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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	in/s	inch per second
ft/h	foot per hour	lb	pound
ft•lbf	foot pound (force)	lbf	pound (force)
ft/s	foot per second	lbf•in	pound (force) inch
g	gram	lbf/in^2	pound (force) per square inch
gal	gallon	min	minute
gal/min	gallon per minute	min/h	minute per hour
h	hour	pct	percent
hp	horsepower	s	second
Hz	hertz	st	short ton
in	inch	wt pct	weight percent
in^2	square inch		
in^3	cubic inch		
in•lbf/in^3	inch pound (force) per cubic inch		

LARGE-SCALE TESTING OF THE RIPPER FRAGMENTATION SYSTEM

By David A. Larson,[1] Roger J. Morrell,[2] and David E. Swanson[1]

ABSTRACT

This is the second in a series of Bureau of Mines reports which describe experiments designed to devise an efficient, economic mechanical fragmentation technique for hard rock. The previous study described the development of the ripper cutting technique to successfully cut hard rock with 3- to 6-in-wide drag cutters. This study was conducted to test the ripper cutting technique at full scale using 9-in-wide drag cutters. The experiments were conducted with a special test device that cut shallow, 6- by 6-ft openings in 9,200-lbf/in^2 compressive-strength concrete blocks.

The tests showed that ripper cutting can excavate large-scale openings of the type required by the mining industry at a production rate that outperforms the conventional drill-blast technique. Moreover, the system can produce openings of various sizes and shapes, is simple to operate and maintain, and produces very little dust or noise during operation. The system appears to meet all of the criteria for a successful hard-rock mining machine.

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INTRODUCTION

BACKGROUND

The Bureau of Mines has long recognized the benefits of mechanized excavation for hard-rock underground mines and has initiated a program to conceive a simple but efficient way to fragment hard rock. It is anticipated that such a fragmentation technique will be used to extend the application of mechanical mining machines into hard rock.

The application of a high-production, low-cost fragmentation technique could revolutionize hard rock mining in the same way as the continuous miner revolutionized underground coal mining, and there have been many attempts to produce such a machine. The problem has always been the lack of a suitable fragmentation technique around which to construct the machine. Analysis of the needs of the underground mining industry has shown that there are several essential characteristics for a successful fragmentation system (4).[3] These characteristics are as follows:

1. The system must be able to cut a wide range of rock types under a variety of underground environments. The system must be able to cut rocks from soft shales through hard granites and basalts. It must be able to operate in massive rock, in broken and jointed rock, in mixed face conditions, and in high water inflows. Essentially, the technique must be versatile enough to handle any conditions that could arise under normal mining operations.
2. The system must be economical. Besides being able to fragment the rock, it has to do so at the same or at a lower cost than conventional techniques. Personnel requirements for maintenance and operation must be minimal. Therefore, the equipment must be amenable to automatic operation, and it must be simple, rugged, and inexpensive.
3. The system must be able to achieve a high rate of production and a consistent product size. It must be able to achieve 500 to 700 st per shift, yield a controlled product size, and be able to operate in conjunction with continuous haulage systems.
4. The system must be capable of operating in current mining operations. That is, it must be able to operate in a mining operation without requiring extensive changes in the basic mining plan. Therefore, the system must be able to excavate openings of required size and shape, and it must be maneuverable and mobile.
5. The system must operate without creating hazards such as dust, noxious gases, radiation, large amounts of heat, etc. The system must be safer and better from a health standpoint than conventional methods.

PREVIOUS BUREAU WORK

Earlier Bureau investigations (5-6) identified a method that promises to meet the above-listed requirements for a fragmentation system. This method is called ripper cutting and is illustrated in figure 1.

The forces acting on the bit in the ripper cutting system are defined in the conventional manner, with F_c representing the cutting force and F_n the normal force. The system uses a single large drag cutter to cut the rock in a series of parallel circular cuts. The system uses the previous cut as one free face, and the depth of cut is limited to one-half or less of the cut width. Using this technique, the Bureau previously conducted experiments in four rocks ranging in strength from 10,000 to 27,000 lbf/in^2 (5). Drag bits, 3- and 6-in wide, were used to make cuts as deep as 2-in per pass. The results of these tests were very encouraging; the energy efficiency of the method was from 50 to 200 pct better than for tunnel boring machines, and 12 to 58 pct better than for roadheaders (5). Moreover, the process can be scaled up to achieve a high

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

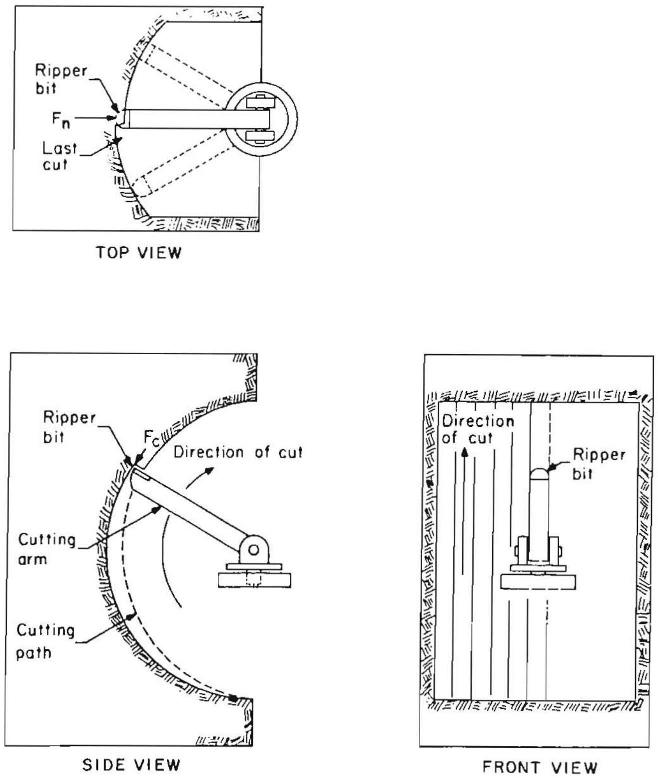


FIGURE 1.—Ripper cutting method.

production rate, and the dust levels and cutter wear appeared to be very low.

Dust levels and cutter wear were not actually measured in these earlier tests, but the following general observations were made: Essentially, no cutter wear was observed during any of the tests except for a slight polishing of the cutting edge, and no dust cloud was visually observed around the bit during cutting (5).

THE NEED FOR FULL-SCALE TESTS

Based on the previous test results using 3- and 6-in-wide drag bits, a decision was made to study ripper cutting at full scale. Full-scale testing was considered necessary because the small-scale tests did not model the complete circular cut, and it was believed that as the excavation deepened, the cutting process could be adversely affected. Full-scale cutting was also considered necessary in order to generate the accurate cutting force and production rate data that would be necessary to judge the usefulness of the system. Full-scale ripper cutting is considered to include openings with cross sections of at least 6 by 6 ft and bit widths of 9 in or more. The maximum opening size and maximum bit size has not yet been defined for ripper cutting. The remainder of this report describes the Bureau's efforts to design and test ripper cutting at full scale.

TEST EQUIPMENT

LARGE-SCALE RIPPER TESTER

For the large-scale excavation tests of ripper cutting, it was determined that the bit had to be at least 9 in wide and the opening to be cut had to be at least 6 by 6 ft to minimize scaling effects. This required the construction of a special test device that could power a bit of this size and a test sample large enough to accommodate a 6- by 6-ft opening (the test cut). The device developed for these tests is called the large-scale ripper tester. It uses two push-pull hydraulic cylinders to power the bit through a 185° vertical cutting arc and generates 150,000 lbf of cutting force at the bit at 3,000 lbf/in^2 hydraulic pressure. It also has a rotation system to move the bit across the face between cuts and an advance system to feed the machine forward. The essential features of the ripper tester are shown in figure 2, and its performance specifications are shown in table 1.

The operation of the ripper tester is as follows: First, the machine is advanced forward by the thrust cylinders the increment to be cut. This is usually 1 to 4 in or from one-third to one-half the cut width. The advance system is then locked and not moved forward again until the entire width of the face has been cut by the bit. The machine is rotated horizontally to begin the first cut on the face. This cut can be either at the center of the face or on one side of the face. When the bit is in the proper position, the machine is locked in place by four vertical jacks. This

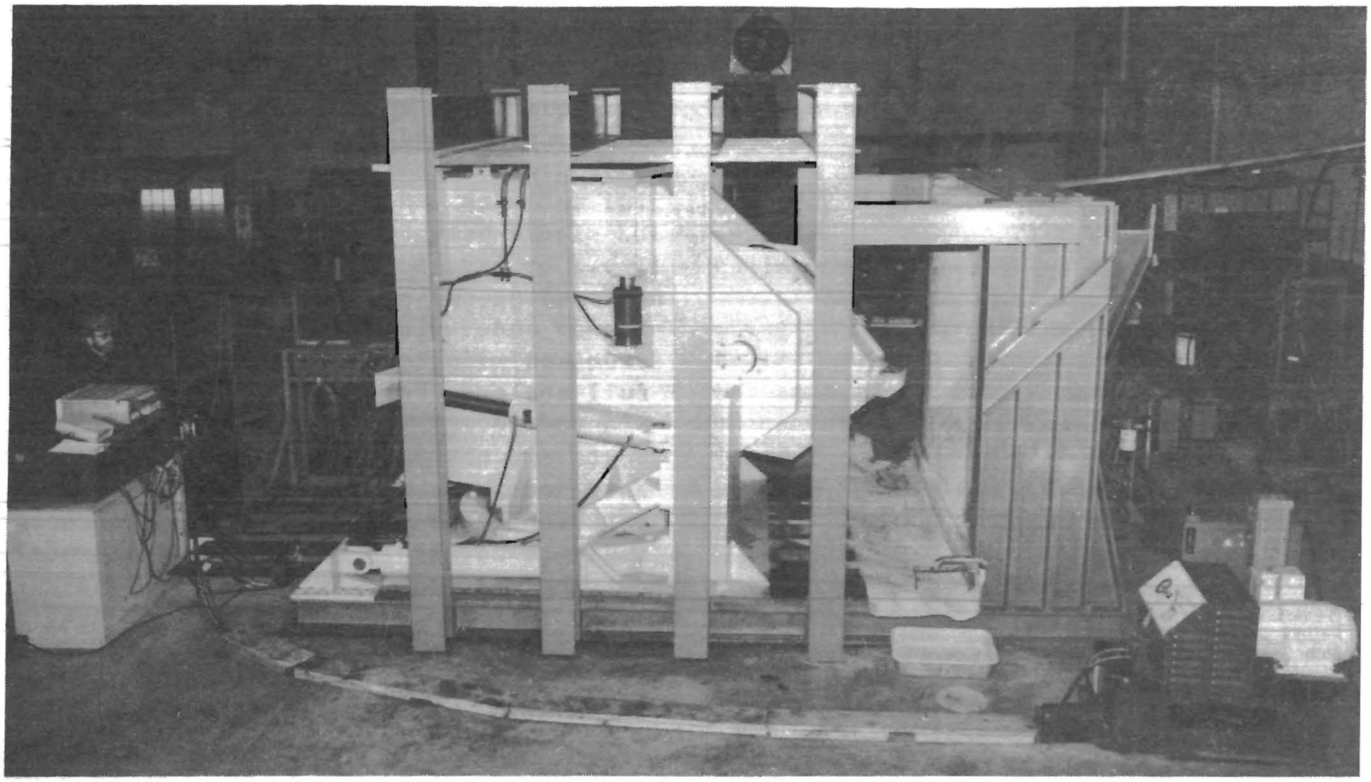


FIGURE 2.—Large-scale ripper tester.

TABLE 1. - Ripper tester specifications

Component	Specifications
Cutting system...	2 8-in-diam-bore hydraulic cylinders, 150,000 lbf max at 3,000 lbf/in^2; speed, + 3-1/2 in/s at 30 gal/min.
Thrust system....	2 6-in-diam-bore hydraulic cylinders, 600,000 lbf max at 10,000 lbf/in^2.
Rotation system..	2 6-in-diam-bore hydraulic cylinders, 600,000 lbf max at 10,000 lbf/in^2.
Holddown system..	4 100-st jacks, 2 forward, 2 rear.
Cutter..........	9- to 12-in wide crown type, bolted on, heat-treated tool steel.
Dust suppression.	Water spray.

prevents the machine from moving while cutting. When the machine is in proper position and locked in place, the cutting system is activated. The push-pull cutting cylinders swing the bit from the bottom to the top of the face through an arc of about 185°. This operation is shown in figure 3. As the bit swings through this are, the rock cuttings are collected in the cutterhead and dropped onto a muck chute at the end of the cut after the bit has returned to its original bottom position. After completion of the cut, the holddown jacks are released, the machine is rotated horizontally to the next cut position, the jacks are reset, and the machine is ready for another cut. Each succeeding cut used the edge of the previous cut as a free face, and cuts can be less than the full width of the bit. Each cut requires about 22 s to complete, and repositioning between cuts requires about 30 s.

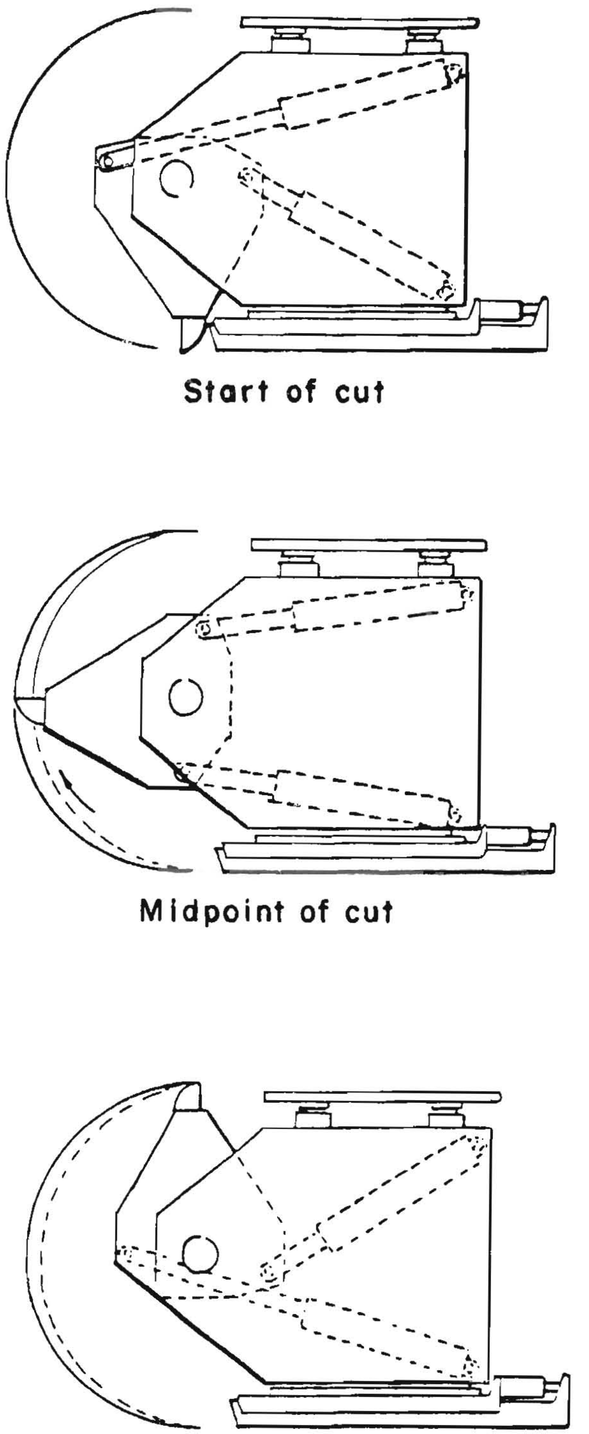


FIGURE 3.—Cutting action of ripper tester showing push-pull cylinders.

DRAG CUTTERS

The cutters used in these experiments were specially designed drag cutters constructed of tool steel and heat treated to a hardness of 58 Rockwell C. The bits were 9 in wide, 1 in thick, and had a circular-shaped cutting edge. The bits were made with a 0° and a 10° rake angle, and the clearance angel was held at 10° for all bits. The bits were attached to the bit holder with three bolts, and bit changing took one operator about 5 min. The bits are shown in figure 4.

CONCRETE TEST SPECIMENS

All of the large-scale excavation tests were conducted in a single 3- by 8- by 8-ft block of concrete. The concrete was poured into a steel form, which was constructed as part of the test device. The concrete block was solid and massive with no visible flaws or weaknesses. The concrete had a 28-day compressive strength of 9,200 lbf/in^2. It was made with 3/4-in limestone aggregate, which was considered to be representative of a nonabrasive low-strength rock. The formulation for a cubic yard of the high-strength concrete is given in table 2.

DATA ACQUISITION

During each test, the cutting force and normal force on the bit were measured and recorded. This was accomplished by measuring the hydraulic pressure in the cutting circuit and the thrust circuit.

TABLE 2. - High-strength (9,200-lbf/in^2) concrete mix design

Ingredient	lb
Portland type 1 cement	971
Water	298
Sand	1,049
Aggregate, 3/4 in angular limestone	1,643

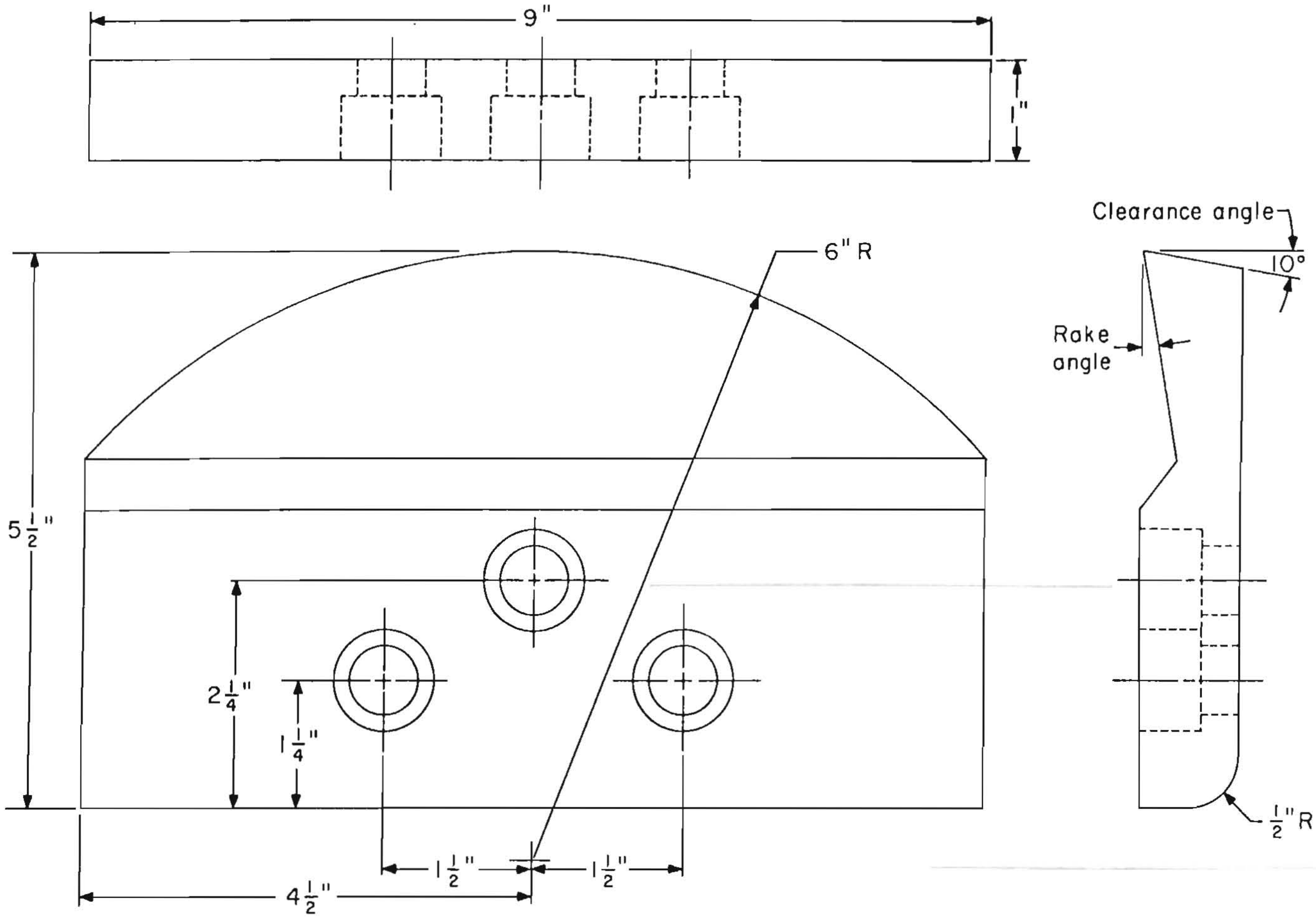


FIGURE 4.—Nine-inch-wide ripper bits tested at 0° and 10° rake angles.

The pressure in each circuit times the cross-sectional area of the cylinder, times the appropriate mechanical linkage geometry, yielded the forces on the bit. The pressures were measured with strain-gauge pressure transducers and recorded on strip chart recorders. The cutting force was considered accurate within 10 pct, as were the specific energies and rock numbers, which were computed from the cutting force data. The normal bit forces were erratic during calibration, due to varying frictional forces, and can only be considered to be rough estimates of the real values. Therefore, throughout this report, the normal forces are given only as a percentage of the cutting force and are not plotted separately. The normal force estimates are still considered extremely important to the design of ripper systems, and the estimates given for each value can still be used as the best-case and worst-case design data.

TEST DESIGN

The experimental test program had two general goals: first, to determine if ripper cutting could excavate a full-size opening in a massive rock specimen, and second, to generate sufficient engineering data on the method to allow the calculation of realistic production rates and energy consumption. To accomplish these goals, a test plan was developed, using results from the previous small-scale tests to set the initial operating conditions. The independent variables that were tested are shown in table 3.

TABLE 3. - Test design variables

Variable	Values used
Bit rake angle..............	0°, +10°
Cutting depth...........in..	1, 1-1/2, 2
Cutting width...........in..	2, 4, 6, 9

The cutter type used throughout the test program was a 9-in-wide crown-type drag bit with a 10° clearance angle. The cutting widths studies were 2, 4, 6, and 9 in. The cutting speed was held constant at 3 in/s, and all cuts were made from bottom to top. While 3 in/s is considerably slower than the 12-in/s bit speed that would be used in field cutting, it was not expected to have any effect on the bit forces reported in this paper, based on previous work (2). The dependent variables that were measured or calculated were bit cutting force in pounds (force), bit normal force, in pounds (force), and specific energy, in inch pounds (force) per cubic inch. A total of 82 tests was conducted. The raw data are shown in appendix A.

EXPERIMENTAL RESULTS AND ANALYSIS

The depth of cut varies over the length of the cut. The cut depth starts at zero and gradually increases to a maximum at the center and then gradually decreases to zero as the cut is completed (fig. 3). Therefore, the depths and the areas of the cuts referred to in this report are calculated at the center of the cut, where the depth and cross-sectional area are greatest.

When using the ripper fragmentation method, the width of cut is independent of the size of the bit. The width of the cut is defined as the width of the cut made by the bit and can be varied simply by rotating the machine to a greater or lesser extent between cuts. A 9-in-wide bit can be used to make cuts from 0 to 9 in wide, depending upon the rotation of the machine.

BIT FORCES VERSUS CUTTING DEPTH

The average cutting force on the bit was plotted as a function of the maximum cutting depth for both bits tested, at a constant width of 4 in (fig. 5). The best-fit equations for these curves are

$$F_c = 10,439\ D^{0.52}$$

for the 0° rake angle bit

and $$F_c = 10,297\ D^{0.52}$$

for the 10° rake angle bit,

where F_c = average cutting force, lbf,

and D = cutting depth, in.

These equations, with exponents less than 1.0, show that the cutting force increases at a slower rate than the depth of cut. This indicates that the cutting process becomes more efficient as the depth of cut increases. The intuitive explanation for this improvement is that deeper cuts produce more large chips and fewer small chips. Since a smaller new fracture surface is created in making large chips, less total fracture surface energy is required, and the process becomes more efficient.

The curves also show that the 0° bit and the 10° bit performed about equally well, so there is no basis for selecting one over the other. This is in contrast

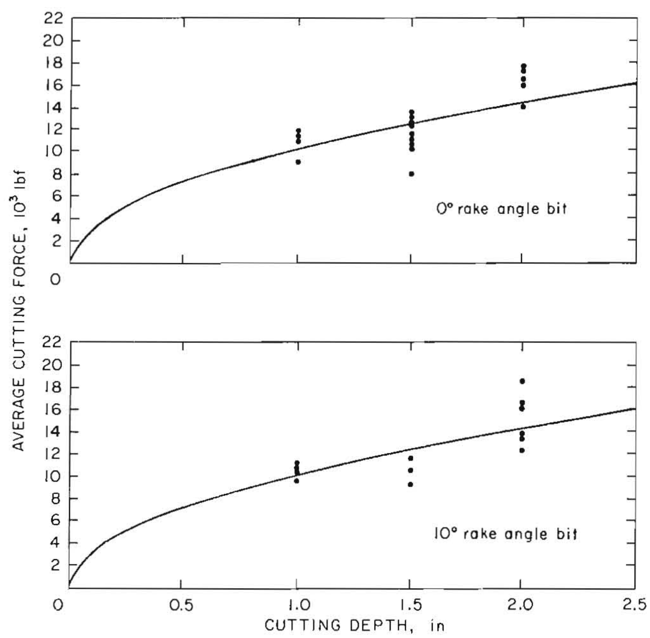


FIGURE 5.—Average cutting force as a function of cutting depth for a 4-in cutting width.

to previous work (5) that showed the bit rake angle to have a significant effect on cutting force. Future tests will be conducted in a wider range of rock samples to clarify this relationship.

While these experiments on cutting depth were conducted using only a 4-in-width of cut, the general result should be valid for all other cut widths as well. That is, the cutting force will increase with an increasing depth of cut. The actual rate of increase, however, may be slightly different than that obtained for the 4-in-wide cut.

All of the previous discussion has dealt with average cutting forces. However, the cutting force acting on the bit during cutting is really a series of force highs and lows with a major frequency of approximately 1/2 to 7 Hz. To fully characterize the cutting forces acting on the bit, the peak cutting force should also be analyzed. The peak cutting force is the force that would be used to design the structural integrity of a mining machine. In this investigation, the peak cutting force was defined as the average of the three highest forces recorded during a cutting run. This averaging was necessary to achieve repeatability between similar experimental runs. The peak cutting force was found to be a function of the average cutting force as follows:

$$F_{cp} = 2.5\ F_c,$$

where F_{cp} = peak cutting force, lbf,

and F_c = average cutting force, lbf.

The normal forces were also measured during these experiments, but, as noted earlier, the normal force data are considered to be estimates only and, therefore, were not plotted along with the cutting force. The data show, however, that on the average, the normal force as a function of cutting force was

$$F_n = 1.2\ F_c$$

where both F_n and F_c are average values.

BIT FORCES VERSUS CUTTING WIDTH

Figure 6 shows the average cutting force as a function of cutting width for both bits tested. The best-fit equations for these curves are

$$F_c = 6{,}204\ W^{0.48}$$

for the 0° rake angle bit

and $$F_c = 8{,}046\ W^{0.26}$$

for the 10° rake angle bit,

where W = width of cut, in.

These curves and equations show the influence of cutting width and bit rake angle on cutting force. These equations are very similar to the depth-force relationship shown in the previous section in that the cutting force increases at a slower rate than the cutting width, and the cutting process becomes more efficient as width is increased.

The graphs also show that the 10° rake angle bit required slightly less cutting force than the 0° bit, but only for the

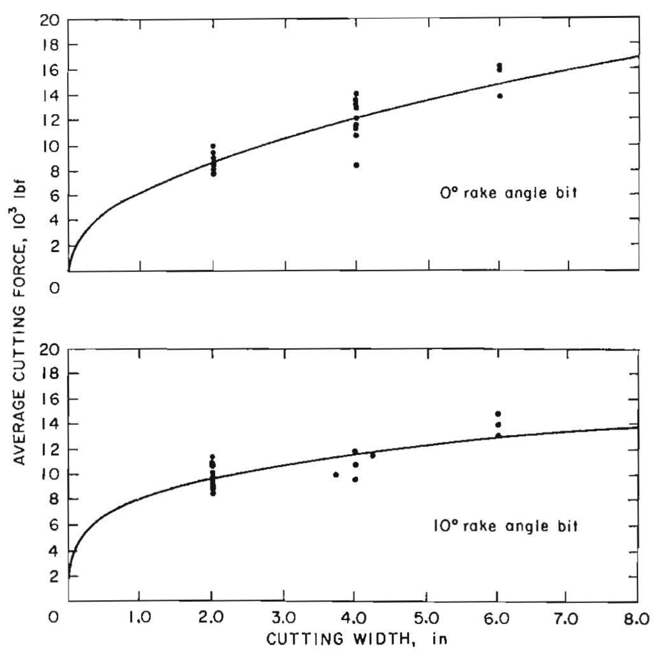


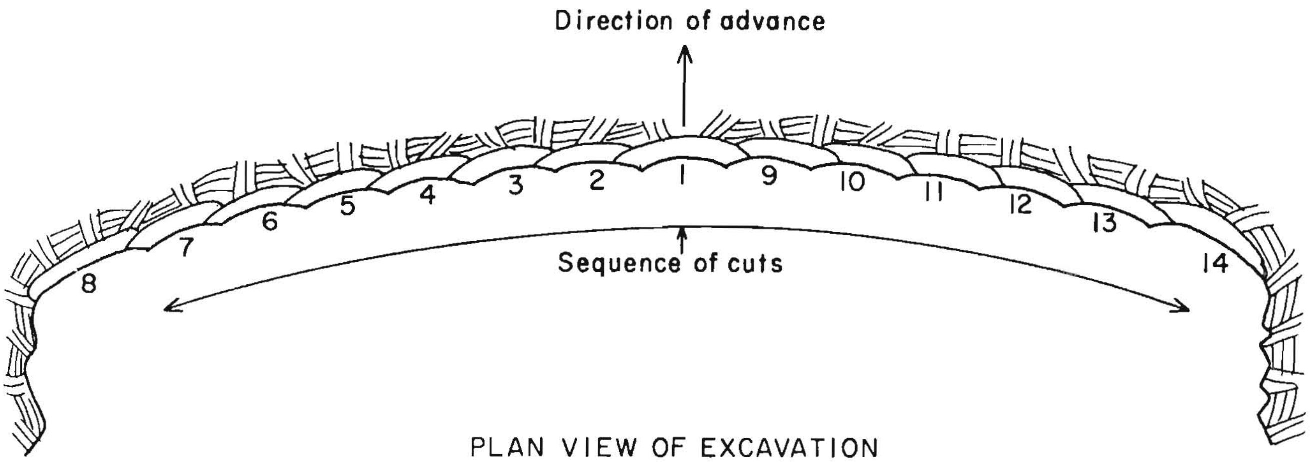
FIGURE 6.—Average cutting force as a function of width for a 1½-in cutting depth.

widest cuts. For the smaller cuts, there was no appreciable difference in cutting force. Again, this result is surprising, based on previous work that showed the 10° rake angle bits to be more efficient than the 0° bits (5). It is expected that more testing in a wider variety of rocks will show the effects of bit rake angle.

BIT FORCES VERSUS POSITION OF BIT ON FACE

The ripper fragmentation method makes a series of vertical circular cuts across the entire face of the rock being excavated. Because of the geometry of the excavation produced, the right and left halves of the excavation are mirror images of each other, so that corresponding cuts to the right and left of center are identical and should experience the same cutting forces. The geometry of each cut varies, however, as the cut proceeds from the bottom to the top of the excavation.

Figure 7 shows the geometry of the various cuts across the face and an example of the average cutting forces associated with each cut. The center cut is usually the first cut made on the face and has a high cutting force because of the full width of the cut and the lack of a free face to the side. The remaining cuts, starting next to the center cut and



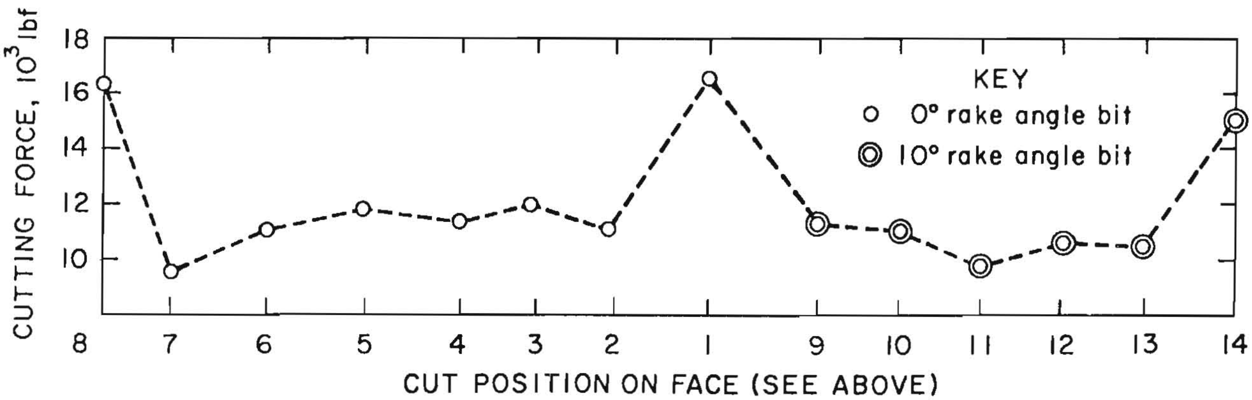


FIGURE 7.—Bit cutting force as a function of horizontal position. (The sequence of cuts 1 through 14 corresponds to actual cuts 69 through 82 as shown in the appendix.)

moving to first to one side of the excavation and then the other, should have gradually reduced forces as the bit approaches the sides. However, since the excavation is quite narrow, the cut volumes are nearly the same and, hence, the average force for each cut is approximately equal. The last cut on each side, which defines the right or left boundary of the excavation, requires very high forces. This is because these corner cuts are much more confined than any of the other cuts. Cuts of the same width and depth on the right side of the excavation require approximately the same cutting force as cuts of equal size on the left side. Thus, experimental data for one side of the face can be compared directly to data for the other side.

SPECIFIC ENERGY OF CUTTING

The specific energy of an excavation process is defined as the energy required to fragment a given volume of rock. The units used are inch pounds (force) per cubic inch, and the lower the value, the more efficient the process is. The mathematical definition of specific energy is as follows:

$$E_s = E/V$$

where E_s = specific energy, in•lbf/in^3,

E = total energy consumed during cutting, lbf•in.

and V = total volume of rock cut, in^3.

The specific energy of cutting is affected by many factors, including the type of material being cut, the type of bit used, and the geometry of the cut. Figure 8 shows how the specific energy varies as a function of bit type and the cross-sectional area of the cut.

For both bits tested, the specific energy decreased steadily as the area of the cut increased (fig. 8). The explanation for this phenomenon is that deeper cuts produce a larger proportion of large chips, so the overall surface area created per unit volume is less than it would be for shallower cuts. This trend was observed for all the tests performed, and it is expected that it would also be observed for larger cuts, but this is not known at this time.

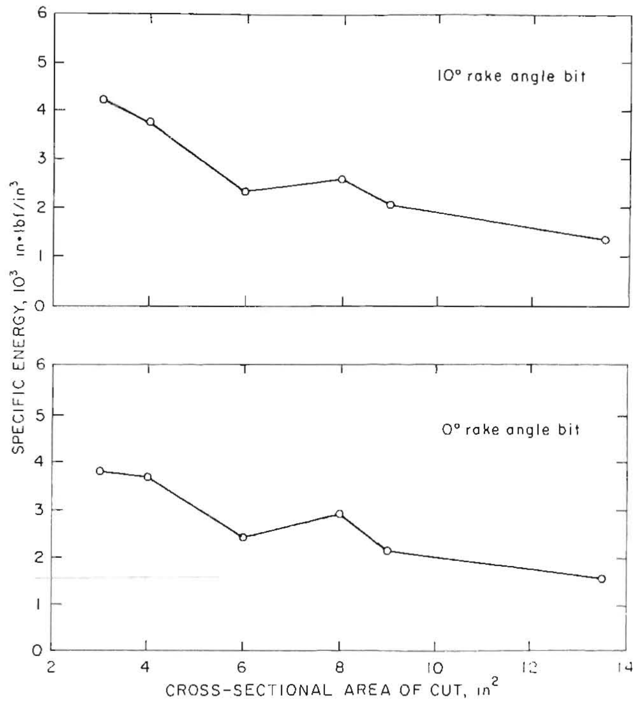


FIGURE 8.—Specific energy as a function of the cross-sectional area of the cut.

The data showed no appreciable difference in specific energy between the 0° and 10° bits. As noted earlier, this is in contrast to previous work (5) which showed a definite effect of rake angle. Future tests in a wider variety of rocks should clarify the relationship of rake angle and specific energy.

While the specific energy of cutting defines the efficiency of the cutting process, it is necessary to take into account the hardness of the rock being cut if the overall efficiency of a given method is to be compared to other cutting methods. To allow comparison of different cutting methods in different rocks, the following method of measuring cutting efficiency, as described by Hughes (3) and Gaye (1), was used:

The efficiency parameter, or rock number, N_R, is defined as follows:

$$N_R = \frac{\sigma c}{E_s}$$

where N_R is dimensionless,

σc = unconfined compressive strength of rock being cut, lbf/in^2,

and E_s = specific energy of the process, $in \cdot lbf/in^3$.

E_s is calculated as the energy consumed, in pound (force) inches, divided by the volume of the cuttings produced, in cubic inches, which yields an E_s value in inch pounds (force) per cubic inch. E_s in inch pounds (force) per cubic inch reduces to pounds (force) per square inch, so N_R becomes a dimensionless number. The larger the rock number N_R, the more efficient the process is.

The N_R calculated at the most efficient operating point for the ripper tester was 6.2. This was achieved using the 10° bit with a $13.5\text{-}in^2$ cut. For comparison, N_R values given by Gaye (1) are 4 to 6 for tunnel boring machines with disk cutters and 8 for roadhead excavators. Thus, the ripper cutting technique is slightly more energy efficient than tunnel boring machines and somewhat less efficient than roadheaders. However, the efficiency number N_R is also dependent on the cutter geometry. Previous work (5) with the ripper in natural rock yielded N_R values of up to 12. Thus, it is very likely that further improvements can be made in the cutting process with the proper selection of cutter geometry.

BIT WEAR

The two bits used in these experiments formed a wear flat about 0.25-in wide on the clearance side of each bit after traveling about 500 ft. This amount of wear did not seriously affect the cutting action, and both bits were used throughout the experiments without resharpening.

It would be advantageous to be able to predict bit life, as bit cost has a significant effect on the economics of the fragmentation system. However, the wear experienced in these tests is difficult to directly compare to field cutting in rock because of significantly different conditions. For example, it is well known that the wear experienced by a bit is directed related to the forces on the bit, the bit speed and metallurgy, and the hardness and abrasiveness of the material being cut.

A 1978 study done under Bureau contract S3371323 provided accurate wear-life data for drag bits in several rock types. These bit-wear data should be directly applicable to ripper drag bits, since the bit speed used was the same as predicted for full-scale ripper cutting and the cutting geometry was identical to full-scale ripper cutting geometry. The results, which should directly predict the wear life of full-scale tungsten carbide ripper bits, are shown in table 4.

The best bit lives were achieved at the lowest bit speed of 12 in/s, when adjacent cuts overlapped each other and when a water mist was used to cool the bit. Bit lives similar to those shown in table 4 could be expected for ripper bits in similar rocks. It is estimated that for a full-size ripper with a 24-in-wide bit, the bit would travel about 9,800 ft in an

TABLE 4. - Maximum drag bit life,[1] ft

Bit rake angle	Sandstone (9,000 lbf/in^2)	Limestone (9,000 lbf/in^2)
+15°....	500	1,200
0°......	300	2,500
-15°....	1,100	10,400

[1]Trona (3,000 lbf/in^2): no wear after 40,000 ft at all 3 angles.

8-h shift. Thus, in some rocks, no bit changes would be required over the entire shift; while in harder, more abrasive rocks, as many as 10 bit changes would be required. Since bit changes can be accomplished by one person in 5 min, and 5 to 10 resharpenings should be achievable for each bit, bit wear and bit changing should not be a serious problem in most nonabrasive rocks. However, bit wear cannot be accurately predicted until more bit-wear studies have been conducted.

DUST GENERATION

During the cutting process, a small amount of airborne dust was created. To control this dust, a single water-spray nozzle was mounted on the cutting head such that the leading edge of the bit was engulfed in the water spray. The nozzle used was a hollow-core spray nozzle with a 0.05-in-diam orifice, and it used about 0.1 gal of water per minute. This single spray was judged, by visual observation, to be very effective in knocking down the dust at the bit. The large dust cloud produced during dry cutting was nearly eliminated when the single water spray was used. For even greater effectiveness, a second spray nozzle should be mounted to cover the area directly behind the trailing edge of the bit, since a substantial amount of dust was also produced in this area. Based on these results, it appears that several water sprays surrounding the bit should effectively control the dust generated during ripper cutting.

MUCK SIZE

It was observed that the largest rock chip formed was approximately square in cross section, with maximum dimensions equal to the width of the cut. The thickness was equal to or less than the depth of the cut. A 9-in-wide cut, 2 in deep, would therefore produce a maximum size chip approximately 2 by 9 by 9 in. The screen size of tunnel boring machine muck is predominantly (20 to 30 pct) about 1 to 2 in, with the largest pieces being about 1 by 3 by 9 in. The sieve analysis of a full-face cut 2 in deep and 6 in wide is shown in table 5, and the cuttings are shown in figure 9. Note the dominance of the large sizes and the lack of smaller particles. The greater proportion of larger size pieces, in comparison with cuttings produced by conventional mechanical fragmentation techniques, reduces the amount of surface area created, which in turn reduces the specific energy of cutting.

TABLE 5. - Sieve analysis of ripper cuttings

Size fraction as shown in figure 9	Screen size[1]	Weight, g	Wt pct	Cumulative wt pct
A................	-8 + 2 in............	6,657	42	42
B................	-2 + 1/2 in..........	4,716	30	72
C................	-1/2 in + 4 mesh.....	2,295	14	86
D................	-4 + 10 mesh.........	908	6	92
E................	-10 + 20 mesh........	627	4	96
F................	-20 mesh.............	614	4	100

[1]"Mesh" indicates Tyler mesh.

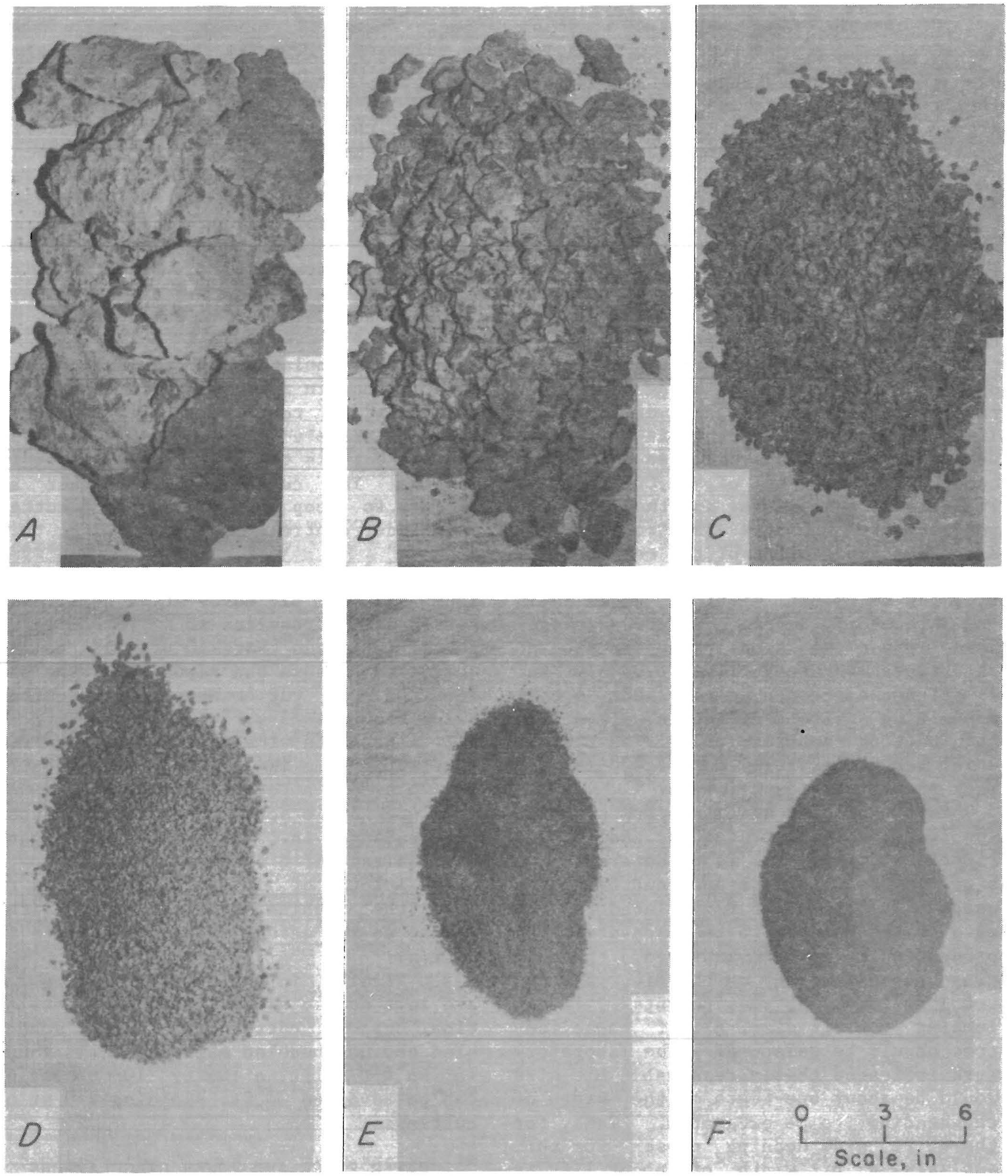


FIGURE 9.—Size fractions of typical muck from full-face cut using 10° bit at a 2-in depth and 6-in width of cut. (See table 5 for screen sizes of fractions shown.)

APPLICATION OF RESULTS

This section illustrates the potential use of the ripper fragmentation system. The ripper fragmentation system is designed to be an alternative to the drill-blast method of fragmentation in most sedimentary rocks with compressive strengths up to 27,000 lbf/in^2. The system could be used either to bulk mine or to drive development openings in sizes from approximately 6 by 6 ft to 20 by 20 ft or more.

To illustrate the use of the ripper cutting method in a mining environment, the following mining scenario was developed: A mining machine using the ripper cutting method is used to drive 10- by 10-ft rectangular headings in a massive nonabrasive limestone with an unconfined compressive strength of 18,000 lbf/in^2. The size of the opening and the rock type were selected to show the most likely areas for application of the method. The 10- by 10-ft stope size is a scale-up from the 6- by 6-ft openings produced in the laboratory, but is considered reasonable, given the simple construction of the ripper machine. The 18,000-lbf/in^2 limestone was chosen to represent a common mining environment and is well within the cutting capabilities of the system, which has successfully cut 27,000-lbf/in^2 rock in previous experiments.

Once the heading size and rock type are specified, the next step in analyzing a ripper cutting system is to determine the size of the single ripper cutter to be used. The bit size is related to the size of the heading to be excavated, the production rate to be achieved, the cutting forces acting on the bit, and the total system power requirements. In selecting the bit size, all of these factors should be balanced. The laboratory work indicated that a reasonable bit size would be about one-tenth of the width of the heading to be excavated. Thus, for the 10-ft wide heading chosen for this analysis, a bit width of about 1 ft is indicated. Once the bit width is selected, the depth of cut can be specified. Previous work with 3- and 6-in bits showed that efficient cutting was achieved at cutting depths that were from one-third to one-half of the bit width. Therefore, for a 12-in-wide bit, the cutting depth should be between 4 and 6 in. Finally, the bit speed should not exceed 1 ft/s in most rock types, if cutter wear is to be kept to reasonable rates. Given these initial conditions, the productivity, bit forces, and total power requirements of the ripper cutting method can be calculated.

PRODUCTIVITY CALCULATIONS

In the calculations that follow, all work is done in a 10- by 10-ft heading in 18,000-lbf/in^2 rock. The bit is 12 in wide and takes a 5-in depth of cut. The cutting path is circular and is 15-ft in length. The cutter speed is set at 12 in/s to keep heat buildup and cutter wear under control.

1. Since each cutter swing is 15 ft long and the bit moves at 1-ft/s, each cutter swing requires 15 s to complete. It is estimated that 10 s will be required to return and reposition the bit for the next cut. Hence, each cutter swing requires 25 s.
2. The 12-in-wide cutter covers the 10-ft-wide face in 10 cuts, each requiring 25 s for a total of 4.16 min. One complete cycle across the face advances the heading 5 in. This yields an instantaneous rate of 6 ft/h.
3. A total of 10 min/h is required to move the machine ahead and reset the jacks, so the actual production rate is 5 ft/h.
4. Finally, in a 8-h shift, assume 2 h are lost due to delays caused by ventilation, support, cutter changes, and scheduled and unscheduled maintenance. Thus, in an 8-h shift, a 10- by 10-ft heading can be advanced 30 ft, yielding 220 st of cuttings.

CUTTER FORCE AND POWER CALCULATIONS

Using the experimental data, the forces acting on the cutter and the power required to excavate at a rate of 220 st per shift can also be calculated.

1. The laboratory studies showed that the efficiency factor N_R for ripper cutting ranges up to 6.2. Assuming an efficiency factor of 6 and a rock compressive strength of 18,000 lbf/in^2, the specific energy is calculated (as explained in the section, "SPECIFIC ENERGY OF CUTTING") to be 18,000/6, or 3,000 $in \cdot lbf/in^3$.

2. The cutter force is considered to be proportional to the area of the bit in contact with the rock times 3,000 lbf/in^2. For a 12-in-wide bit cutting 5 in deep, the area is 60 $in^2 \times 3,000$ lbf/in^2, which yields an average cutter force of 180,000 lbf. The peak cutting force is 2.5 times the average cutting force, or 450,000 lbf.

3. The energy and horsepower requirements are computed by the total energy consumed per cut as follows: The volume cut per pass is 5 in deep by 12 by 120 in, or 7,200 in^3. Since the energy per unit volume is 3,000 $lbf \cdot in/in^3$, the total energy consumed per cut is 1,800,000 ft•lbf.

4. The average horsepower requirement for the ripper miner is the total energy used divided by the time of the swing, which yields 131 hp.

SUMMARY AND CONCLUSIONS

The specific conclusions that can be made based on the experimental data are as follows:

1. The ripper cutting method has demonstrated the ability to excavate rectangular-shaped openings of 6 by 6 ft. This is considered full-scale cutting. The method is capable of excavating larger size openings, but the maximum size has not yet been defined.

2. The ripper cutting method is able to cut full scale in 9,200-lbf/in^2 concrete, and smaller scale tests have shown the method capable of cutting rocks up to 27,000 lbf/in^2. The hardness limit of the method has not yet been defined.

3. The best energy efficiency achieved by the method, as measured by the rock number N_R, is 6.2, which compares to 4 to 6 for tunnel boring machines and 8 for roadheaders. This efficiency was achieved with the 10° rake angle bit, cutting 9 in wide and 1.5 in deep.

4. The energy efficiency of the cutting process improved steadily as the cross-sectional area of the cut increased. Therefore, to achieve high efficiency cutting, the bit should make the largest cut possible within the limitations of the machine.

5. Both the 0° and 10° rake angle bits performed equally well in terms of energy efficiency, and there is no basis for choosing between them. It is known from other tests, however, that rake angle has a significant effect on efficiency, so the selection of the optimum bit geometry remains a trial-and-error process for each rock type.

The cutting experiments described here have shown that the ripper cutting method can successfully cut the large, rectangular-shaped excavations required by the mining industry. Previous experiments showed that the method is capable of cutting a wide range of rocks ranging in strength from 5,000 to 27,000 lbf/in^2, giving it a wide field of application. In addition, the ripper cutting method possesses certain other advantages which make it very useful for mining. These advantages are as follows: (1) The simple, inexpensive drag cutters used (with no moving parts) would yield the lowest cutter cost per ton mined, compared to any type of rolling cutter; (2) the method has the potential to achieve high production rates which can be varied by simply adjusting the width and depth of the cut; (3) ripper cutting is not sensitive to geologic conditions such as mixed face, high water inflows, or blocky ground; and (4) cutter changes can be made quickly and easily by one operator when necessitated by wear or to be better match formation cutting characteristics.

Because of the success of these experiments, the ripper cutting method will continue to undergo further large-scale laboratory testing. The purpose of these tests will be to generate accurate cost data that will permit a realistic economic feasibility analysis to be performed. A patent for a universal mining machine based on the ripper cutting method, has been granted to the U.S. Government (7).

REFERENCES

1. Gaye, F. Efficient Excavation With Particular Reference to Cutting Head Design of Hard Rock Machines. Tunnels and Tunnelling, v. 4, 1972, No. 1 (pt. 1), pp. 39-48; No. 2 (pt. 2), pp. 135-143.
2. Hignett, H. J., R. A. Snowdon, and J. Temporal. Rock Cutting Trials and Lower Chalk. Paper in Energy Resources and Excavation Technology, Proceedings 18th U.S. Symposium on Rock Mechanics (CO School of Mines, Golden, CO, June 22-24, 1977). CO School of Mines Press, 1977, 34 pp.
3. Hughes, H. M. Some Aspects of Rock Machining. Int. J. of Rock Mech. Min. Sci., v. 9, No. 2, 1972, pp. 205-211.
4. Larson, D. A., and R. C. Olson. Design Consideration of Mechanical Fragmentation Systems for Entry Development in Oil Shale. Paper in Proceedings of 10th Oil Shale Symposium (CO School of Mines, Golden, CO, Apr. 21-22, 1977). CO School of Mines Press, 1977, pp. 99-107.
5. Morrell, R. J., D. A. Larson, and D. E. Swanson. Large-Scale Drag Cutter Experiments in Hard Rock. BuMines RI 9003, 1986, 18 pp.
6. Morrell, R. J., and R. J. Wilson. Toward the Development of a Hard Rock Mining Machine--Drag Cutter Experiments in Hard Abrasive Rocks. BuMines RI 8784, 1983, 19 pp.
7. Morrell, R. J., and D. A. Larson. Universal Ripper Miner. U.S. Pat. 4,501,448, Feb. 26, 1985.

APPENDIX.--RAW DATA

Cut No.	Rake angle, °	Advance distance, in	Cut				Force, lbf						Cut vol., in^3	Total energy, lbf·in	Specific energy, $\frac{in \cdot lbf}{in^3}$	Av cut pressure, lbf/in^3
			Depth, in	Width, in	Length, in	Time, s	Mid cut	Av cut	Peak cut	Mid normal	Av normal	Peak normal				
1....	0	11.75	1.50	4.00	60.7	19.8	13,326	12,945	NA	7,800	8,500	NA	304	785,761	2,585	1,820
2....	0	11.75	1.50	4.00	60.5	18.4	14,311	11.096	NA	11,400	12,500	NA	302	671,308	2,223	1,560
3....	0	11.75	1.50	4.00	60.2	18.0	14,012	13,737	NA	14,200	13,800	NA	299	826,967	2,766	1,932
4....	0	11.75	1.50	4.00	59.7	18.0	10,317	12,734	NA	13,000	11,500	NA	296	760,220	2,568	1,791
5....	0	11.75	1.50	2.00	59.3	17.4	11.509	9,300	NA	8,500	8,200	NA	146	551,490	3,777	5,231
6....	0	13.25	1.50	9.00	65.1	28.4	23,241	16,054	42,023	17,500	17,000	31,500	755	1,045,115	1,384	446
7....	0	13.25	1.50	4.00	64.9	20.4	15,669	11,930	33,462	7,700	8,000	16,200	303	774,257	2,555	1,678
8....	0	13.25	1.50	4.00	64.7	19.5	10,442	8,325	29,308	14,000	9,300	14,300	318	538,627	1,694	1,171
9....	0	13.25	1.50	4.00	64.5	21.1	15,661	11,879	37,975	14,500	12,200	20,500	316	766,195	2,425	1,670
10...	0	13.25	1.50	4.00	64.1	20.5	11,820	10,560	29,502	9,500	10,500	17,000	314	676,896	2,156	1,485
11...	0	13.25	1.50	4.00	63.7	19.7	16,252	13,458	43,242	17,000	12,800	28,500	310	857,274	2,765	1,893
12...	0	13.25	1.50	4.00	63.2	17.3	12,805	11,372	29,149	15,000	13,000	22,000	306	718,710	2,349	1,599
13...	0	13.25	1.50	2.50	62.8	17.3	17,138	13,767	31,355	13,500	18,500	21,000	188	864,568	4,599	4,956
14...	10	13.25	1.50	3.75	64.9	21.0	9,258	10,032	27,962	10,400	13,000	24,900	303	651,077	2,149	1,605
15...	10	13.25	1.50	4.25	64.7	20.3	12,953	11,523	34,774	12,500	11,600	28,000	318	745,538	2,344	1,435
16...	10	13.25	1.50	4.00	64.5	19.8	11,870	9,628	33,542	15,500	12,000	27,000	316	621,006	1,965	1,354
17...	10	13.25	1.50	4.00	64.1	20.7	12,400	11,925	29,706	18,500	13,500	26,500	314	764,393	2,434	1,677
18...	10	13.25	1.50	4.00	63.7	18.9	10,442	10,913	36,862	14,000	12,500	23,500	310	695,158	2,242	1,535
19...	10	13.25	1.50	4.00	63.2	18.9	15,366	15,980	38,253	19,000	17,500	31,000	306	1,009,936	3,300	2,247
20...	10	14.75	1.50	9.00	68.9	22.5	17,335	16,873	42,288	28,000	23,500	41,000	789	1,162,549	1,473	469
21...	10	14.75	1.50	2.00	68.8	21.5	9,944	9,522	14,340	15,000	13,000	15,500	147	655,114	4,457	5,356
22...	10	14.75	1.50	2.00	68.7	21.6	10,835	9,060	17,640	17,640	9,500	12,500	166	622,422	3,750	5,096
23...	10	14.75	1.50	2.00	68.7	21.6	11,426	10,223	19,486	10,000	7,000	11,000	165	702,320	4,256	5,750
24...	10	14.75	1.50	2.00	68.4	21.3	9,130	8,918	17,159	9,000	8,000	9,800	165	609,991	3,697	5,016
25...	10	14.75	1.50	2.00	68.3	21.1	11,225	11,449	19,409	10,500	9,000	11,500	164	781,967	4,768	6,440
26...	10	14.75	1.50	2.00	68.1	21.5	10,934	10,829	23,861	12,600	10,000	12,400	163	737,455	4,524	6,091
27...	10	14.75	1.50	2.00	67.9	21.5	10,048	8,547	20,681	12,300	7,500	12,800	163	580,341	3,560	4,808
28...	10	14.75	1.50	2.00	67.7	21.2	11,377	9,649	21,317	10,000	8,600	11,500	162	653,237	4,032	5,428
29...	10	14.75	1.50	2.00	67.5	20.7	11,081	11,004	17,143	10,000	9,000	10,700	161	742,770	4,613	6,190
30...	10	14.75	1.50	2.00	67.2	20.5	9,555	9,620	15,095	14,500	13,000	14,500	160	646,464	4,040	5,411
31...	10	14.75	1.50	2.00	66.9	19.8	10,589	9,218	15,314	9,000	7,000	9,000	159	616,684	3,879	5,185
32...	10	14.75	1.50	2.00	66.7	19.6	13,790	11,796	21,873	22,000	17,200	22,500	157	786,793	5,011	6,635
33...	0	14.75	1.50	2.00	68.8	22.2	9,949	8,199	18,373	8,500	6,500	10,000	147	564,091	3,837	4,612
34...	0	14.75	1.50	2.00	68.7	21.6	11,180	8,103	20,365	13,500	9,800	13,000	166	556,676	3,353	4,558
35...	0	14.75	1.50	2.00	68.7	21.4	9,703	8,733	19,369	9,000	6,500	13,000	166	599,957	3,614	4,912
36...	0	14.75	1.50	2.00	68.5	21.4	9,949	8,929	29,209	8,000	7,500	10,800	165	611,636	3,707	5,023
37...	0	14.75	1.50	2.00	68.4	21.6	8,964	8,852	19,568	8,000	7,000	8,800	165	605,477	3,670	4,979
38...	0	14.75	1.50	2.00	68.3	21.5	9,949	9,901	24,915	9,000	8,600	13,000	164	676,238	4,123	5,569
39...	0	14.75	1.50	2.00	68.1	21.1	9,415	9,453	21,933	7,700	7,000	9,400	163	643,749	3,949	5,317

See footnote at end of table.

RAW DATA--Continued

Cut No.	Rake angle, °	Advance distance, in	Cut				Force, lbf						Cut vol., in^3	Total energy, lbf.in	Specific energy, $\frac{in\cdot lbf}{in^3}$	Av cut pressure, lbf/in^2
			Depth, in	Width, in	Length, in	Time, s	Mid cut	Av cut	Peak cut	Mid normal	Av normal	Peak normal				
40...	0	14.75	1.50	2.00	67.9	21.2	7,979	8,518	21,754	13,000	10,000	13,400	163	578,372	3,548	4,791
41...	0	14.75	1.50	2.00	67.7	21.2	9,703	8,511	17,977	8,400	8,600	9,000	162	576,195	3,557	4,787
42...	0	14.75	1.50	2.00	67.5	20.2	7,979	8,706	22,152	11,500	10,500	14,000	161	587,655	3,650	4,897
43...	0	14.75	1.50	2.00	67.2	20.6	9,456	7,902	19,568	7,200	8,400	9,000	160	531,014	3,319	4,445
44...	0	14.75	1.50	2.00	66.9	21.0	14,381	12,394	25,199	12,800	11,100	15,300	159	829,158	5,215	6,972
45...	0	16.25	1.50	9.00	72.6	22.5	20,290	19,139	40,002	23,000	24,000	44,000	820	1,389,491	1,695	532
46...	0	16.25	1.50	6.00	72.3	21.7	16,351	15,659	41,732	24,000	20,000	39,000	494	1,132,146	2,292	979
47...	0	16.25	1.50	6.00	71.9	21.8	19,797	15,673	37,361	23,500	20,500	39,000	511	1,126,888	2,205	980
48...	0	16.25	1.50	6.00	71.3	20.7	16,351	15,759	40,837	14,500	16,200	35,000	505	1,123,617	2,225	985
49...	0	16.25	1.50	6.00	70.5	20.4	16,351	13,401	38,452	19,000	19,500	35,500	496	944,770	1,905	838
50...	0	16.25	1.50	4.00	69.6	18.0	25,706	21,711	47,397	23,500	23,000	42,000	314	1,511,086	4,812	3,053
51...	0	16.25	1.50	6.00	72.3	20.4	12,904	14,720	34,277	20,000	22,500	37,000	494	1,064,256	2,154	920
52...	10	16.25	1.50	6.00	71.9	19.5	15,366	13,895	33,085	21,500	18,500	41,000	511	999,050	1,955	868
53...	10	16.25	1.50	6.00	71.3	19.8	13,642	13,126	31,296	23,000	20,000	30,500	505	935,884	1,853	820
54...	10	16.25	1.50	6.00	70.5	19.8	19,305	17,226	35,470	23,300	21,000	32,000	496	1,214,433	2,448	1,077
55...	10	18.25	2.00	9.00	77.4	25.6	30,140	26,506	58,727	47,500	28,000	57,000	1,136	2,051,564	1,806	1,309
56...	10	18.25	2.00	4.00	77.2	20.4	16,844	17,034	37,259	22,500	21,000	44,000	441	1,315,025	2,982	4,259
57...	10	18.25	2.00	4.00	76.9	25.6	15,859	18,914	51,571	22,000	22,500	42,000	472	1,454,486	3,082	4,729
58...	10	18.25	2.00	4.00	76.6	21.0	22,261	16,837	39,645	22,300	21,500	32,000	469	1,289,714	2,750	4,209
59...	10	18.25	2.00	4.00	76.2	19.2	14,874	14,204	36,066	15,500	17,000	29,000	465	1,082,345	2,328	3,551
60...	10	18.25	2.00	4.00	75.7	19.8	12,904	13,893	38,452	18,500	16,000	28,500	460	1,051,700	2,286	3,473
61...	10	18.25	2.00	4.00	75.1	20.1	13,151	12,740	36,066	14,000	15,000	24,000	454	956,774	2,107	3,185
62...	10	18.25	2.00	4.00	74.9	20.1	23,245	18,412	40,241	23,000	20,000	31,500	447	1,379,059	3,085	4,603
63...	0	18.25	2.00	4.00	77.2	21.0	15,858	14,616	46,204	20,500	17,500	37,500	441	1,128,355	2,559	3,654
64...	0	18.25	2.00	4.00	76.9	19.8	19,305	16,891	47,397	21,000	21,800	40,500	472	1,298,918	2,752	4,223
65...	0	18.25	2.00	4.00	76.6	20.8	20,290	17,800	50,379	20,000	17,500	37,500	469	1,363,480	2,907	4,450
66...	0	18.25	2.00	4.00	76.2	20.1	18,566	18,057	52,168	23,500	24,200	39,000	465	1,375,943	2,959	4,514
67...	0	18.25	2.00	4.00	75.1	21.0	22,260	16,490	46,204	23,000	21,500	38,500	460	1,238,399	2,692	4,123
68...	0	18.25	2.00	4.00	74.4	21.0	22,752	20,449	52,764	22,500	21,000	36,500	454	1,521,405	3,351	5,112
69...	0	19.25	1.00	9.00	79.7	19.2	19,305	16,691	37,856	18,500	16,500	29,000	584	1,330,273	2,278	206
70...	0	19.25	1.00	4.00	79.5	20.7	11,919	11,294	30,699	14,500	14,500	24,500	225	897,873	3,991	706
71...	0	19.25	1.00	4.00	79.2	20.8	14,381	12,055	30,302	17,500	15,500	25,000	242	954,756	3,945	753
72...	0	19.25	1.00	4.00	78.9	20.8	14,381	11,549	31,494	19,500	16,000	30,500	240	911,216	3,797	722
73...	0	19.25	1.00	4.00	78.5	20.4	11,426	11,919	27,519	12,500	15,000	23,000	238	935,641	3,931	745
74...	0	19.25	1.00	4.00	78.0	18.0	17,089	11,169	26,525	16,000	15,500	24,500	236	871,182	3,691	698
75...	0	19.25	1.00	4.00	77.4	19.6	8,472	9,216	23,543	12,000	12,500	21,500	233	713,318	3,061	576
76...	0	19.25	1.00	2.00	76.6	20.8	18.813	16,548	33,880	14,000	20,500	32,500	115	1,267,577	11,022	4,137
77...	10	19.25	1.00	4.00	79.5	20.7	14,873	11,407	26,823	20,500	17,500	26,500	225	906,856	4,030	713
78...	10	19.25	1.00	4.00	79.2	21.0	9,949	11,132	28,115	15,000	17,000	28,500	242	881,654	3,643	696
79...	10	19.25	1.00	4.00	78.9	21.6	10,934	9,846	27,718	20,000	17,500	27,500	240	776,849	3,237	615
80...	10	19.25	1.00	4.00	78.5	21.7	11,919	10,747	26,525	27,500	22,500	32,000	238	843,639	3,545	672
81...	10	19.25	1.00	4.00	78.0	21.9	10,442	10,567	25,332	18,500	15,500	24,000	236	824,226	3,492	660
82...	10	19.25	1.00	4.00	77.4	22.2	16,843	15,171	32,290	25,500	22,000	34,000	233	1,174,235	5,040	948

NA Not available.

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