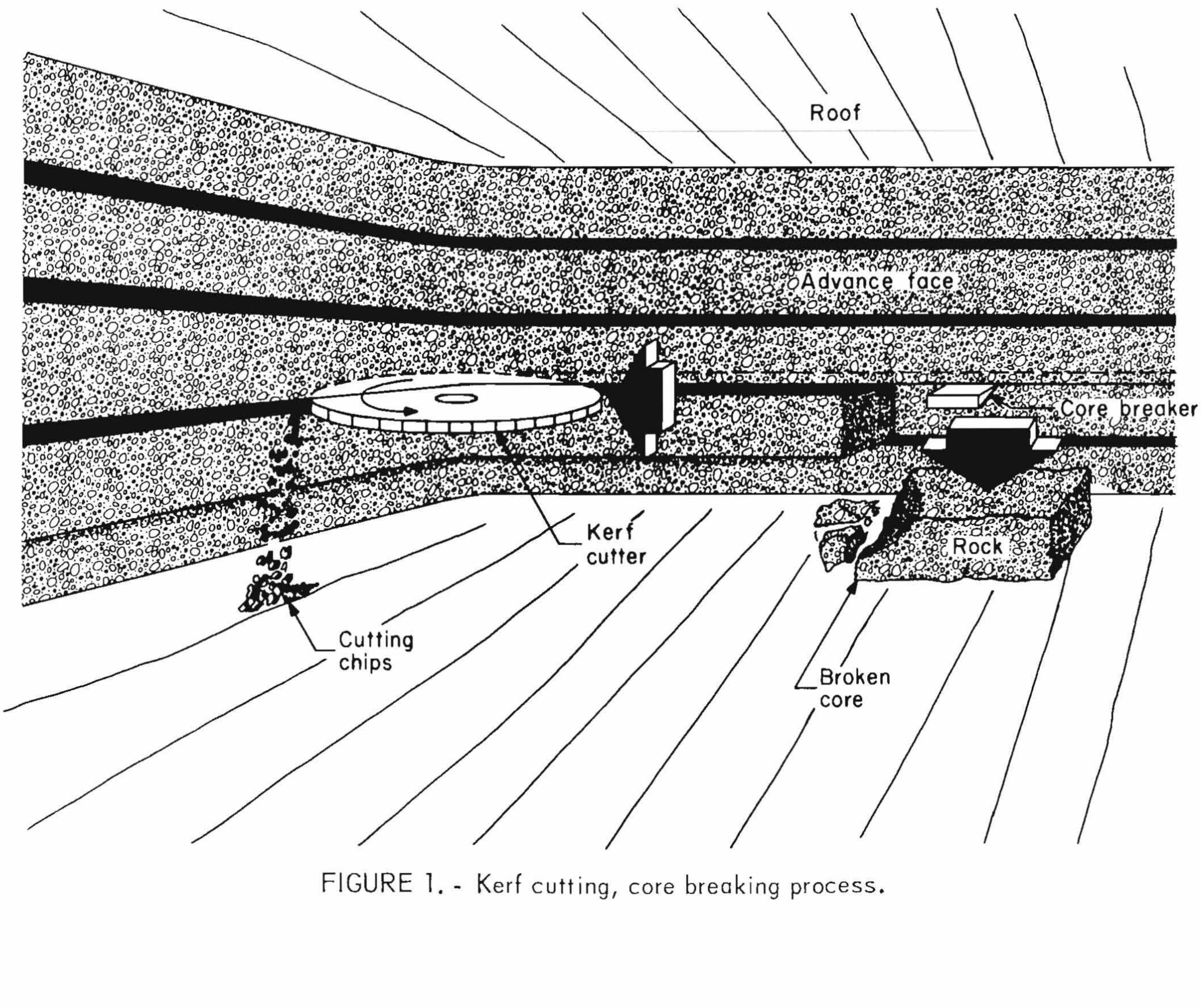


FIGURE 1. - Kerf cutting, core breaking process.

strength, nonabrasive rocks. The primary advantages of the kerf-core system is that only a small amount of rock is actually cut while the major portion is efficiently broken out in tension as large rock cores. Additionally, the narrow, deep kerfs required are amenable to being cut with relatively inexpensive, lightweight, drag-type cutters. Kerf-core systems also allow a large amount of energy to be concentrated on the kerfing process, which yields a high kerfing rate and an overall high production rate, while the overall energy required is kept within reasonable limits (4).[4]

The kerf-core mining machine operates by first cutting deep, narrow kerfs into the rock with a wheel dressed with drag cutters (fig. 2). In practice, this wheel rotates slowly so that cutter speed is kept between 12 and 24 ips and the drag cutters cut as deeply as possible, sometimes up to 1 in per pass. The kerfs themselves are 1.5 to 3 in wide, 12 to 24 in deep, and spaced 12 to 24 in apart depending on what is required for efficient core breaking in the particular rock type. In all cases, research has shown that the kerf spacing-to-depth ratio should be less than 1 for efficient breakage. It is felt that 24- by 24-in cores are the maximum size that can be handled easily underground. As each rock core is formed, it is fragmented by a "core breaker," some examples of which are shown schematically in figure 3. The final configuration of the core breakers and the complete kerf-core mining system will be available at the conclusion of contract J0100081.

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

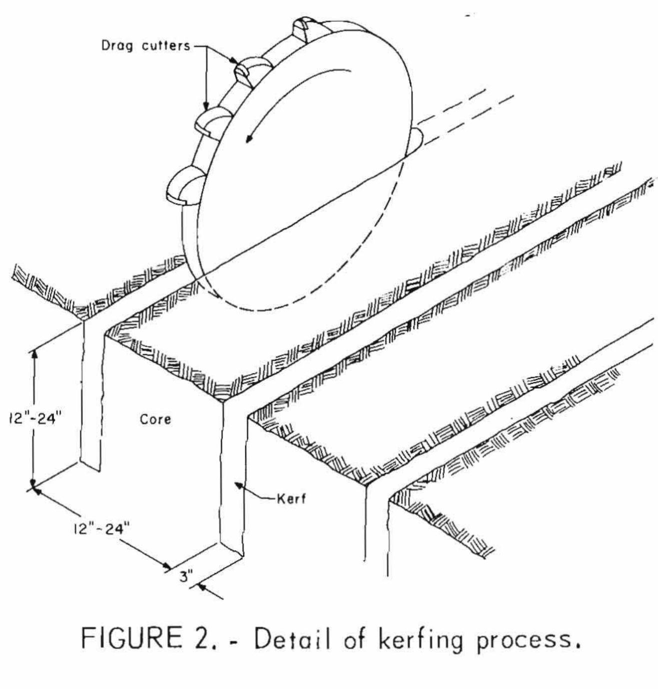


FIGURE 2. - Detail of kerfing process.

The basic system is designed to be capable of mining nonabrasive rocks of up to 20,000-psi compressive strength. The ability to cut all rocks, both abrasive and nonabrasive, up to 30,000 psi would give this machine much wider applicability in the mining industry.

To make the system work in abrasive rocks, the major problem that must be overcome is excessive kerf-cutter wear. Cutter cost alone would make the difference between an economical or noneconomical system as compared to conventional drill and blast methods. While low cutter cost is possible in soft nonabrasive rock such as oil shale, it is not possible in hard abrasive rock.

One way to solve the cutter wear problem is to develop an improved cutter that is more resistant to wear. The other way is to develop an improved, more efficient cutting process which is less demanding of the cutter. The first approach is being actively pursued by bit manufacturers and some research organizations (5).

The second approach was chosen for investigation and is the subject of this report. The technique investigated is called "preweakening" and consists of conditioning the rock ahead of the drag cutter. The basic assumption is that easing the cutter's task (as measured by a drop in cutting force) will reduce its wear. This assumption could not be verified during these experiments owing to limitations of the test equipment, which prevented extended runs on the bits. Future efforts will attempt to quantify cutter wear as a function of cutting

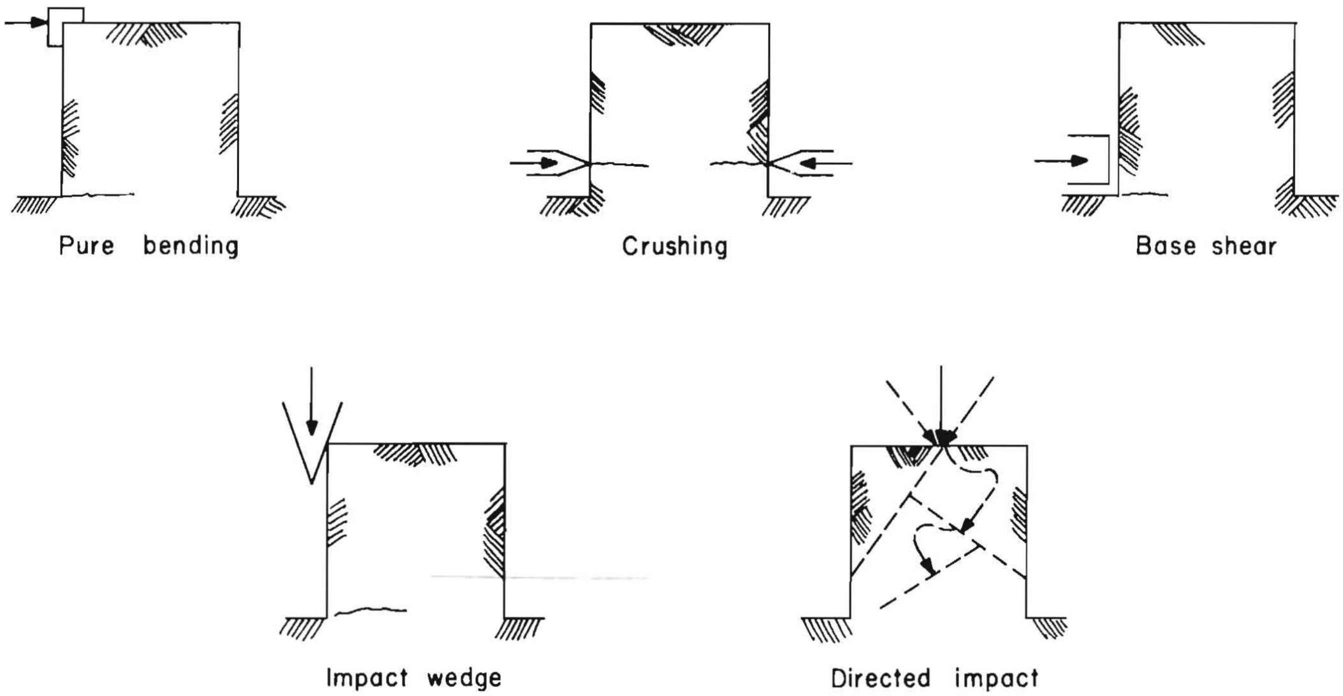


FIGURE 3. - Core breaking methods to be investigated.

force. In this testing program, the measure of success for each preweakening technique was taken to be the amount of cutting force reduction that was achieved.

Two methods of preweakening were investigated: mechanical indenting and mechanical slotting. These methods were chosen because they are proven, practical techniques for fragmenting rock, and because they could be used underground without creating safety hazards. Numerous other techniques could have been used, but were considered beyond the scope of this program because they were either impractical for underground use, or had environmental or economic limitations.

EQUIPMENT

To simulate closely the kerfing process of a full-scale mining machine, it was necessary to develop testing methods and equipment that would use full-size cutters that cut up to 0.5 in per pass. It was also determined to measure the cutting force only in the direction of travel since the normal and side forces are related to it in a known fashion. Cuts as short as 6 in were considered acceptable as long as a steady-state condition was reached. Based on these requirements, it was concluded that a compression testing machine could be used to supply the required motion, forces, and instrumentation. Consequently, a special drag bit tester (fig. 4) was developed that mounted on the platens of a compression testing machine.

In operation, the rate of cutting (i.e., the rate of closure of the platens) was preset at 12 ipm and the length of the cut was 6 in for all tests. It should be noted that field cutting is expected to take place at 12 ips. This represents a speed difference of 60 times, but previous Bureau work and that of others (1), has shown that cutting speed has very little effect on cutting force over a wide range of speeds. Thus, using a lab speed of 12 ipm is not considered to affect the results in any significant way.

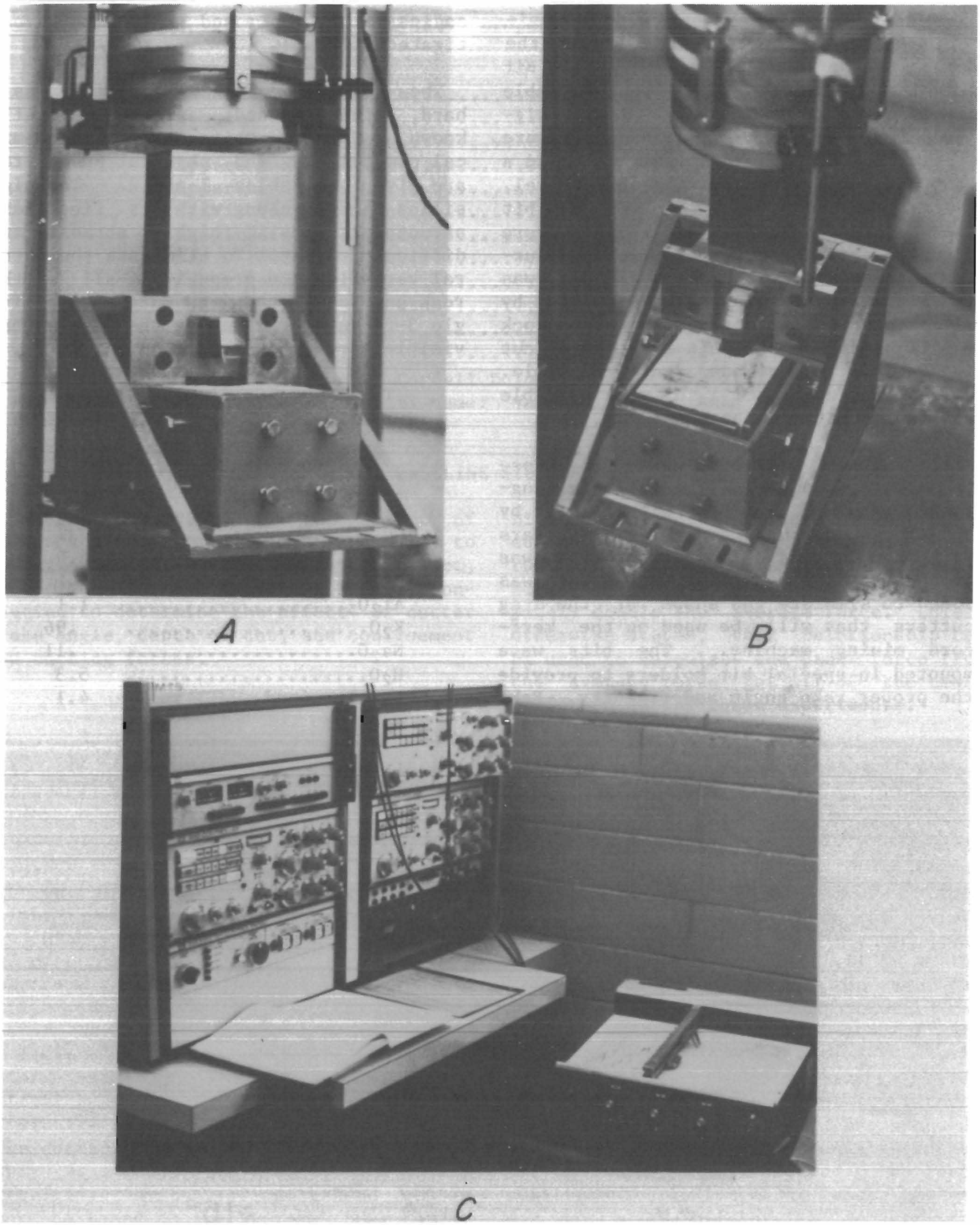


FIGURE 4. - Drag cutter tester installed on compression test machine (A and B), instrumentation and force recording (C).

The applied force was continuously monitored by a load cell that measured the force in the direction of travel. Bit travel was monitored by a linear variable displacement transducer (LVDT). The signals from the load cell and the LVDT were transmitted to an X-Y recorder to yield a plot of cutter force versus bit travel. The normal and side forces on the bit were reacted internally by the structure of the tester and were not measured during these tests. The depth of cut was preset at the beginning of each run by adjusting the distance between the rock sample holder and the bit. Depths of cut up to 0.5 in per pass were possible. Cumulative depths of 1 in were possible utilizing multiple passes.

All of the drag bits used in these tests were commercially available tungsten carbide finger bits with a 0.5- by 0.5-in carbide cutting face. The corners were rounded off and a slight crown was ground onto the cutting edge. This was done to simulate the shape of the drag cutters that will be used on the kerf-core mining machine. The bits were mounted in special bit holders to provide the proper rake angle and rigidity. Rake angles of 0°, -15°, and +15° were investigated (fig. 5).

The rock used for all testing was a hard, fine-grained dolomite, locally known as Valders white rock. Its chemical composition and physical properites are given in tables 1 and 2. The high silica content along with its fine grain structure makes it highly abrasive and difficult to cut. To eliminate the natural variation in properites, all of the rock samples tested were cut from a single 3-ft cube. None of the samples had visible structure or defects.

TABLE 1. - Chemical analyses of Valders dolomite, percent

Component	
SiO_2	30.1
CO_2	26.7
CaO	16.5
MgO	15.1
Al_2O_3	1.1
K_2O	.96
Na_2O	.11
H_2O	5.3
Undetermined	4.1

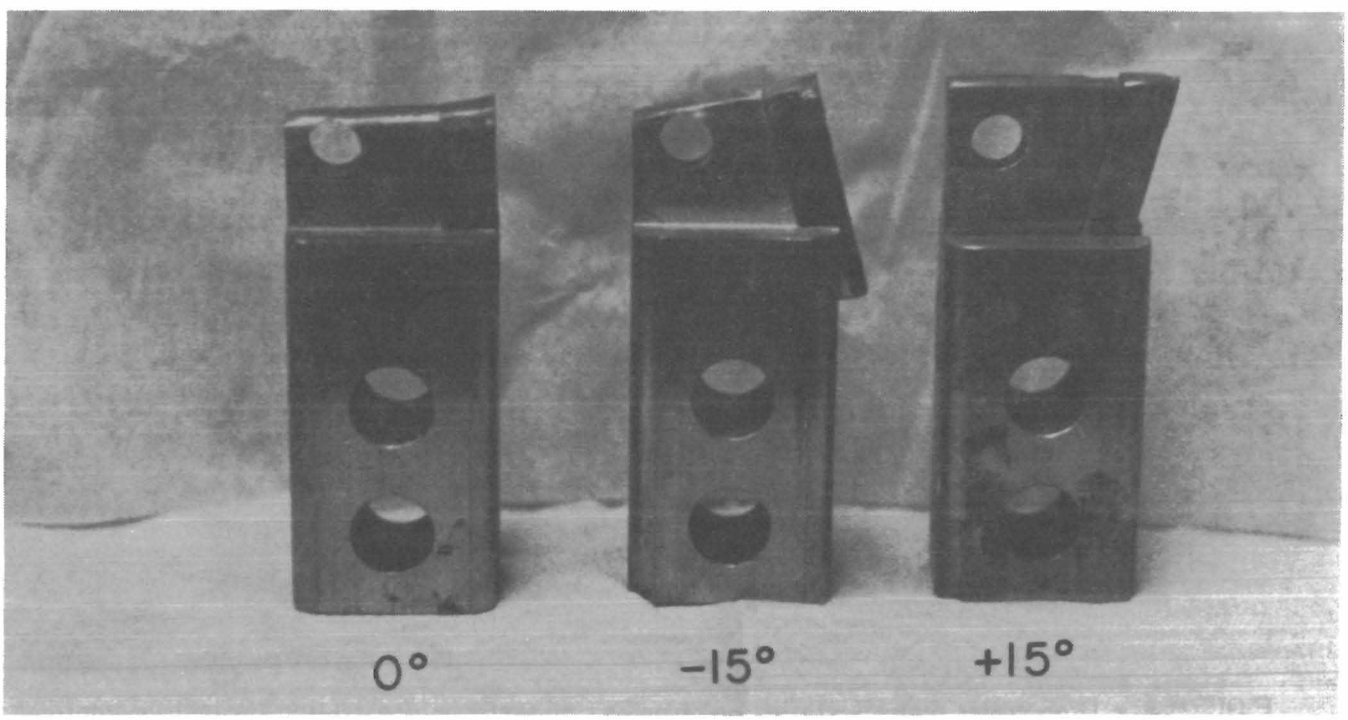


FIGURE 5. - Drag cutters in three rake angles, all 1/2-in wide.

TABLE 2. - Physical properties of Valders dolomite[1]

Compressive strength....................psi..	27,230
Tensile strength........................psi..	793
Shore hardness............scleroscope units..	68
Apparent density.................slugs/ft^3..	5.056
Apparent density.....................g/cm^3..	2.613
Static Young's modulus..............10^6 psi..	5.7
Longitudinal velocity...................fps..	12,815
Bar velocity............................fps..	12,118
Shear velocity..........................fps..	8,513
Dynamic Young's modulus.............10^6 psi..	5.17
Poisson's ratio.............................	0.20
Shear modulus.......................10^6 psi..	2.55

[1]Geologic name: Cordell Dolomite Member, Manistique Formation; commercial name: Valders white rock; locality: Valders, Wis.

BASELINE STUDIES

In order to determine the effect of preweakening, it was first necessary to obtain baseline cutter forces for intact, unaltered rock. Experiments were conducted to determine the effect of cutter rake angle, depth of cut, and confinement on cutting forces.

ROCK CHIP FORMATION

The cutting of hard rock by a drag cutter is essentially the forming of a series of individual chips. As force on the cutter builds up, the rock directly under and in front of the cutting edge is crushed and one or more large chips are formed. The force drops with chip formation. This process continuously repeats so that the force record of the bit as it moves across the rock is a series of maximums and minimums as shown in figure 6.

These erratic force versus displacement plots show the difficulty in comparing bit force data, since the peak forces are typically two to three times the average. The concept of average force is useful only as a measure of the average energy required. Any bit or cutterhead design must be based on the average peak force, the force actually required for chip formation in hard rock. The average peak force is defined as the average of the highest peak force measured in each of 10 equal intervals along the length of the run. It was found that with few exceptions the average peak force was approximately double the average force. Unless otherwise stated, this relationship can be used to calculate the peak force from the average force for all of the tests performed during these experiments.

EFFECT OF CONFINEMENT

Because the data generated during these tests had to be relevant to a deep-kerfing mining machine, the first variable to be investigated was the effect of confinement of the cutter caused by cutting at the bottom of a slot. To perform this experiment, a series of cuts, each the same depth, was made starting at the surface and working down as the kerf was formed. The experiment was conducted for three rake angles and two depths of cut.

A typical result is shown in figure 7. Note that each successive cut required a higher force level than the one preceeding it, for all rake angles tested and for all depths of cut tested. The force continued to increase for each cut and did not level off for the deepest kerf investigated (0.75 in). The force for the deepest cut was between two and three times that of the surface cut. Work by

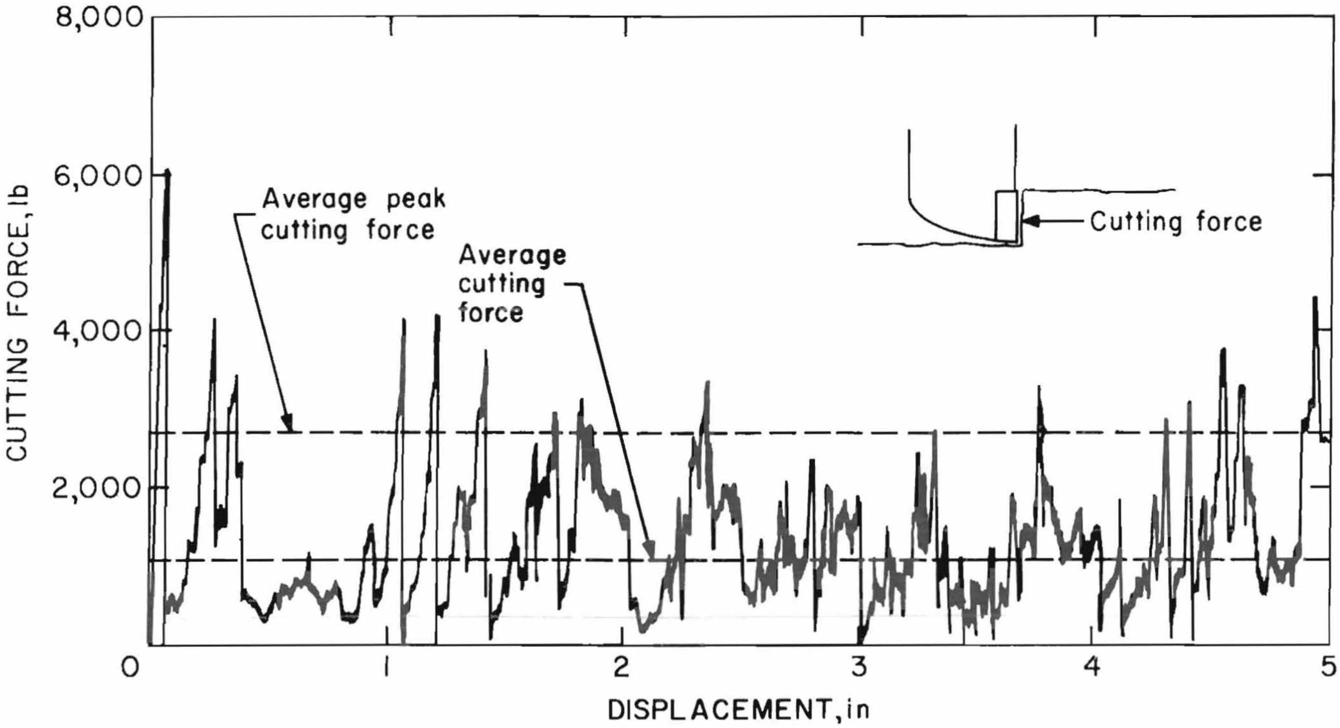


FIGURE 6. - Typical cutter force versus displacement plot (1/4-in depth of cut, 1/2-in-wide bit, 0° rake angle).

Hill (2) indicates that the forces should reach a steady-state maximum of approximately four times that of the first surface cut.

As a result of these experiments, all of the preweakening tests were conducted in a precut 0.5- by 0.5-in slot so as to include the confinement effects of a deep kerf. This was the deepest slot that could be used because of equipment limitations. However, because this is not deep enough to achieve a steady state, all of the forces obtained from the preweakening experiments should be considered as minimum values; a more realistic value would be about one-third higher.

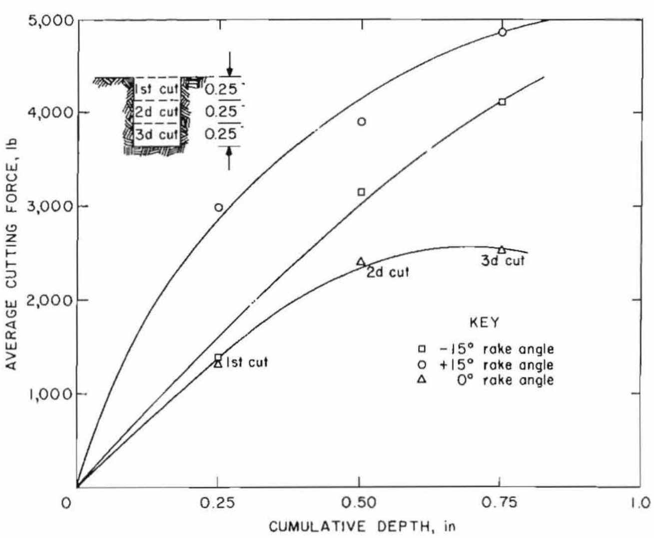


FIGURE 7. - Effect of cutter confinement on cutting surface.

EFFECT OF RAKE ANGLE

These experiments investigated three rake angles, -15°, 0°, and +15°. The depth of cut was held constant at 0.25 in and all runs were made in a precut kerf that was 0.5-in deep and 0.5-in wide. The average cutting forces for each bit are shown in table 3. While the forces between individual runs show some scatter, they are reasonably consistent. The average of the cutting forces for each bit was therefore used as the basis of comparison for the preweakening experiments.

TABLE 3. - Effect of rake angle on average cutting force[1]

	Rake angle		
	0°	+15°	-15°
Average cutting force (0.25-in cut depth), lb:			
1st cut....................	4,500	4,185	3,780
2nd cut....................	2,520	4,851	4,950
3rd cut....................	2,550	4,140	2,520
4th cut....................	2,250	NT	NT
Mean average.............	2,955	4,392	3,750
Standard deviation.......	1,039	398	1,215

NT Not tested.

[1]All cuts were made in a 1/2- by 1/2-in precut slot.

The pressure exerted by the cutter (cutting force per area of cut) is about 24,000 psi for the 0° rake and about 32,000 psi for the -15° and +15° cutters. The compressive strength of this rock is about 27,000 psi. Also, while the 0° bit achieved the lowest average force in these tests, in actual field use, a slight negative rake angle generally gives the longest bit life.

EFFECT OF DEPTH OF CUT

The depth of cut per pass is an important variable in drag cutting, and an experiment was conducted in an attempt to quantify this relationship. The tests were limited to the 0° cutter with the assumption that the general behavior of the -15° and +15° cutters would be similar. The tests were conducted in both the unconfined and the confined states (within a precut kerf).

The results (fig. 8) show that increasing the depth of cut increases the cutter force, but the rate increases faster than a linear relationship. The data were too limited to satisfactorily quantify this relationship but other Bureau research in oil shale has also shown this nonlinear trend. This nonlinear force-depth relationship becomes apparent only at deep cuts (>0.25-in) and does not hold true at shallow cuts (<0.25-in). This may explain the mixed results obtained by different researchers. A consequence of this behavior is that in deep kerf cutting the fragmentation process becomes less efficient as the depth per pass is increased. This is in marked contrast to surface cutting where deeper cuts are generally more efficient than shallow cuts (3, 6).

Inspection of the force recordings also shows that the cutting process becomes very erratic (with large force fluctuations) during deeper cuts. Based on this information and the fact that the process deteriorates with deep cuts, it is

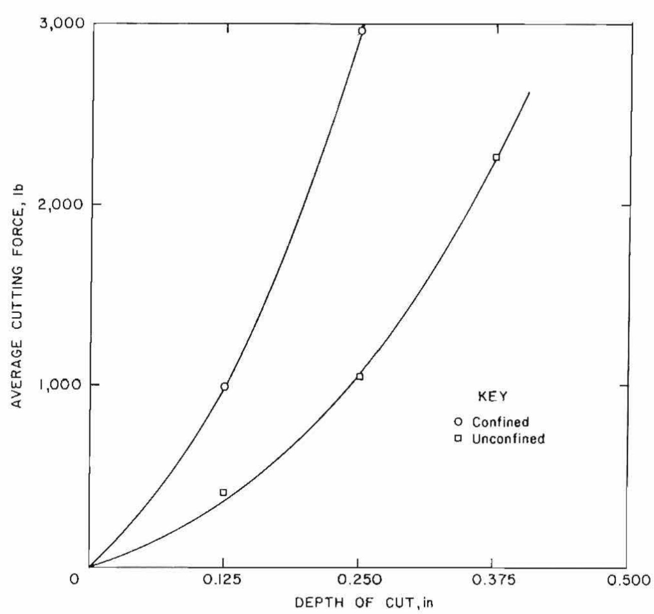


FIGURE 8. - Effect of depth of cut on cutting force (0° rake angle, 1/2-in-wide bit).

recommended that the depth of cut be limited to no more than one-half the cutter width. Since 0.5-in-wide cutters were used, 0.25 in was selected as the standard cut depth for all of the preweakening tests.

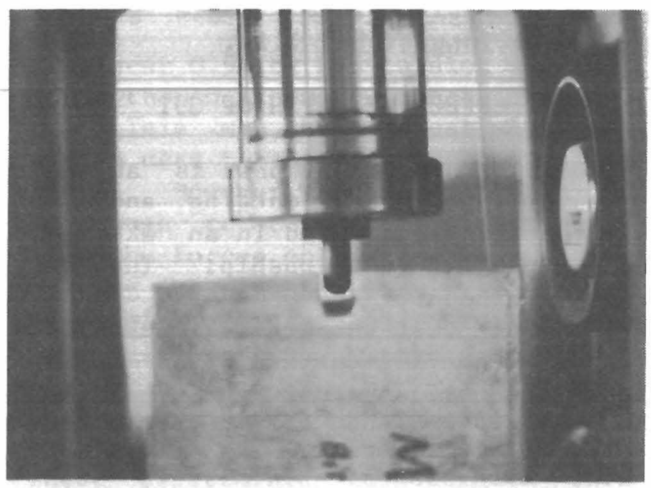
MECHANICAL INDENTING

Based on the results obtained from the baseline studies, a decision was made to test the combination of variables that would most realistically simulate the kerfing process for the kerf-core miner. The depth of cut selected was 0.25 in, and all experiments were conducted in the confined state. Again, the measure of success of the preweakening techniques was the reduction in cutting force achieved as compared with untreated rock.

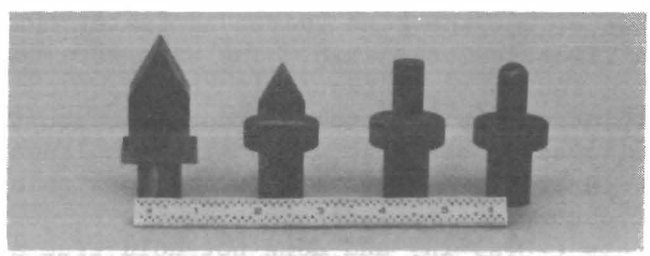
Mechanical preweakening is a method of applying a concentrated load to the rock ahead of the drag cutter. In this study, static loadings were used for convenience, but in actual field practice dynamic loadings from impactors would be used. The bits used for preweakening were a hemispherical punch, a simple wedge, and a flat punch. It was found that the flat punch was not effective and its use was discontinued. The mechanical preweakening equipment and technique are shown in figures 9 and 10.

For all the mechanical tests, the preweakening force was applied at the bottom of a precut 0.5- by 0.5-in kerf to reduce surface effects. For both the hemisphere and the wedge, the spacing between force applications was 0.5 in. When loaded to 10,000 lb for the wedge and 20,000 lb for the hemisphere, this spacing was sufficient to cause some fracturing between adjacent craters. The damage from both the 60° wedge and the 0.5-in hemisphere at these loadings extended to a depth of approximately 0.25 in. After the entire length of the kerf was preweakened, a 0.25-in-deep cut was made through this damaged zone by the drag cutter. The results of these tests are shown in table 4.

The results show, first, that preweakening with the wedge bit reduced drag cutter force by about 69 pct while the hemispherical bit yielded a 40 pct reduction. Besides the reduction in average cutting force, the average peak force was reduced by a similar amount. That is, if the average cutting force was reduced by 40 pct, then the average peak cutting force was also reduced by 40 pct. The ratio of average cutting force and average peak cutting force remained at approximately 2, however. The second result is that cutter rake angle did not significantly affect drag cutter force for the wedge bits, but varied for the hemispherical bits in the same manner as for untreated rock, i.e., the 0° rake was most efficient and the +15° rake the least efficient. The force reductions obtained in these tests could be duplicated by similar conditions where depth



A



B

FIGURE 9. - Mechanical indenting machine (*A*) and preweakening bits (*B*).

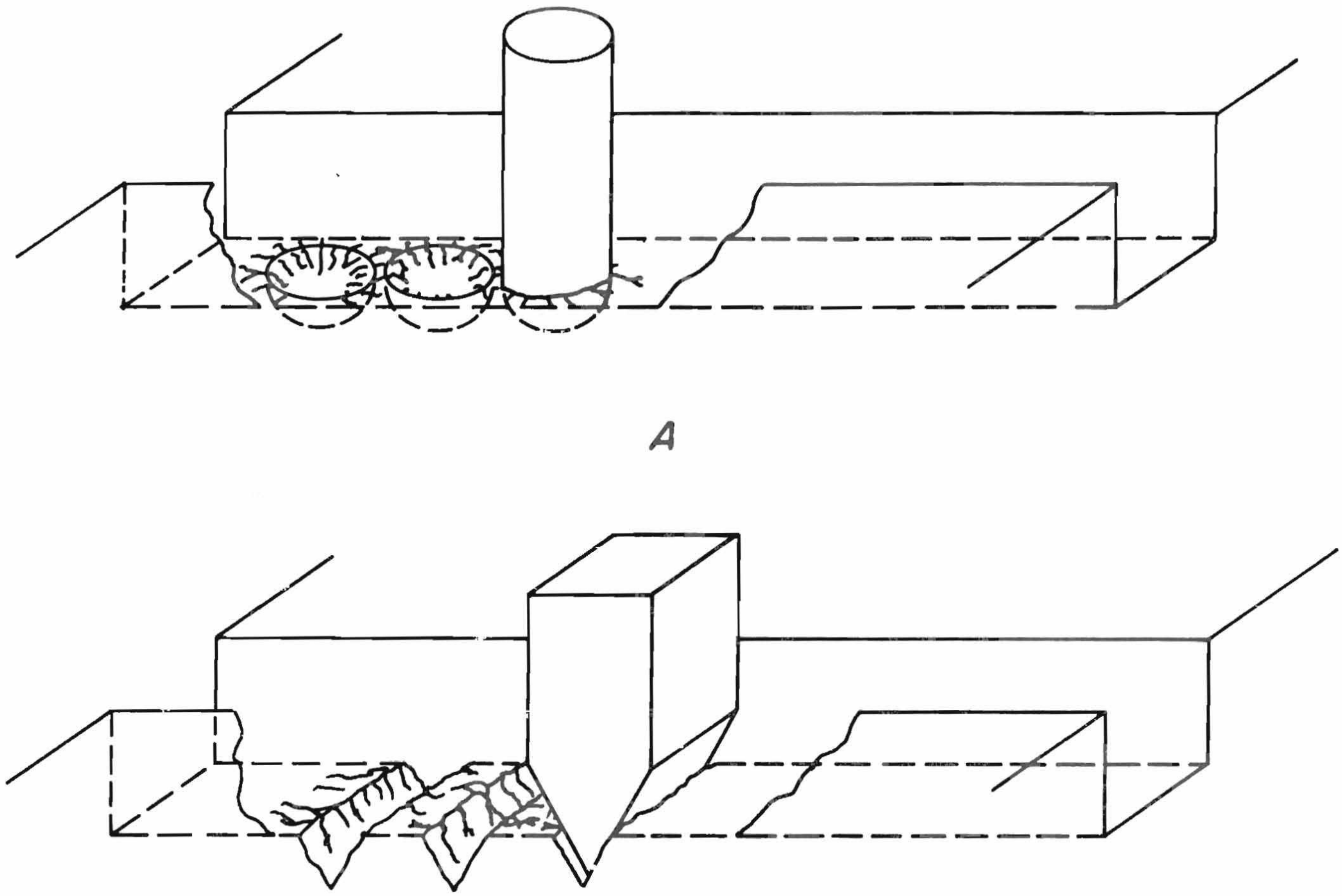


FIGURE 10. - Mechanical preweakening with the hemisphere (*A*) and the wedge (*B*).

of predamage and depth of cut are approximately equal. An analysis of the energy required for the predamage technique using the wedge indentor and the 0° drag bit is as follows:

$$E_{Total} = E_{Wedge} + E_{Drag}.$$

Each application of the wedge bit requires approximately 1,250 in-lb of energy. This is computed by assuming that the force on the wedge starts at 0 and increases linearily to a maximum force of 10,000 lb as it travels through a distance of 0.25 in. At a spacing of 0.5

TABLE 4. - Mechanical indenting drag cutter forces

Drag cutter rake angle	Preweakening bit	Force applied, lb	Drag cutter force,[1] av mean cutting lb	Change[2] from untreated rock, pct
-15°.......	Hemisphere..	20,000	2,220	-40
	Wedge, 60°..	10,000	1,191	-68
0°.......	Hemisphere..	20,000	1,237	-58
	Wedge, 60°..	10,000	927	-69
+15°.......	Hemisphere..	20,000	3,300	-24
	Wedge, 60°..	10,000	1,273	-71

[1]Average based on 2 runs each.
[2]Computed against the mean average cutting force for untreated rock (table 3).

in, it would require 24 × 1,250 or 30,000 in-lb per foot. The 0° drag cutter would require 927 lb × 12 in or 11,124 in-lb. Thus, the total energy required per foot of cut for the combined process would be

$$E_T = 30{,}000 + 11{,}124 = 41{,}124 \text{ in-lb.}$$

For comparison, a 0° drag bit cutting in untreated rock would require 3,000 lb × 12 in.

$$E = 36{,}000 \text{ in-lb.}$$

Thus, the combined technique requires about 14 pct more energy. This is not surprising since the chips are smaller and more crushing is produced in the modified system.

Mechanical preweakening should be applicable in all rock types because of the universal utility of mechanical indentors. The technique is versatile enough to allow the degree of force reduction to be adjusted simply by varying the spacing and magnitude of the preweakening force. The tradeoff is between the use of preweakening energy and drag cutter wear. The mechanical technique creates no additional safety hazards over normal kerfing techniques. An economic analysis is included in a following section.

MECHANICAL SLOTTING

The second preweakening technique consisted of cutting one or two deep, narrow slots ahead of the drag cutter using a thin blade diamond saw. Slots were cut in either one or both sides of the precut 0.5- by 0.5-in kerf. Slot depths were 0.25 and 0.5 in. After the slots were cut, a drag cutter was used to cut through this relieved zone. These slotting techniques are shown in figure 11.

The results of these tests are shown in table 5. Both the single slot and the double slot reduced the mean cutting force dramatically. The double slot reduced the cutter force by 87 to 99 pct, while a reduction in cutting force of 56 to 75 pct was attributable to the single slot. The average peak cutting force was reduced by the same amount as the average cutting force. The ratio of average cutting force and average peak cutting force remained at approximately 2. Again, the rake angle of the drag cutter did not appear to be significant in these tests. For example, for the 0.25-in double-slot tests, the force reductions achieved for the -15°, 0°, and 15° bits were 99, 97, and 99 pct, respectively. The cutting process for the double slot

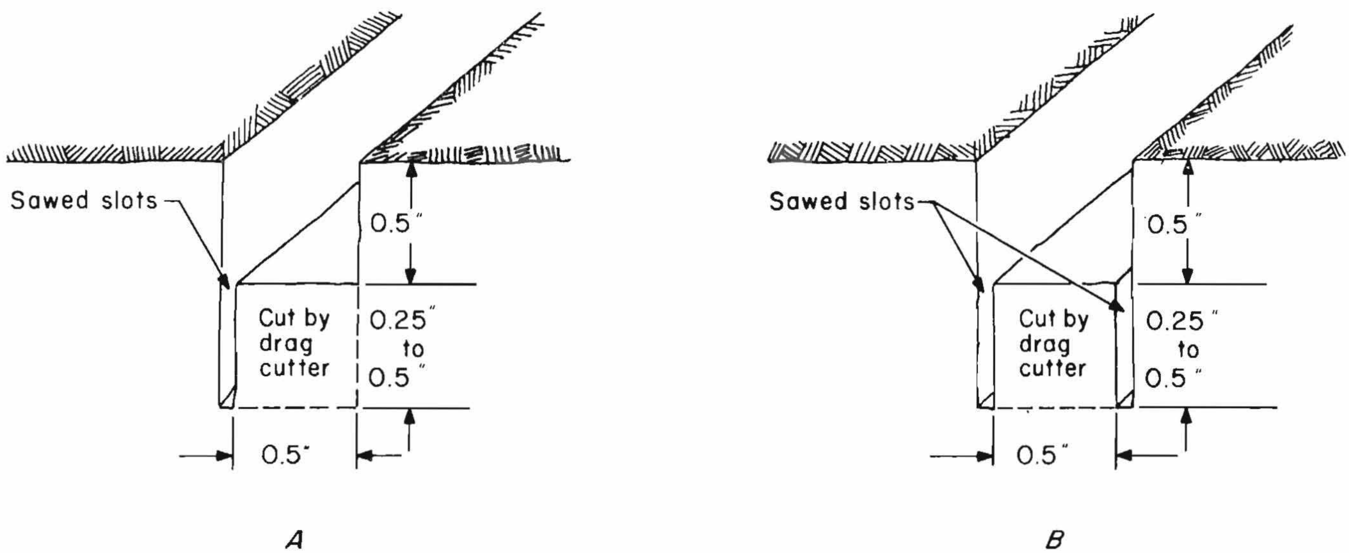


FIGURE 11. - Single- (*A*) and double-slot (*B*) preweakening techniques.

TABLE 5. - Mechanical slotting drag cutter forces

Drag cutter rake angle	Slot geometry, in	Mean cutting force,[1] lb	Change from untreated rock, pct[2]
-15°..	1/4, single..	990	-74
	1/4, double..	40	-99
	1/2, single..	1,530	-75
	1/2, double..	58	-99
0°..	1/4, single..	1,125	-56
	1/4, double..	73	-97
+15°..	1/4, single..	1,710	-61
	1/4, double..	10	-99
	1/2, single..	2,655	-58
	1/2, double..	810	-87

[1]Single runs.
[2]Computed from mean cutting forces for untreated rock (table 3).

tests yielded a series of very large chips with a cutting force at nearly zero throughout most of the run.

An analysis of the energy required for this technique is as follows:

$$E_{Total} = E_{Slot} + E_{Drag}.$$

The energy required to slot the rock using diamond saws can be estimated from the time required to cut the slots and the power drawn by the electric motor. The actual energy required to cut a double slot, 0.25 in deep and 12 in long, is approximately 264,000 in-lb.

$$E_{Slot} = 264{,}000 \text{ in-lb}.$$

The -15° drag cutter would require about 40 lb of force to cut a double-slotted 1/4-in deep kerf. The energy used is

$$E_{Drag} = 40 \times 12 \text{ in} = 480 \text{ in-lb}.$$

The total energy of the combined processes is then

$$E_{Total} = 264{,}000 + 480 = 264{,}480 \text{ in-lb}.$$

For comparison, a -15° drag bit cutting at 0.25-in-deep kerf without preweakening would require only

$$E = 3{,}750 \text{ lb} \times 12 \text{ in} = 45{,}000 \text{ in-lb}.$$

Thus, it is obvious that double slotting requires much more energy to cut an equal volume of rock than does mechanical cutting alone. The tradeoff is that the mechanical effort required to cut pre-slotted rock is minimal and drag cutter wear should be virtually eliminated. An analysis of the cost of the energy tradeoff is included in the economic feasibility study.

CONCEPTUAL DESIGNS OF FULL-SCALE PREWEAKENING SYSTEMS

The preweakening experiments just described were designed to determine if preweakening would have any effect on drag cutter forces and hence wear rates. While the results were promising, the data are much too limited to draw any firm conclusions as to the ultimate usefulness of preweakening techniques. More detailed testing must be done to verify changes in wear rates for a variety of rock types, bit types, and methods of preweakening.

While the data do not permit a conclusive technical or economic feasibility analysis to be performed, they are sufficient to illustrate how these feasibility studies would be organaized. Consequently, a preliminary feasibility analysis of both indenting and slotting preweakening systems is included to illustrate the process.

INDENTING USING HIGH-ENERGY IMPACTORS

Technical Feasibility

To determine the technical feasibility of the indenting system, the following must be considered: the ability to retrofit onto the basic kerf cutterhead, the ability to predamage the rock at the speed required for an acceptable production rate, the ability to supply the additional energy required, and the ability to operate underground without creating safety hazards. To assess each of these factors it is necessary to identify a potential prototype system.

A possible mechanical preweakening system that can be retrofitted onto the basic kerfing cutterhead is shown in figure 12. This concept uses one pneumatic or hydraulic impactor ram to predamage the rock ahead of each drag cutter. The use of individual impactors is not considered to be optimum, but it does allow a technical and economic analysis of a state-of-the-art system. The system is designed so that only tools in contact with the rock would operate while the others would automatically retract. In most instances only three to four impactors would be operating at any one time. To physically accommodate the impactors, the basic kerf cutterhead would have to be widened and its diameter increased. Also, the impactors would need to be supplied pressurized fluid through a rotary swivel of the type used on rotary drills.

The mechanical system must also be able to preweaken the rock ahead of each cutter at a rate equal to its fastest anticipated speed. The drag cutters on this machine are designed to cut a kerf 1.5 in wide, 24 in deep, take a 0.5-in cut per pass, and have a tip velocity of 12 ips. To meet the production goal of 700 tons per shift in a 10- by 20-ft heading, two kerfing cutterheads would be required. If the same indent spacing to depth ratio is used for the full-scale machine as for the lab experiments, then the 0.5-in indentions would need to be spaced every 1 in. To keep pace with the drag cutters moving at 12 ips would require 12 impacts per sec or 720 per minute.

Drop test experiments have shown that a force of 200 ft-lb is required to indent 1/2 in deep using a 1/2-in-wide wedge bit

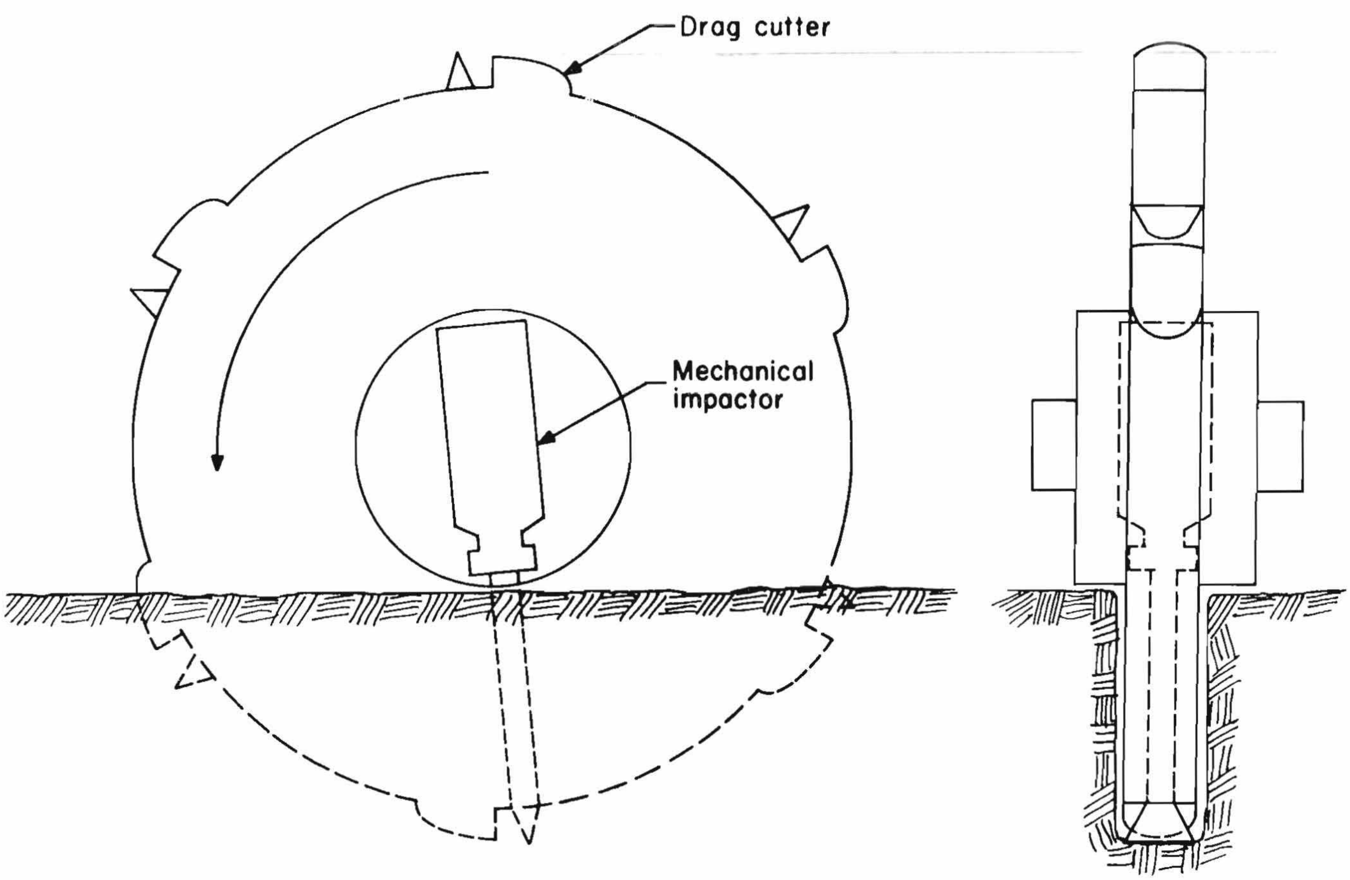


FIGURE 12. - Kerfing cutterhead equipped with high-energy impact preweakening system.

in Valders rock. To maintain the same loading force per contact area of the bit, three times the energy or 600 ft-lb is required for a 1.5-in-wide bit. This would require a total energy output of 600 × 720 or 432,000 ft-lb/min. This work rate could be met by a number of commercially available hydraulic or pneumatic rams, some of which can produce 1,000-ft-lb impacts at a rate of 600 impacts per min.

Assuming that such a commercial air ram was used, the energy requirements for the total system would be calculated as follows: 250 cfm of air at 100 psi is required for full operation of a single impactor. Since only four impactors are operating at any one time, 1,000 cfm is required for one cutterhead and 2,000 cfm for two heads. This amount of air should be available in any reasonable size underground mining operation and the air would be piped to the machine by the conventional air distribution system.

The addition of the mechanical preweakening system onto the kerf-core mining machine would not add any significant health and safety hazards except for increased noise levels. Impactors are state-of-the-art and have been used widely underground without problems. Because of the additional noise created along with the airborne dust and rock fragments generated by the basic kerf-core system, it is anticipated that the two operators would need to be isolated from the face in a soundproof, filtered, and fragment-protected cab. However, no other change would be required in the mining subsystems including ventilation and roof support.

Economic Feasibility

To be economically viable, the kerf cutting with preweakening must be able to produce a ton of ore for less than the cost to produce it with the basic kerfing system. A major assumption of this analysis is that the cutter wear rate in any rock is related to the cutting force experienced by the bit. As shown by the lab tests, preweakening the rock using a wedge bit reduces the cutting force by 70 pct. Therefore the cutter wear is assumed to also be reduced by 70 pct. As noted earlier, this assumption was not verified, but a future study will be conducted to quantify this force-wear relationship. This cost analysis uses a production rate of 700 tons per 6-hr shift in a 10- by 20-ft heading. Also, the core breaking is considered to be taking place simultaneously with the kerfing.

The cost to cut a ton of ore from the face with the basic kerf-core mining machine (fig. 1) is calculated in table 6 at $3.10 per ton. Note that the drag cutters constitute the largest item in the total cost and are the primary reason that the basic kerfing system cannot be used in abrasive rocks of over 20,000-psi strength. In addition, the cost of $3.10 is only for cutting the ore loose from the face and picking it up. It does not include haulage or any other mining operation.

In contrast, the cost to fragment a ton of highly abrasive, 30,000-psi-strength rock using mechanical preweakening is calculated in table 7 at $3.00 per ton. This lower cost is achieved through a reduction in drag cutter cost which more than compensates for the additional capital cost of the impactors, the air required to operate the impactors, and the additional cost of maintenance.

As a practical matter, the cost savings of only 10 cents per ton obtained by the use of the impact preweakening system would not justify the use of such a complicated and expensive system. This does not indicate that the technique has no merit, but rather that the example shown (using 24 impactors) is not a very efficient method of providing the preweakening energy. The successful application of the preweakening method will, however, require the development of a more efficient, less costly preweakening system. The development of such a practical preweakening system will be the subject of a future research effort by the Bureau.

TABLE 6. - Basic kerf-core mining cost[1]

Ownership costs per shift:	
Amortization of mining machine, \$750,000 over 2,500 shifts	\$300
Interest, insurance, and taxes based on 20 pct of the average investment per year, 20 pct × \$450,000 over 500 shifts	[2]180
Operating costs per shift:	
Power, 113 kw per head × two heads × \$0.05 kwhr × 6 hr	68
Maintenance cost, 60 pct of amortization of mining machine	180
Drag cutter cost, \$0.0016/in^2 × 760,320 in^2/shift	[3]1,216
Labor cost per shift: Operator labor plus fringe benefits, \$14.15/hr × two operators × 8 hr	226
Total	2,170
Total cost per ton (700 tons/shift)	\$3.10

[1]Assume a basic kerf-core mining machine cost of \$750,000 with a 5-yr and 2,500-shift life. The heading being driven is 10 by 20 ft in 20,000-psi-strength rock.

[2]Average annual investment = (capital cost) × $\frac{N+1}{2N}$, where N = number of years depreciated.

[3]760,320 in^2 = area of kerfs cut by cutterhead per shift. Based on 11 vertical kerfs and 2-ft spacing, each 10 ft high and 48 ft long.

TABLE 7. - Kerf-core mining cost with high-energy impactors[1]

Ownership costs per shift:	
Amortization of mining machine, \$750,000 over 2,500 shifts	\$300
Amortization of 24 impactors, \$240,000 over 1,250 shifts	192
Interest, insurance, and taxes based on 20 pct of the average investment per year for the basic machine, 20 pct × \$450,000 over 500 shifts per year	180
Interest, insurance, and taxes based on 20 pct of the average investment per year for the impactors, 20 pct × \$168,000 over 500 shifts per year	67
Operating costs per shift:	
Power, 113 kw/head × two heads × \$0.05 kwhr × 6 hr	68
Compressed air for impactors, \$14.02/1,000 cfm × two heads × 6 hr	168
Impactor wedge bits, \$10 each × 24	240
Maintenance costs, 60 pct of amortization of mining machine and impactors	295
Drag cutter cost (assume 70 pct reduction from basic cost of \$1,216 owing to 70 pct force reduction)	365
Labor cost per shift: Operator labor plus fringe benefits, \$14.15/hr × two operators × 8 hr	226
Total	2,101
Total cost per ton (700 tons/shift)	\$3.00

[1]Assume a mining machine cost of \$750,000 with a 5-yr and 2,500-shift life and 24 impactors at a cost of \$240,000 with a 2.5-yr and 1,250-shift life.

SLOTTING USING HIGH-PRESSURE WATER JETS

Technical Feasibility

Slotting was also found to be a very effective method of reducing the load on a drag cutter. Force reductions of up to 99 pct were achieved with a double slot. This means that the kerfing cutterhead has a very low power requirement and the supporting structure can be much lighter and less expensive. One possible double slot preweakening system that could be retrofitted onto the basic kerfing cutterhead is shown in figure 13. This concept uses a double row of high-pressure jets to cut slots in the rock ahead of each drag cutter. The system is designed so that only those jets actually in contact with the rock would operate while the others would automatically shut down. In most instances, only three to four cutters and jets would be operating at any one time. The drag cutters again would be designed to cut a kerf 1.5 in wide, 24 in deep, cut 0.5 in per pass, and have a tip velocity of 12 ips. Two kerfing cutterheads would be required to produce 700 tons in a 6-hr working period.

To achieve 0.5 in per pass with a double slot would require a double row of single-file jets in front of each cutter. Actual experiments have shown that 30,000-psi rock can be cut at 0.1 in per pass with a 50,000-psi-pressure jet traveling at 12 ips. With a 0.012-in-diam nozzle, each jet would consume about 20 hydraulic hp. Thus five jets are required to cut a 0.5-in-deep slot and 10 jets are required to double slot in front of each cutter, which would require about 200 hp for each cutter in contact with the rock. This analysis assumes that each jet deepens the slot created by the jets ahead of it so that the required depth can be achieved in a single pass.

Since only four cutters are operating at any one time, about 800 hp are required for each cutterhead or for two heads a total of 1,600 hp. Hydraulic power units are available to supply pressures of 50,000 psi and any number of smaller units can be grouped to provide the required flow rate.

The addition of the high-pressure hydraulic jets onto the kerf-core mining machine is not considered to add any significant hazards. High-pressure jets have been used underground in many experimental operations without problems. In

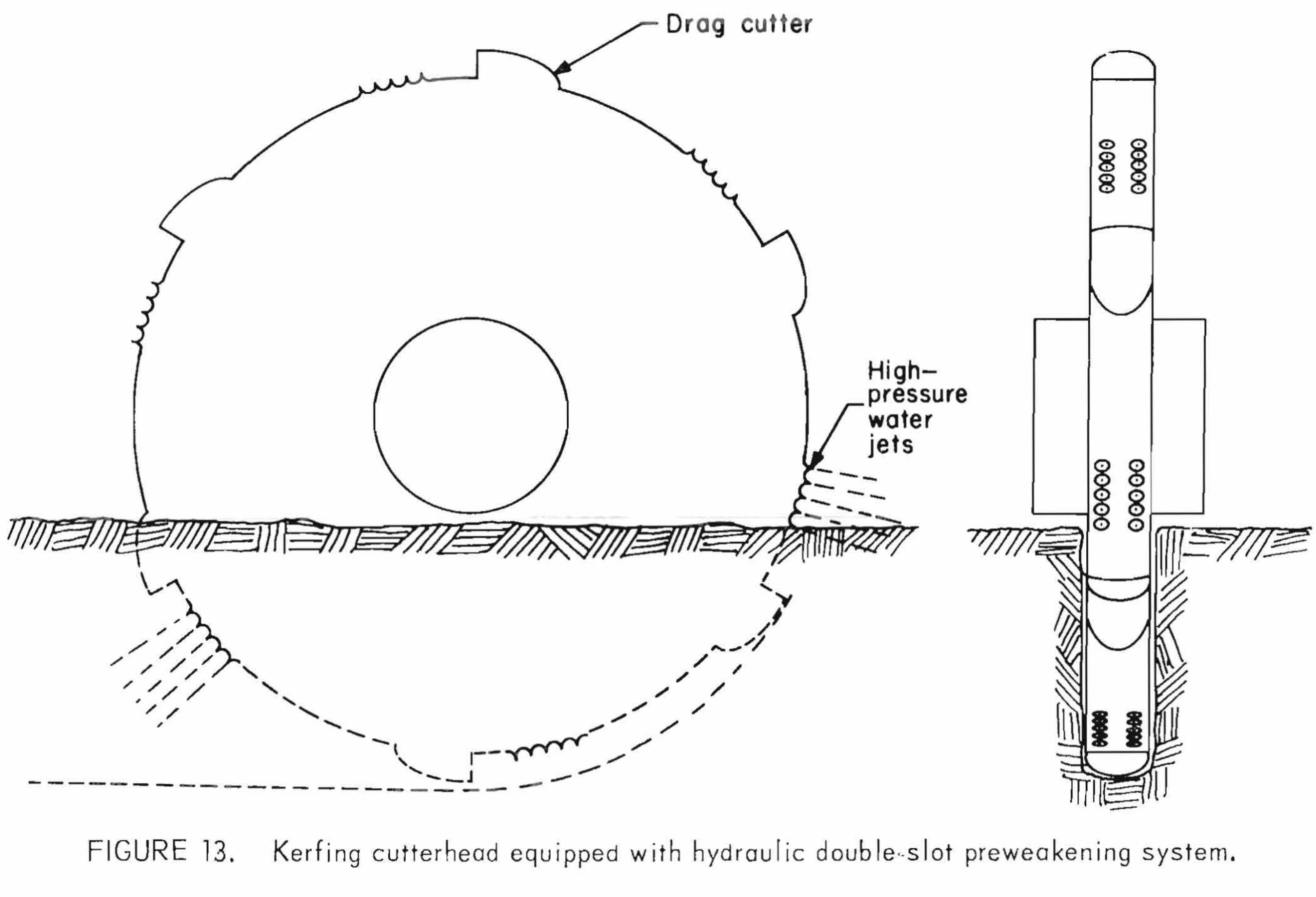


FIGURE 13. Kerfing cutterhead equipped with hydraulic double-slot preweakening system.

fact, high-pressure water jets could greatly reduce or eliminate the dust problem and eliminate methane ignition hazards due to tool sparking. Again, the operators would be located in a filtered, soundproofed cab to protect them from the activities at the face.

Economic Feasibility

To be considered economical, kerf cutting with hydraulic preweakening must be able to fragment a ton of hard rock for less than the cost to produce it with the basic kerfing system. Again, the cutter wear rate in any rock is assumed to be proportional to the cutting forces experienced by the bit. In this analysis, it is assumed that, with a double 0.5-in-deep slot, the cutter force would be reduced by about 90 pct compared to intact rock. The cost of the machine has been reduced from $750,000 to $250,000 because the reduced force and power requirements would require a less expensive cutterhead and supporting frame. Overall, however, the capital cost of the total system, including the machine and high-pressure pumps, would increase from $750,000 to $1,850,000. Also, all calculations are based on a production rate of 700 tons per 6-hr working shift.

The cost to fragment a ton of ore at the face using hydraulic preweakening is calculated in table 8 at $2.91. This is less than the $3.10 per ton for the basic kerfing system. However, while the hydraulic preweakening does yield a slight improvement in the cost of fragmentation, the increased capital cost of the equipment along with the increased complexity of the system would probably make the adoption of the system highly unlikely. It is emphasized that the technical and economic analyses shown in this report are for illustration only and that better cutter wear data are required before a final conclusion can be drawn.

Finally, it should be pointed out in fairness that while the water jet slotting does not yield a significant improvement in cutting cost, the use of a high-pressure water jet applied directly to the bit may be a much more efficient

TABLE 8. - Kerf-core mining cost with hydraulic double slotting[1]

Ownership costs per shift:	
Amortization of mining machine, $250,000 over 2,500 shifts	$100
Amortization of high-pressure water pumps, $1,600,000 over 5,000 shifts	320
Interest, insurance, and taxes based on 20 pct of the average investment per year for basic mining machine, 20 pct × $150,000 over 500 shifts	60
Interest, insurance, and taxes based on 20 pct of the average investment per year for the high-pressure pumps, 20 pct × $880,000 over 500 shifts	352
Operating costs per shift:	
Power for cutterhead (90 pct reduction from basic kerfing cutterhead power cost of $68)	6.8
Power for high-pressure pumps, 1,192 kw × $0.05 kwhr × 6 hr	358
Maintenance cost, 60 pct of amortization of mining machine and high-pressure water pumps	252
High-pressure nozzles, $50 each and 100-hr life	240
Drag cutter cost (assume 90 pct reduction from basic cost of $1,216 due to 90 pct force reduction)	122
Labor cost per shift: Operator labor plus fringe benefits, $14.15/hr × two operators × 8 hr	226
Total	2,037
Total cost per ton (700 tons/shift)	$2.91

[1]Assume a basic machine cost of $250,000 with a 5-yr and 2,500-shift life and a high-pressure hydraulic pump cost of $1,600,000 with a 10-yr and 5,000-shift life.

and cost-effective process. For example, experiments with directly assisted drag cutters have shown cutter force reductions of up to 60 pct. This method would require only 150-kw hydraulic power per cutterhead as opposed to the 800-kw required with the double slotting method. Based on these results, it appears that the direct assist hydraulic method is the most efficient way of using high-pressure water jets.

CONCLUSIONS

Preweakening of rock ahead of a drag cutter has been shown to be an efficient method of reducing drag cutter forces in hard abrasive rocks. Cutter force reductions of up to 70 pct were achieved with mechanical indentors and up to 99 pct were achieved for double slotting. These results are considered valid for cutter depth-to-width ratios of up to one-half and for predamage that extends to the same depth as the depth of cut of the drag cutter.

While these results appear promising, their usefulness is based on the hypothesis that reducing drag cutting forces will result in a corresponding reduction in drag cutter wear. The experimental program did not, however, achieve sufficient cutter wear to be evaluated. Hence, the cutter-force wear relationship will have to be established in future tests before the economic feasibility of preweakening methods can be determined.

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