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UNITED STATES DEPARTMENT OF THE INTERIOR

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## CONTENTS



## ILLUSTRATIONS



## TABLES

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

### With Factors for Conversion to Units of the International System of Units (SI)

| Abbreviation | Unit of measure | To convert to-- | Multiply by-- |
|---|---|---|---|
| ft | foot | meters | $3.048 \times 10^{-1}$ |
| $ft^3$ | cubic foot | cubic meters | $2.831 \times 10^{-2}$ |
| ft/s | foot per second | meters per second | $3.048 \times 10^{-1}$ |
| in | inch | meters | $2.540 \times 10^{-2}$ |
| $in^3$ | cubic inch | cubic meters | $1.638 \times 10^{-5}$ |
| $in^3/in$ | cubic inch per inch | cubic meters per meter | $6.451 \times 10^{-4}$ |
| $in \cdot lb/in^3$ | inch pound per cubic inch | meter newtons per cubic meter | $6.898 \times 10^{3}$ |
| in/s | inch per second | meters per second | $2.540 \times 10^{-2}$ |
| lb | pound | newtons | $4.448 \times 10^{0}$ |
| pct | percent | percent | NAp |
| psi | pound per square inch | newtons per square meter | $6.894 \times 10^{3}$ |
| rpm | revolution per minute | revolution per minute | NAp |
| st | short ton | newtons | $8.896 \times 10^{3}$ |

NAp Not applicable.

# A LABORATORY COMPARISON OF DRAG CUTTING METHODS IN HARD ROCK

**By S. J. Anderson,[1] R. J. Morrell,[2] and D. A. Larson[1]**

ABSTRACT

The Bureau of Mines compared three methods of rock cutting using drag cutters under controlled laboratory conditions. The methods tested were the conventional drag cutting method used on continuous miners, the kerf-core method used on some boring machines, and an experimental method called ripper cutting. All three methods were tested in blocks of Indiana and Kasota limestone.

The results of this testing showed ripper cutting to be 30 to 40 pct more energy efficient than both the conventional and the kerf-core methods in Kasota limestone and 35 pct more efficient than the kerf-core method in Indiana limestone. The conventional method was, however, 9 pct more energy efficient than the ripper method in Indiana limestone. These results are considered promising, and more tests are planned with the ripper cutting system.

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# INTRODUCTION

The Bureau of Mines, in its continuing efforts to improve productivity and enhance the workplace environment of hard-rock underground mines, has investigated mechanical excavation techniques and in particular drag cutting techniques to achieve these goals. Two fragmentation techniques that use drag cutters have found some success in the mining industry: the kerf-core technique and, the conventional technique.

The conventional technique is characterized by machines that use a multiplicity of cutters fixed to a rotating cutterhead that make shallow, parallel cuts spaced sufficiently close to break out the intervening material (fig. 1). This most common drag cutting excavation technique is represented in the industry by drum-type continuous miners and roadheaders. Some of these machines employ over 100 individual cutters on a single cutterhead that may rotate at speeds up to 70 rpm. These machines are generally limited in the amount of cutting force they can supply by their own weight. Because of the high cutter speeds and the low cutter forces available, continuous miners are limited by their performance to coal or very soft rock; roadheader machines can be used in rock with compressive strength up to 12,000 to 18,000 psi, depending on its abrasiveness (1-2).[3]

In contrast, the kerf-core technique is characterized by fewer cutters arranged in rows or lines of action (fig. 2). With this technique, deep slots or "kerfs" are cut into the rock; the ridge of rock between the kerfs is normally broken off in large pieces by an additional tool, or in some cases by cutter action. This technique is used on machines such as the full facer models from Atlas Copco Co. and Martin Marietta Corp.'s twin borer. These machines have lower cutter speeds, use fewer cutters, and have more force available per cutter than do the machines representative of the conventional cutting technique. These factors allow machines using the kerf-core cutting technique to excavate harder rock than is practical with the conventional technique, but their range of flexibility and applicability is narrow, and their primary use is in long, straight drivages of a fixed cross-sectional area.

Owing to the limited range of applicability of the conventional and kerf-core cutting techniques, the Bureau of Mines developed an experimental drag cutting technique called ripper cutting. The ripper cutting technique differs from the conventional and kerf-core cutting techniques in that it uses a single large-drag cutter to make a series of deep, parallel, and intersecting cuts (fig. 3). In preliminary tests with the ripper cutting technique, various rocks with compressive strengths as high as 27,000 psi have been cut with promising results (3).

To better analyze the potential of this new cutting technique, laboratory experiments were conducted that directly compared the ripper cutting technique with the kerf-core and conventional cutting techniques. This investigation covered the areas of cutting forces, specific energy of excavation, size distribution of the cuttings, and length of cut. This report discusses these comparison tests.

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

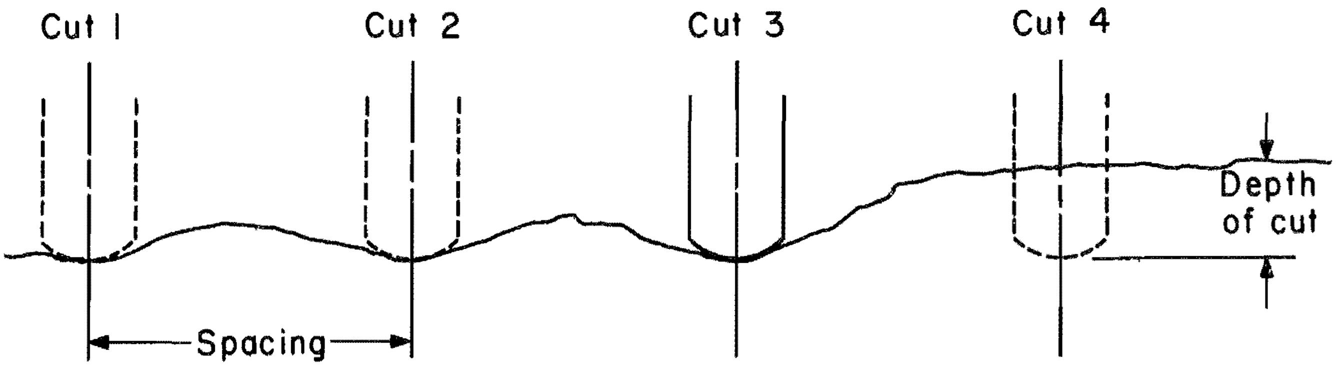


FIGURE 1.—Conventional cutting technique.

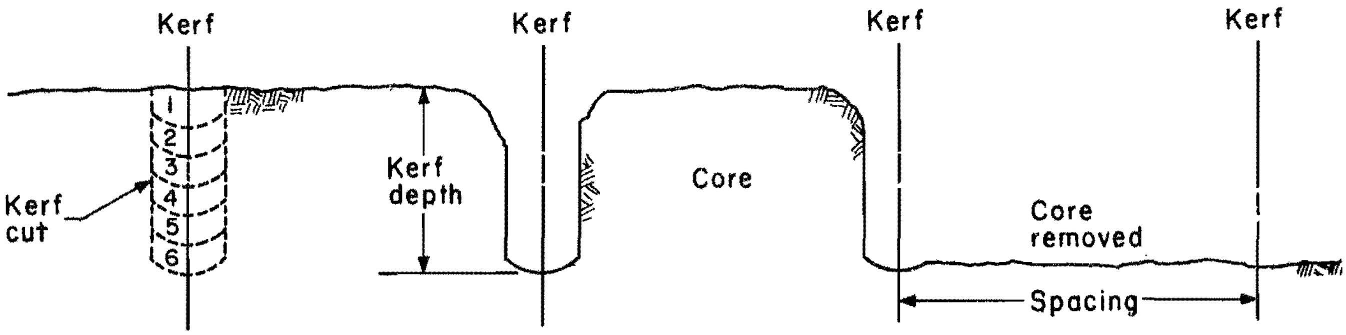


FIGURE 2.—Kerf-core cutting technique.

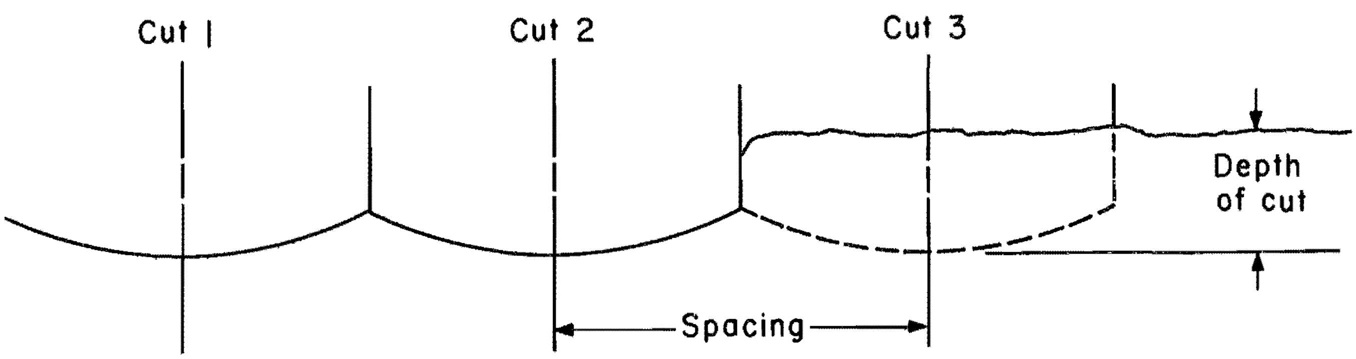


FIGURE 3.—Ripper cutting technique.

## EXPERIMENTAL EQUIPMENT

This section describes the equipment and materials used to evaluate the three drag cutting techniques. All testing was conducted in the laboratory with a machine that duplicates a portion of the crescent-shaped cut that is typically generated by conventional and kerf-core cutting machines.

### TEST BED

Cutting tests were performed using a single test bed (fig. 4). The bed makes use of a 100-st hydraulic cylinder to actuate a cutter arm assembly in a third-class lever arrangement. The cutter arm assembly is comprised of the bolted-together cutter, cutter backing block, and cutter arm sections. The assembly is 24 in long, from its pivot point to the cutter tip, simulating a 4-ft-diam cutterhead; its full stroke encompasses approximately 65° of arc.

The test bed also holds the block of rock to be cut, and it reacts the forces of cutting through its space frame of wide-flange steel beams. Ancillary equipment includes manually operated hydraulic rams for the positioning and holddown of the block, and an electrically driven hydraulic pump and accumulator unit capable of producing 100,000 lb of cutting force and cutter speeds up to 1 in/s.

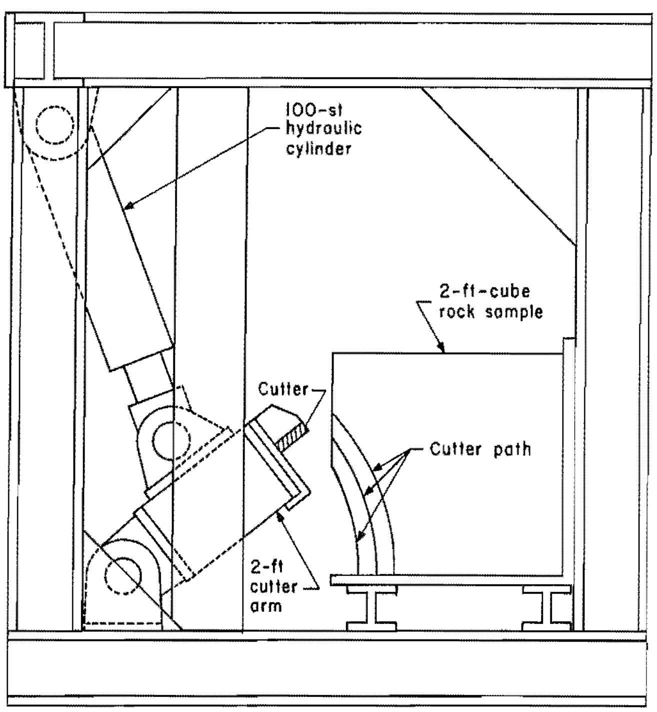


**FIGURE 4.—Laboratory test bed.**

### CUTTERS

To minimize the influence of cutter geometry on the results of this testing, all of the cutters used in the tests were machined to similar shapes with 0° rake angles and 10° clearance angles; and the width of the cutter face was varied (fig. 5). Cutters of 1-in width were used in the kerf cutting and conventional technique tests. This width was selected because it falls within the 1/2- to 1-1/2-in range of widths typical of commercial cutters. A cutter of 6-in width was used in the tests of the ripper technique; this width is considered half-scale. All of the cutters used in the tests were machined from tool steel and heattreated to a hardness of 60 Rockwell C.

### INSTRUMENTATION AND MEASUREMENTS

The test bed was instrumented to monitor the three orthogonally resolved force components of cutting: normal, cutting, and side. The normal and cutting forces were measured at the clevis joints by instrumented strain-gauge-style load pins (fig. 6). These pins were designed to resolve the radial load acting upon them, a vector quantity, into its two orthogonal components. Pin mounting was such that each rotated with the cutter arm, maintaining a constant orientation with the cutter, and thereby with the cutting and normal forces of cutting. As a result of this constant orientation, the cutting and normal force values were arrived at by summing the appropriate responses from these two pins. This

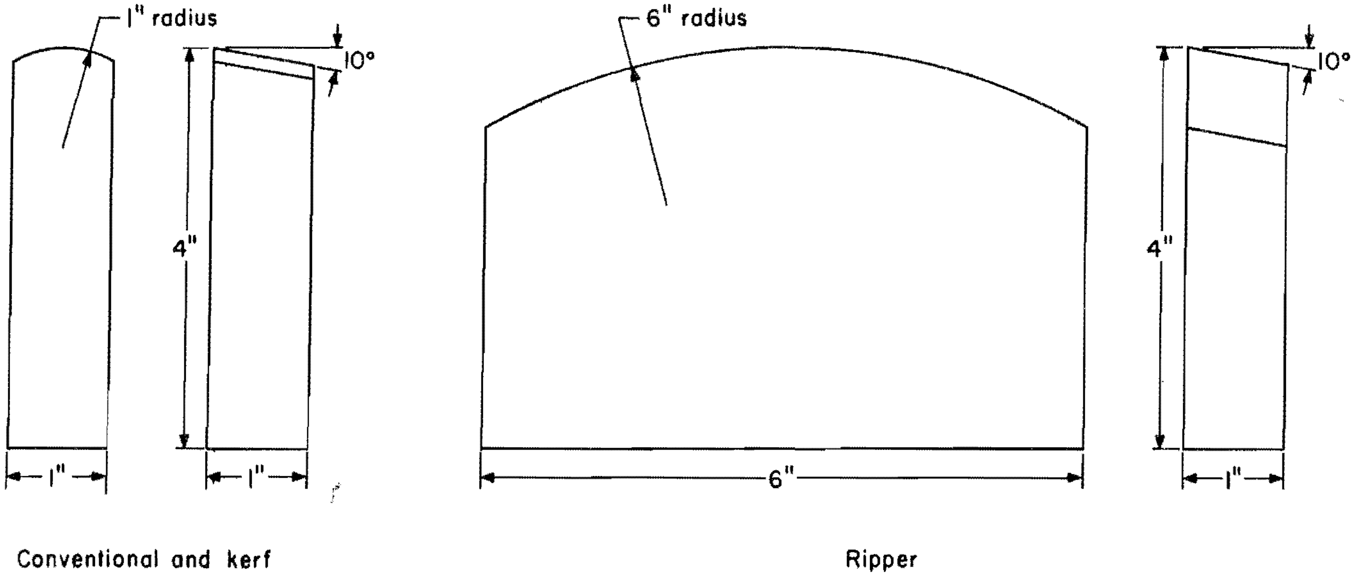


FIGURE 5.—Cutters.

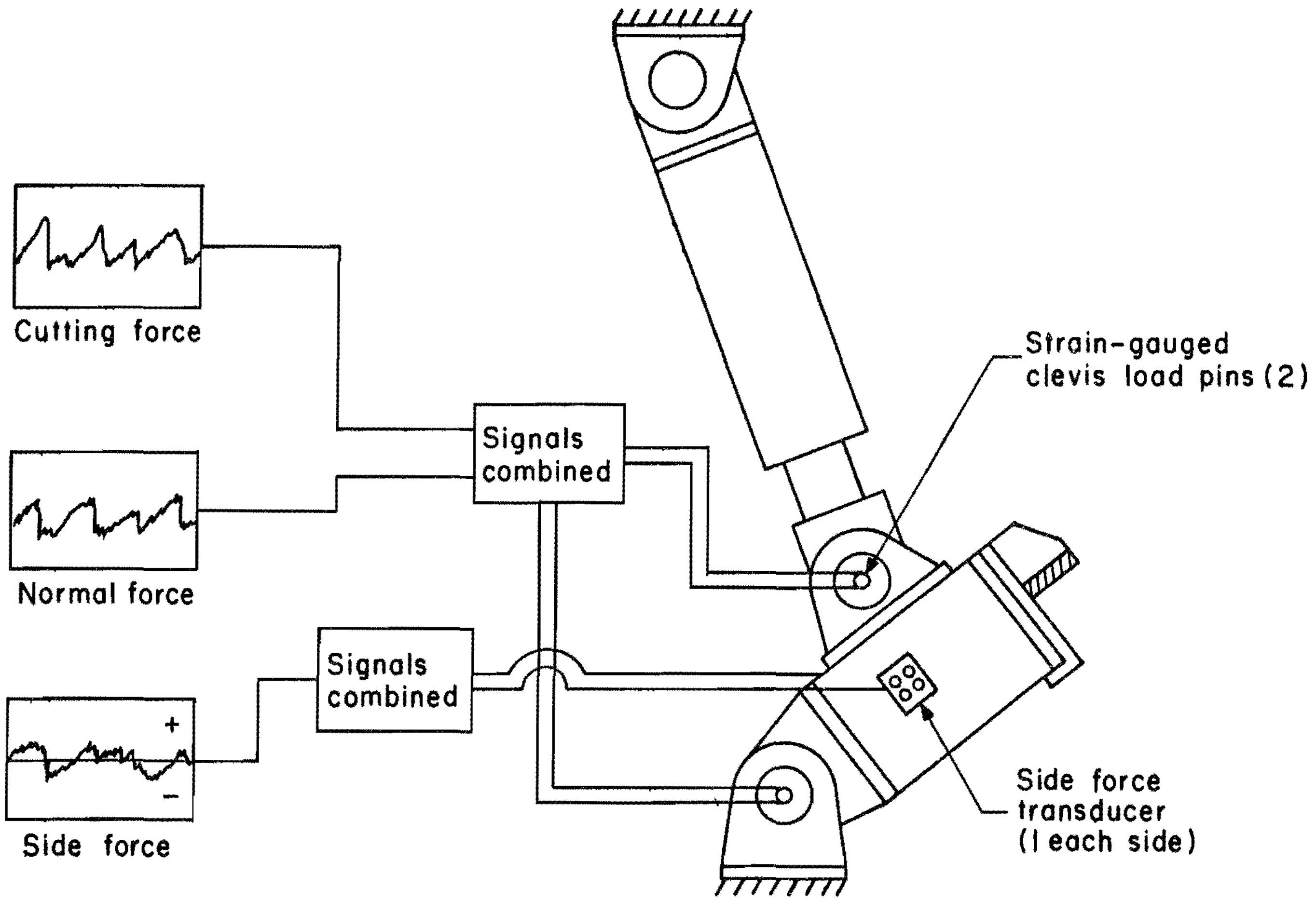


FIGURE 6.—Instrumentation.

summation was done electronically prior to recording.

The side loads acting on the bit were measured by special load transducers mounted on each side of the cutting arm. Each side load transducer was constructed with four load washers which were connected to complete a full Wheatstone bridge with an active and a temperature-compensating gauge in each leg. Force was transmitted to the load washers by spherical load buttons which contacted the side support beams during cutting. The right and left side loads were distinguished on the recording by a positive and negative convention.

Two channel strip chart recorders were used to record the cutting forces as a function of time. Recorder tracings of the cutting force documented the loading and chip formation cycle that typifies rock cutting by drag cutters; see figure 7 for a representative tracing. While the average force was used for determining the energy of cutting, the force actually required to cut rock is the peak force. The succession of peaks represents the forces that were required to produce the chips during the cut. The peak force was three to four times the average force for most rocks in this study.

A representative sampling of the rock cuttings was taken from each test series, and a particle size analysis was performed using standard screening techniques. The volume of rock generated and the cut length for each cut were calculated based on the geometry of the test bed and the position of the cutter as it entered the rock block.

## MATERIALS

Indiana and Kasota limestones were selected for these drag cutter tests because they could be effectively cut by the kerf-core and conventional cutting techniques. These rocks have compressive strengths in the 9,900- to 13,200-psi range; their physical properties are given in table 1.

Constraints imposed by the test bed limited the size of the rocks to 2-ft cubes. Because of this limited block size, only two cutting methods could be tested in each block. Therefore, to provide good comparative data, testing was conducted on a one-to-one basis with one of the commercial cutting techniques matched against the ripper technique in each block.

TABLE 1. - Physical properties of rocks tested

| | Indiana limestone[1] | Kasota limestone[2] |
|---|---|---|
| Strength, psi: | | |
| Compressive strength.............. | 9,991 | 13,184 |
| Tensile.......................... | 502 | 792 |
| Shore hardness--scleroscope units... | 32 | 37 |
| Apparent density: | | |
| Slugs per cubic foot.............. | 4.635 | 4.818 |
| Velocity, ft/s: | | |
| Longitudinal...................... | 14,610 | 17,119 |
| Bar............................... | 12,007 | 14,708 |
| Shear............................. | 8,489 | 9,360 |
| Modulus, $10^6$ psi: | | |
| Static Young's.................... | 4.4 | 5.7 |
| Dynamic Young's................... | 4.65 | 7.42 |
| Shear............................. | 2.32 | 2.90 |
| Poisson's ratio.................... | 0.33 | 0.28 |

[1]Salem Limestone from Bedford, IN.
[2]Oneonta Member, Praire du Chien Formation, Kasota, MN.

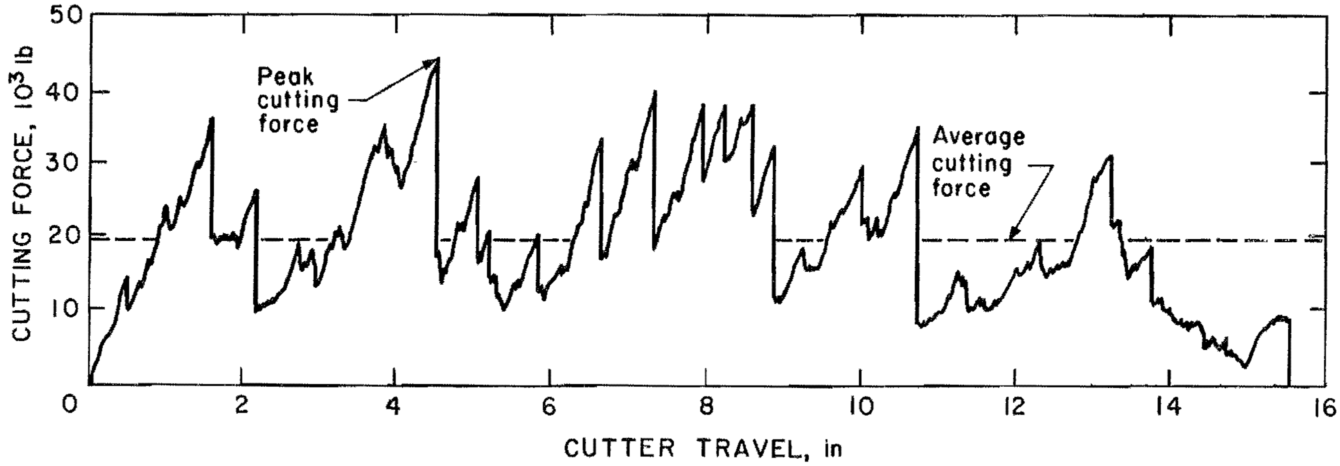


**FIGURE 7.—Typical recorder tracing of the cutting force.**

## EXPERIMENTAL RESULTS

The primary objective of these experiments was to compare the ripper cutting technique with the two commercial cutting techniques. Toward this end, the testing was separated into two parts. Each technique was first tested individually to establish cutting conditions that provided optimal efficiency. Once these conditions were established, the comparison testing was done.

### OPTIMIZATION EXPERIMENTS

Because the efficiency of cutting is affected by the geometric relationship between the cutter and the rock, preliminary tests were conducted to establish the optimal cutting conditions for each cutting technique.

#### Conventional Cutting Technique

When cutting with the conventional technique, it is essential that the material between the cuts be removed by the cutter action with each successive pass. If the material is not broken out after each pass, the bit becomes more confined on subsequent passes and the cutting efficiency begins to decrease (4). To determine the optimal operating conditions for this technique, a series of tests was performed in which both the cut depth and the spacing between cuts were varied. These tests were conducted at cutting depths of 1/2, 3/4, and 1 in with cut spacings of 2-1/2, 3, and 3-1/2 in. Optimal cutting conditions were determined to occur at a cut depth of 1 in with a center-to-center cutter spacing of 3-1/2 in for both the Indiana and Kasota limestones. These operating conditions represent the largest spacing at which the requirement for effective material removal between the cuts was still met. These conditions are in good agreement with Evans (5-6), who calculated that the optimum spacing should be from three to four times the cutter width and 3-1/2 times the cutting depth.

#### Kerf-Core Cutting Technique

The cutter holder design restricted the maximum achievable kerf depth to 3 in. Therefore, all testing was conducted at this depth with trial kerf spacings of 4, 5, and 6 in. The 3-in-deep kerf was completed in six cutter passes of 1/2-in depth each. Core removal was accomplished with a single pass of a 3-in-wide trimmer cutter. Trials established that a kerf spacing of 6 in was the most energy efficient for both rock types. The trials, however, did not extend past this spacing, and it is possible that better energy efficiency may be achievable. The specific energy of excavation for this technique was calculated three ways: (1) for the kerf cutting process,

(2) for the core removal process, and (3) for the combination of the two. As others have found (7), the efficiency of the core removal process in these tests was exceptional, while that of the kerfing process was very poor.

### Ripper Cutting Technique

With this technique, a succession of parallel cuts was made using a 6-in-wide cutter that slices off consecutive portions of the rock face. To maximize the energy efficiency of this technique, the width of the cut was tested at 3 and 6 in and the depth of the cut was tested at 1, 1-1/2, and 2 in. In Kasota limestone, the optimal operating conditions for this technique occurred at a cut depth of 2 in and a cut width of 6 in. In Indiana limestone, the optimal cutting depth was difficult to establish, and as a result, depths of 1 and 1-1/2 in were used for the comparative testing. Previous work has shown that the larger the cross-sectional area of the cut, the more efficient the process becomes. It was expected, therefore, that a deeper cut (2 in) would have yielded a more efficient fragmentation process. Part of this poor performance at the deeper cuts was related to the tendency of the bit to crush the rock instead of forming larger chips. This tendency to crush instead of chip at the deeper cuts was noted only for the Indiana limestone, which is softer and less brittle than Kasota stone. Presumably, this phenomenon would also occur in other softer, more plastic rock types at this larger depth of cut. This tendency to crush could have been significantly reduced if a more aggressive, positive rake angle bit had been used, as previous work had shown the positive rake angles to be more efficient than 0° rake angles. However, the use of a positive rake angle would have violated the experimental design, which required that all the bits tested have the same 0° rake angle. Therefore, the shallow 1- and 1-1/2-in depths were accepted as optimum for the conditions under which the experiments were performed. The cut width in Indiana limestone was optimal at 6 in. The optimum cutting conditions established for all of the cutting techniques are shown in table 2.

TABLE 2. - Optimum cutting conditions

| Cutting technique | Depth of cut, in | Width of cut,[1] in |
|---|---|---|
| Indiana limestone: | | |
| Conventional..... | 1 | 3-1/2 |
| Kerf-core........ | 1/2, 3 | 6 |
| Ripper cutting... | 1, 1-1/2 | 6 |
| Kasota limestone: | | |
| Conventional..... | 1 | 3-1/2 |
| Kerf-core........ | 1/2, 3 | 6 |
| Ripper cutting... | 2 | 6 |

[1]On spacing between cuts.

## COMPARISON EXPERIMENTS

Once the parameters that produced the best performances were established for the three cutting techniques, the one-to-one comparative testing was conducted. The data obtained from these tests included the three orthogonal force components, screen analyses of the cuttings, and the length and volume of the cuts. Table 3 presents a summary of these data.

### Cutting Force

An analysis of the average cutting forces presented in table 3 shows that, as expected, the ripper cutting forces are two to three times larger than the forces of the commercial methods tested. This is due to the relatively large size of the cutter and the increased depth at which this cutting takes place.

In contrast to the ripper style of cutting, the coring cuts required less force even though they removed a 5-in-wide by a 3-in-deep core. The advantage of this cut lies in the ridgelike geometry of the core, enabling it to be removed with much less effort than confined or partly confined material. Conversely, in order to produce this favorable geometry, many shallow, successively overlain cuts must be made to produce the kerfs. This highly confining geometry causes cutting force requirements to greatly exceed force requirements when cutting on a free surface. Figure 8 presents the average cutting force in the kerf cutting

TABLE 3. - Comparative data for the alternative cutting methods

| Rock type and block | Cutting technique | Depth of cut, in | Cut spacing, in | Cutting force, lb | | Cut $\frac{\text{volume}}{\text{length}}$, $in^3/in$ | Specific energy, $in \cdot lb/in^3$ |
|---|---|---|---|---|---|---|---|
| | | | | Average | Peak | | |
| Indiana limestone: | | | | | | | |
| Block 9.. | Ripper....... | 1 | 6 | 5,882 | 20,800 | 5.23 | 1,128 |
| | Conventional. | 1 | 3-1/2 | 3,112 | 11,600 | 3.02 | 1,032 |
| Block 2.. | Ripper....... | 1-1/2 | 6 | 7,598 | 23,200 | 7.44 | 1,021 |
| | Kerf-core: | | | | | | |
| | Kerf......... | 1/2 | 6 | 3,012 | 11,400 | .42 | 6,520 |
| | Core......... | 3 | 6 | 4,620 | 20,300 | 12.87 | 359 |
| | Total.... | NAp | NAp | NAp | NAp | 2.17 | 1,386 |
| Kasota limestone: | | | | | | | |
| Block 3.. | Ripper....... | 3 | 6 | 16,043 | 63,000 | 9.39 | 1,728 |
| | Conventional. | 1 | 3-1/2 | 6,502 | 23,800 | 2.68 | 2,426 |
| Block 4.. | Ripper....... | 2 | 6 | 15,754 | 45,000 | 9.03 | 1,747 |
| | Kerf-core: | | | | | | |
| | Kerf......... | 1/2 | 6 | 4,839 | 23,400 | .45 | 11,122 |
| | Core......... | 3 | 6 | 6,003 | 22,800 | 11.60 | 518 |
| | Total.... | NAp | NAp | NAp | NAp | 2.22 | 2,317 |

NAp Not applicable.

operation; the numbers 1 to 6 represent the succession from the shallowest to the deepest cut. This graph displays the strong influence that cut geometry has on the cutting force requirements, not only by the increases in force required to make deeper kerf cuts, but also by the relatively small (considering the volume of material removed) cutting force required to make the core cuts.

Finally, note that for all cutting methods, the peak cutting force is three to four times larger than the average cutting force. The average cutting force is used to calculate energy consumed during cutting, but the peak forces are required by the system to actually form rock chips. The concepts of average and peak cutting forces are illustrated in figure 7.

## Specific Energy

In this study, cutting efficiency is based on specific energy. Specific energy is defined as the energy required to fragment a unit volume of rock and is calculated as follows:

$$E_s = \frac{\bar{F}_c\ (L)}{V},$$

where $E_s$ = specific energy, $in \cdot lb/in^3$

$\bar{F}_c$ = average cutting force, lb,

$L$ = cut length, in,

and $V$ = theoretical volume of the cut, $in^3$.

From the geometry of cut, the cut length and the cut volume can be calculated. The cut length is a simple calculation based on the arc through which the cutter arm moves:

$$L = \sin^{-1} \frac{h}{r} \left(\frac{2\pi r}{360}\right),$$

where $L$ = cut length, in,

$h$ = starting height of the cut, in,

and $r$ = length of the cutter arm, in.

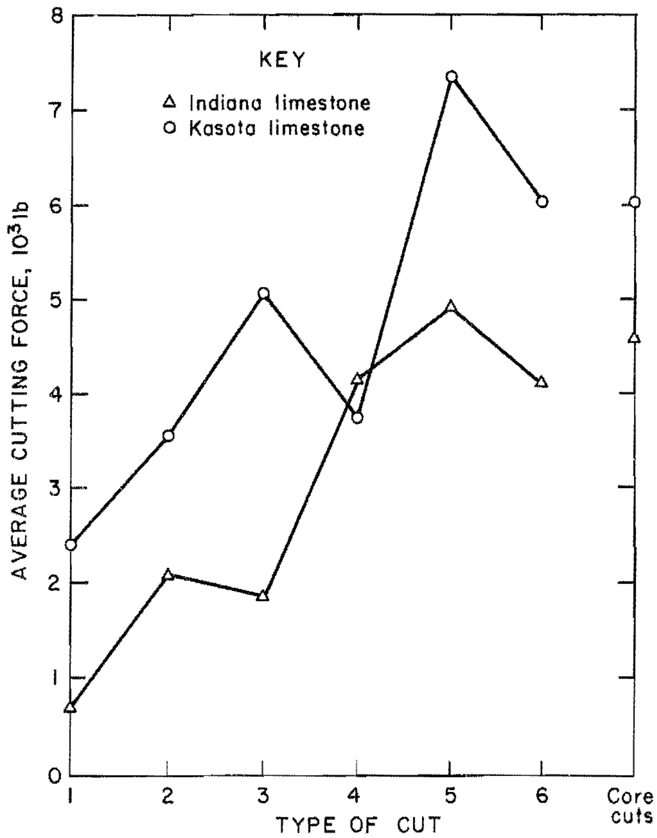


**FIGURE 8.—Kerf-core cutting forces. (In horizontal scale, 1-6 represent the successive ½-in-deep kerf cuts used to make the 3-in-deep kerf; core cuts represent the cuts used to remove the core between the kerfs.)**

The theoretical volume of the cut is calculated as follows:

$$V = S\left[\frac{x+d}{2}\sqrt{r^2-(x+d)^2} + \frac{r^2}{2}\sin^{-1}\frac{x+d}{r} - \left(\frac{x}{2}\sqrt{r^2-x^2} + \frac{r^2}{2}\sin^{-1}\frac{x}{r}\right)\right],$$

where $V$ = cut volume, $in^3$,

$S$ = cut spacing, in,

$d$ = cut depth, in,

and $x = \sqrt{r^2-h^2}$ (r and h as earlier defined).

Refer to table 3 for the specific energies calculated for each technique in each block tested. When compared with the kerf-core technique, the ripper cutting technique was 33 and 35 pct more efficient in the Kasota and Indiana limestones, respectively. Ripper cutting was 40 pct more efficient than conventional cutting in Kasota limestone, but conventional cutting was 9 pct more efficient than ripper cutting in Indiana limestone.

## Side and Normal Forces

In addition to the cutting forces, the normal and side or lateral forces were also monitored. The normal load on the cutter corresponded with the chip formation, producing a strong proportional relationship between it and the cutting load. Fluctuations in the cutting force were matched with corresponding changes in the normal force. In a comparison between these two forces in Kasota limestone, the normal force averaged out as 62 pct of the cutting force for the ripper cutting technique, 54 pct for the kerf-core technique, and 46 pct for the conventional technique.

The lateral load on the cutter was averaged across the length of the cut and compared to the average cutting force. The lateral force was typically less than 10 pct of the cutting force and never greater than 16 pct. In direct relation to the confined and unconfined side of the cutter, the average lateral load switched from one side to the other with the load corresponding to the confined side of the cutter. A point of interest is the lack of correspondence between the fluctuating cutting and lateral forces. Unlike the normal force, which matched the cutting force's fluctuations, the lateral load appears to vary indiscriminately. A probable explanation may be that the lateral load is responding to the unique geometry that the cutter encounters as each chip is formed.

## Size Analysis of Rock Cuttings

Cuttings from the testing in Kasota limestone were collected and screened for comparisons for all three cutting

TABLE 4. - Screen analysis of rock cuttings in Kasota limestone

| Cutting technique | Cuttings, pct passing screen size of-- | | | | |
|---|---|---|---|---|---|
| | 4 in | 2 in | 1/2 in | 28-mesh[1] | 48-mesh[1] |
| Block 3: | | | | | |
| Ripping.......... | 73.38 | 42.43 | 18.13 | 4.72 | 3.94 |
| Conventional..... | 88.94 | 41.77 | 17.52 | 4.08 | 3.39 |
| Block 4: Ripping.. | 68.92 | 42.01 | 10.27 | 5.18 | 4.31 |
| Kerf-core: | | | | | |
| Kerfing........ | 75.44 | 55.55 | 31.43 | 9.17 | 7.41 |
| Core breaking.. | 35.24 | 23.97 | 8.10 | 1.87 | 1.43 |

[1]Tyler mesh.

techniques. The results from the screen analysis in terms of percentage passing are given in table 4.

According to Rittinger's hypothesis (8), the energy required to comminute a unit volume of rock is proportional to the increase in surface area of the fragments. It was, therefore, expected that this relationship would be apparent in the comparisons of specific energy and the screen analyses for the alternate cutting techniques. The lowest specific energy cutting technique was expected to produce the coarsest product and vice versa. By examining tables 3 and 4, a clear demonstration of this theory is not apparent. While the ripper technique clearly demonstrated a superiority in specific energy over the conventional one, the product distributions are nearly identical. The best support for Rittinger's hypothesis comes from the kerf and core cutting data, where the finer size distributions from the kerf cutting have correspondingly higher specific energy.

## CONCLUSIONS

Comparative testing has shown the ripper cutting technique to be 33 pct more energy efficient than the kerf-core technique and 40 pct more efficient than the conventional one when working in Kasota limestone. In the softer Indiana limestone, the ripper method was 35 pct more efficient than the kerf-core technique but was 9 pct less efficient than the conventional one. The high average cutting forces inherent with the ripper cutting technique were more than offset by its high ratio of volume excavated to cut length, resulting in these competitive specific energies.

The results of this work have shown the ripper cutting technique to be more efficient than the kerf-core technique. While it was less efficient than the conventional technique when working in Indiana limestone, it was more efficient than the conventional technique when working in the harder Kasota limestone. Previous work with ripper cutting has demonstrated its ability to cut a wide variety of rock with compressive strengths to 27,000 psi. As noted earlier, the poor performance by the ripper cutting technique when working in Indiana limestone may have been due to the 0° rake angle cutter designed for these tests. Cutting efficiency for less brittle rocks, such as Indiana limestone, may be improved by cutting at increased depth with a positive rake angle cutter.

Based on these results, the ripper cutting technique is considered to be a promising alternative to current commercial techniques. However, more laboratory tests need to be conducted with ripper cutting to further define and optimize its performance.

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