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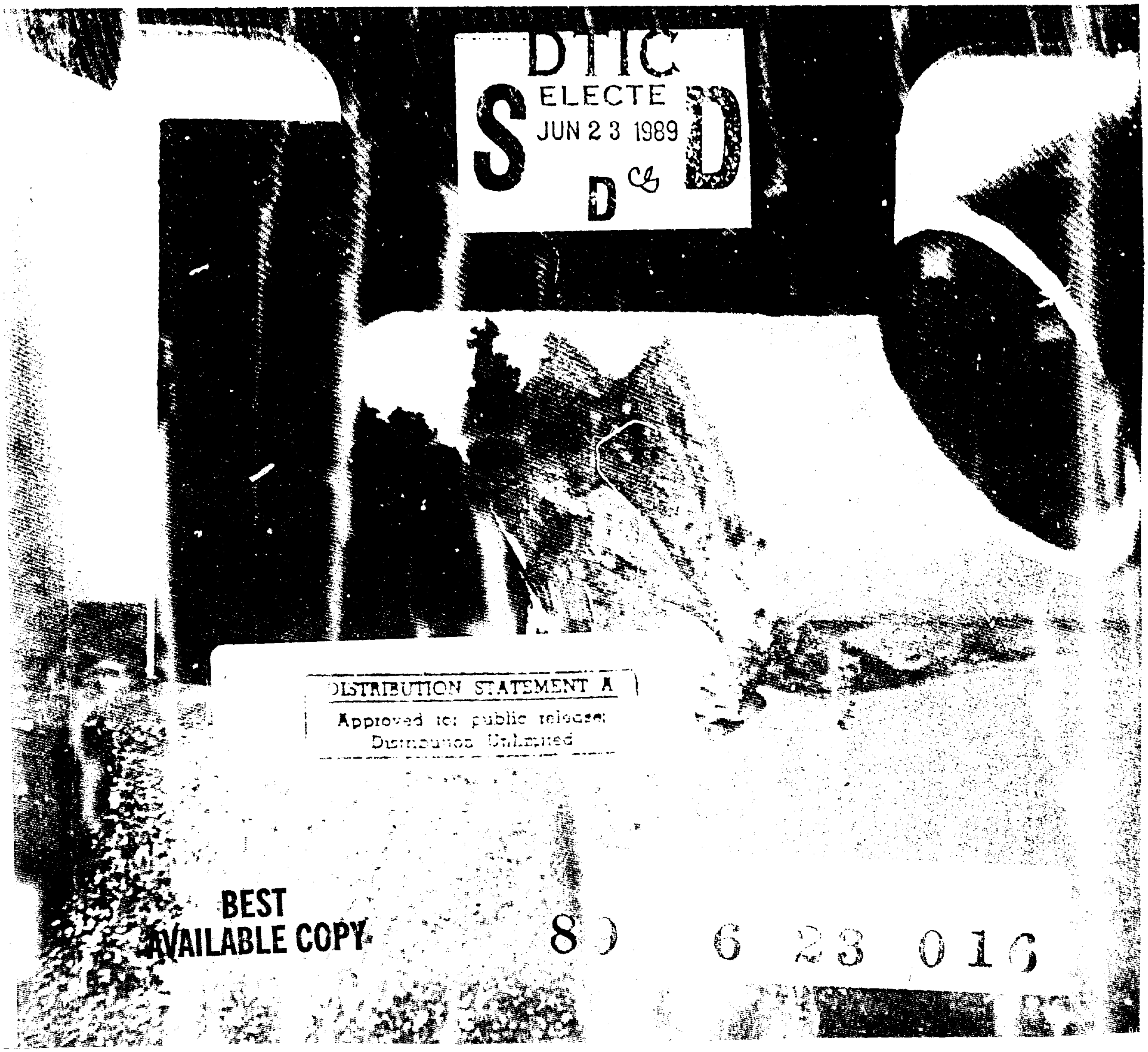
Experiments on the cutting process in ice



CRREL Report 89-5

April 1989

Experiments on the cutting process in ice

Herbert T. Ueda and John Kalafut

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Cutting tests were carried out on natural lake ice using parallel motion, orthogonal cutting tools. Parameters that varied were cutter rake angle, from –5 to 30°; cutter velocity from 4.0 to 10.6 in./s; and depth of cut from 0 to 0.200 in. The average horizontal and vertical components of force and the average of the five highest peak horizontal forces were determined and the specific energies were calculated. The maximum average horizontal force was 67 lb and the maximum average vertical force was 33 lb. The 30° rake angle cutter had the lowest specific energy. Since some of the cuts were made from a free surface and some from within a groove made by earlier cuts, all of the data cannot be compared. The sequence of going from the shallowest to the deepest cuts or vice versa in the same groove has a significant effect on the cutting forces and on the contour of the fractured surface. The effect of cutter velocity was not clearly evident, at least within the range of velocities employed.

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PREFACE

This report was prepared by Herbert T. Ueda, Mechanical Engineer, and John Kalafut, Electronics Engineer, Engineering and Measurements Services Branch, Technical Services Division, U.S. Army Cold Regions Research and Engineering Laboratory. The investigation was funded under DA Project 4A161101A91D, *In-House Laboratory Independent Research Program*; Work Unit 332, *The Effect of Some Parameters on the Cutting Process in Frozen Material*; and Work Unit 470, *Cutting Frozen Materials.*

This report was technically reviewed by Donald Haynes, Donald Garfield and Dr. Malcolm Mellor, all of CRREL.

CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS: U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the *ASTM Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4	millimeter
inch/second	0.0254	meter/second
pound-force	4.448222	newton
pound-force/inch^2	6894.757	pascal
volt per inch/second	39.37	volt per meter/second
degrees Fahrenheit	T°C = (T°F−32)/1.8	degrees Celsius

Experiments on the Cutting Process in Ice

HERBERT T. UEDA AND JOHN KALAFUT

INTRODUCTION

The technology of efficient drilling and excavating in frozen material has become increasingly important as our search for natural resources continues to expand toward the polar regions. Many of the machines currently used in these environments are simply modified versions of equipment intended for use in unfrozen material. In some cases, this is an adequate approach, albeit not necessarily an efficient one. In other cases such as a manually operated ice auger, however, it is obviously desirable to improve the cutting process to decrease the effort exerted by the operator.

Ice and frozen ground are brittle materials under sufficiently high loading rates and, as yet, there is no practical theory useful for designing cutting tools for such materials. Mellor (1977) provides an excellent analysis of the mechanics of the forces on cutting tools such as those used in this investigation. He has examined and formulated theory on the general subject of cutting in brittle materials, and he has comprehensively reviewed and discussed the theory and experimental results of many investigations.

In the specific area of frozen materials, however, there is a dearth of experimental information in the literature. To our knowledge, the only experimental work has been that of Peng (1958), Zelenin (1959), Bailey (1967), and Mazur (1974). It is our objective to fill some existing voids in the knowledge of cutting in ice and to perhaps contribute information that may someday be helpful in formulating a practical empirical design theory.

BACKGROUND AND OBJECTIVES

Frozen material is usually mechanically removed by one of two basic actions: 1) the material is dislodged by the indentation action of teeth such as in roller cone drill bits and percussive drills, or 2) the material is removed by an action commonly called shearing, ploughing or planing, such as with drag bits on drills, cutting edges on planes and teeth on saw blades. This study will focus on the second type, using cutting tools that move parallel to the ice surface with the cutting edge being perpendicular to the direction of relative motion between the tool and the ice sample.

The effectiveness of a cutter for frozen materials depends on several variables such as cutter geometry, material temperature, material prop-

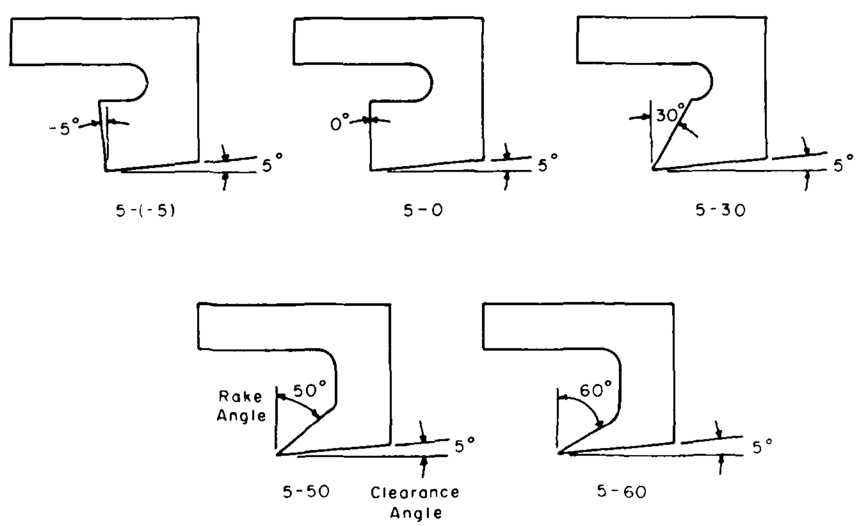


Figure 1. Cutter configurations.

erties, cutter speed, cutter wear and depth of cut. To study the effect of all of the variables would be a major task. So, the scope of this work was limited to the effect on the horizontal force, vertical force and the specific energy (work per unit volume of material removed) of varying the cutter rake angle (Fig. 1), the depth of cut and the velocity. The experiments were conducted in natural lake ice and, in most instances, in a previously cut groove.

EXPERIMENTAL TECHNIQUE AND PROCEDURE

Test equipment

We needed a device that could accurately measure the horizontal and vertical components of force exerted on the cutting tool. It had to be stiff enough so as not to interfere with the cutting process, yet compliant enough to provide sufficient strain at the detection points. So, the force

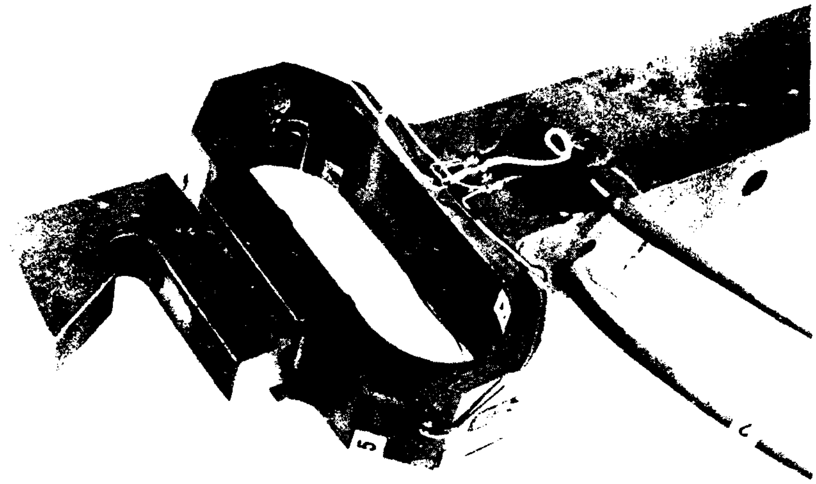


Figure 2. Force dynamometer and cutter assembly.

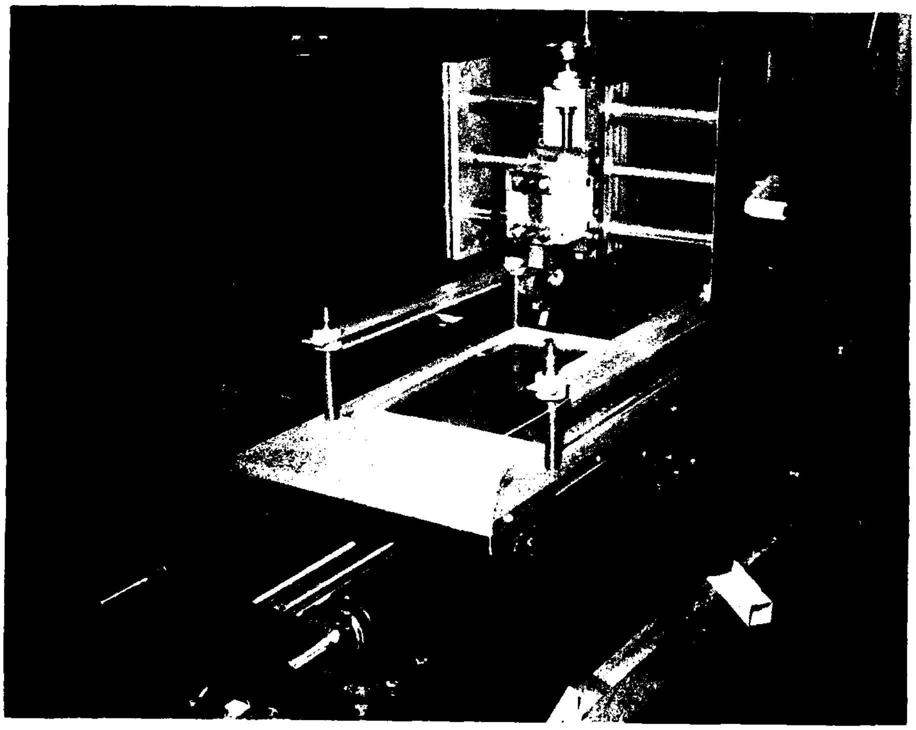


Figure 3. Test apparatus showing dynamometer mount and movable sample holding table.

dynamometer becomes the critical element of the measurement apparatus.

Figure 2 shows the dynamometer, which used electrical resistance strain gauges in a modified ring arrangement. It was designed by D. Garfield, Technical Services Division, CRREL (Garfield 1967). The basic concept is described by Loewen and Cook (1956) and is briefly discussed in Appendix A.

Figure 3 shows the dynamometer mounted over the movable sample-holding table. It could be moved perpendicular to the table with a coarse screw drive and moved vertically with a fine feed drive that permitted controlled vertical motion to the closest 0.001 in.

The sample-holding table was mounted with low-friction ball bushings on two guide bars that ran the length of the apparatus. A pneumatic cylinder was attached to the table and provided 16 in. of travel for the table and sample. The velocity of the table was varied by restricting air flow from the cylinder exhaust port.

The velocity was measured with a Houston Scientific Model 1100-38 velocity transducer. It is essentially a dc generator operated by a thin cable attached to the moving table and a reel mounted on the output shaft of the generator. Output from the transducer was 0.107 V/in. per second.

Output signals from the strain gauges were amplified through Vishay BA-4 amplifiers and recorded on a Hewlett-Packard HP-3960 tape recorder running at a maximum speed of 15 in./s. Data were reduced on a Nicolet 4094 series digital oscilloscope. A discussion of the data processing procedure and equipment appears in Appendix B.

Test samples and procedure

The ice for this investigation was harvested from three local lakes: Lake Fairlee and Lake Morey in Vermont and Post Pond in New Hampshire. The thickness of the ice covers varied from 17.3 to 23.2 in. The grain structure of the ice was columnar, with the c-axis vertical and with large grain sizes, typical for ice covers in the area (Gow 1986).

The ice was trimmed to remove any snow ice layers and only clear, bubble-free samples were used in the tests. Horizontally sliced blocks approximately 12 by 15 in. by 6 in. thick were frozen to a base plate that was clamped to the moving table of the test apparatus. Prior to each test, the ice surface was scraped smooth and flat until there were no visible surface fractures. A light cleanup cut at a shallow depth was made to ensure that the ice surface beneath the cutter was parallel to the plane of motion of the table.

The cutter made five passes at various cutting depths, all in the same groove. The cutting depth was varied incrementally in two different sequences: from the shallowest to the deepest cuts, and from the deepest to the shallowest cuts (Fig. 4). The depth-of-cut increments were 0.010 in., 0.025 in., 0.050 in., 0.100 in. and 0.200 in. The only cuts started from a free surface were those with a depth of 0.010 in. and 0.200 in. The remaining cuts occurred essentially within a groove. Therefore, a valid comparison of the data is not possible in all cases. Most of the information would be applicable to certain cutting conditions, such as those experienced by a tool in a coring drill where the cutting tool is confined to the annulus being removed. The difference in starting from a free surface or from within a previously cut groove was evident in the size and shape of the chips formed and the magnitude of the cutting forces.

After a sequence of five passes, the cutter and the tool-holding assembly were repositioned laterally a few inches over fresh ice. When all of the usable surface of the ice block was consumed, the ice was scraped clean until a fresh, crack-free surface was again available, whereupon the cutting procedure was repeated.

A total of 500 cutting passes were completed with five different cutters at five cutting velocities ranging from 4.0 to 10.6 in./s. After four sets of five passes at five different depths at one velocity, the cutter was replaced by one with a different rake angle. We tested rake angles of −5, 0, 30, 50 and 60°. The clearance angle on all the cutters was 5°. A side clearance was provided on the sides of the cutter by a circular mill cut and resulted in an estimated side clearance of 15 to 25°.

All tests were conducted at 25°F.

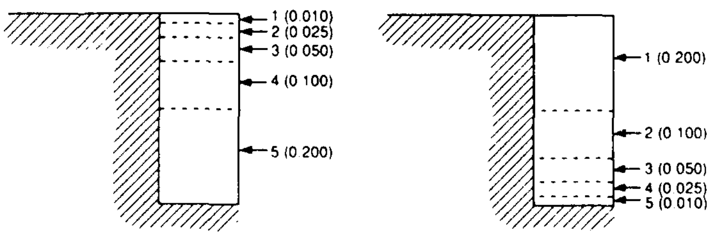


Figure 4. Cutting sequences.

RESULTS AND DISCUSSION

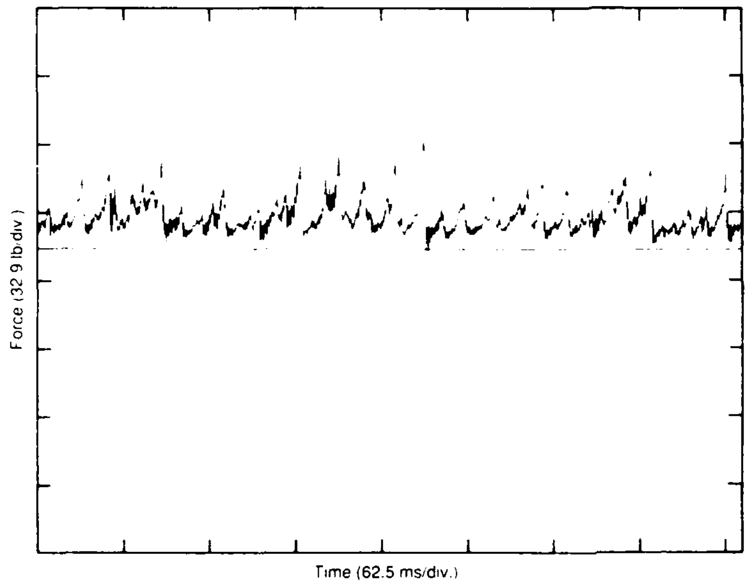
Chip formation and typical results

As mentioned before, ice is a brittle material, and chips produced by these tests are not unlike those produced by coal, rock and other brittle materials. This is desirable because this type of chipping expends the least energy per volume of material removed. Unlike ductile materials, where the chips produced by a shearing action are continuous and the forces encountered relatively constant, chips from brittle materials are produced by a repeated series of breaks, producing a large number of forces that vary in magnitude depending upon the size of the chip. To find the mean force over the length of each test, we used a digital averaging technique that gave rational and reasonably reproducible results.

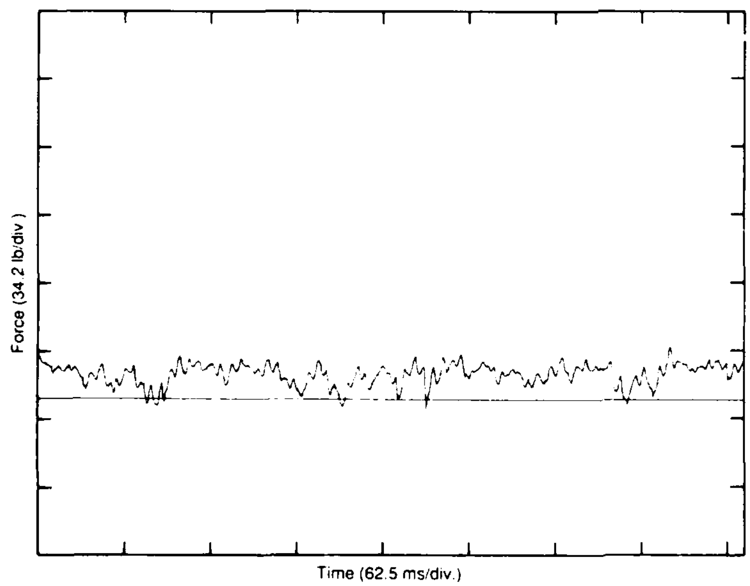
Typical horizontal and vertical force traces are shown in Figure 5. The horizontal force fluctuations consist primarily of two frequencies. The higher frequency, about 800 Hz, is the natural frequency of the cutter and dynamometer assembly. The lower frequency, which ranges from 20 to 80 Hz, is related to the formation of large chips in the ice and should vary with the cutter velocity. As the cutter presses into the ice, the force begins to rise and elastic energy is stored in the cutter assembly. Some of the energy is expended in local crushing as the force continues to rise. At some point in the penetration, the cutting force reaches a magnitude necessary to induce a major fracture. A crack propagates into the ice, releasing the cutter elastic energy and dislodging a major chip. The force then drops abruptly, sometimes to a negative value because of tool inertia, before the cycle repeats. The vertical forces generally did not produce the pronounced peaks observed with the horizontal forces. In this example the vertical depressions correspond in time to the peaks of the horizontal forces.

A typical velocity trace is shown in Figure 6. The trace oscillates at a mean frequency of about 200 Hz in this example, which can be attributed to the slip ring construction within the velocity transducer.

Each of the following curves was determined from five data points from five different depths of cut. Each data point represents an average of four tests. Since the rake angle was the only angle varied, the term "rake angle" is often omitted and is im-



a. Horizontal force.



b. Vertical force.

Figure 5. Typical force trace from run 30b (depth of cut = 0.200 in.; rake angle = 50°; velocity = 4.0 in./s).

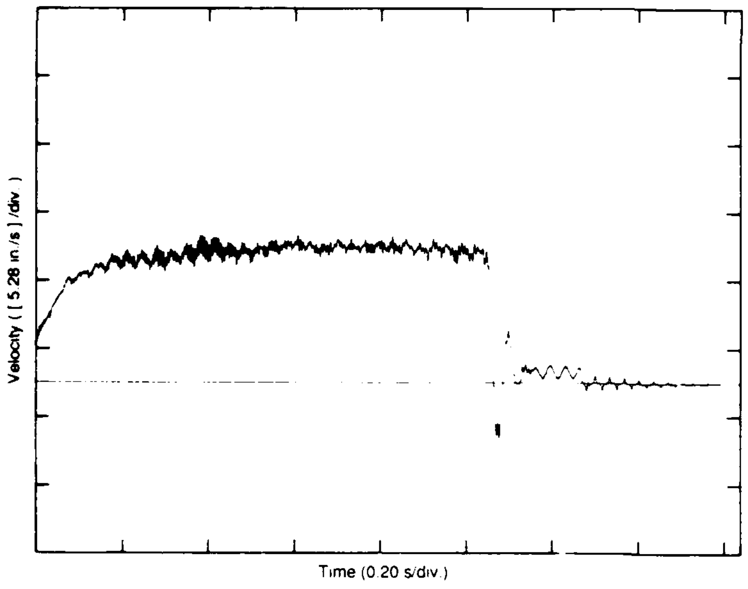


Figure 6. Typical velocity trace from run 35c (velocity = 10 in./s).

plied in the following discussions. Figure 7 shows the scatter of data points for some typical plots. All of the experimental results are presented in Appendix C.

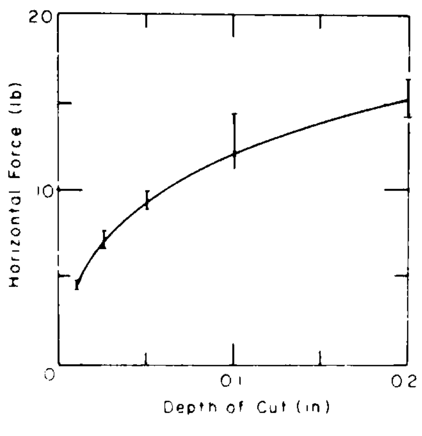
Figure 8 shows the contours of some typical fractures and the formation of some large chips, starting from a free surface.

Horizontal force

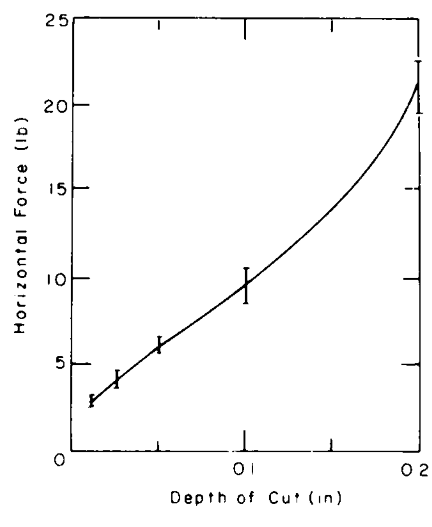
In many applications, the horizontal component of force is of prime interest since it determines the ploughing or dragging effort required of an excavating device, or the torque in the case of a drill. Plots of the average horizontal force versus depth of cut are shown in Figure 9.

For the depth of cut sequence progressing from the shallowest to the deepest cut (Fig. 9c–e), the forces show a small increase with depth for the 30, 50 and 60° cutters. For the opposite sequence—deepest to shallowest cut (Fig. 9a and b)—the curves are flatter for the same cutters. In all of the tests, the 0 and –5° cutters show a rapid rise in horizontal force with increased cutting depth. The –5° cutter forces were consistently higher in all cases, reaching a maximum of 67 lb at a depth of 0.200 in.

The effect of the depth of cut sequence is clearly visible in the shape of the excavation as the cutter proceeds through the ice. If the first cut is the deepest and on a free surface, fracture

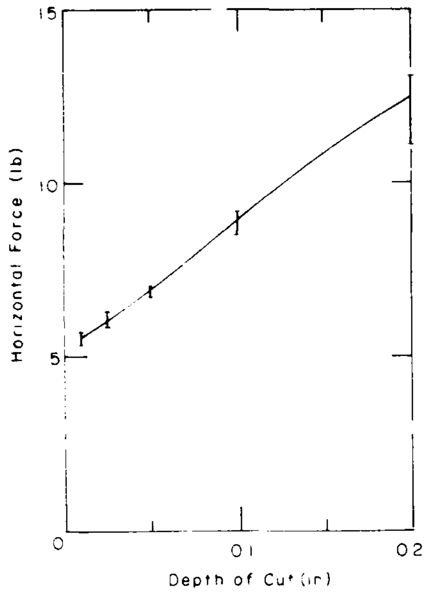


a. Runs 41c–60c.

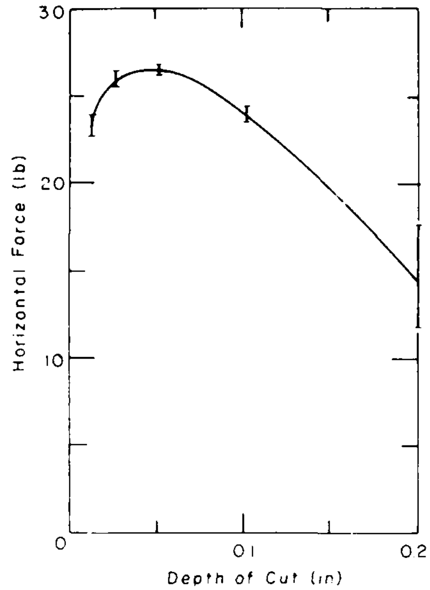


b. Runs 1d–20d.

Figure 7. Data scatter for some typical plots.



c. Runs 81c–100c.



d. Runs 21c–40c.

Figure 7 (cont'd). Data scatter for some typical plots.

a.

Figure 8. Fracture surface contours and the formation of some large chips. Cylindrical object is vacuum hose used to remove chips.

b.

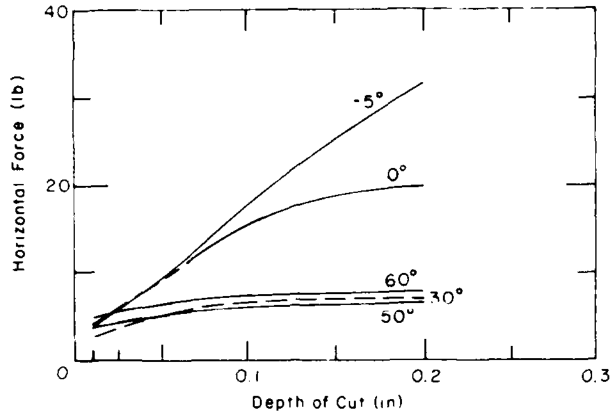
c.

Figure 8 (cont'd).

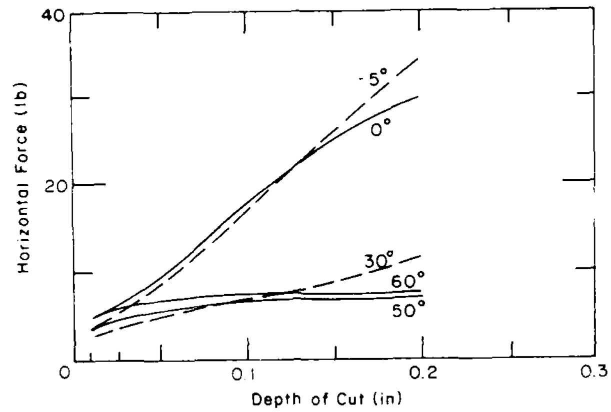
cracks frequently extended from the bottom of the cut diagonally to the surface of the sample, resulting in large chips and a groove cross section as in Figure 10. Chips from succeeding cuts were normally confined to the groove.

With the deepest cut last, fracture cracks propagated in all directions in front of the cutter but seldom did they extend to the free surface and release a large chip (Fig. 10). Changing to this sequence resulted in a 70 to 100% increase in the horizontal forces at the greater depths because of the added shearing forces. With either sequence, the existence of fractures from a previous cut undoubtedly influences the chip-forming process.

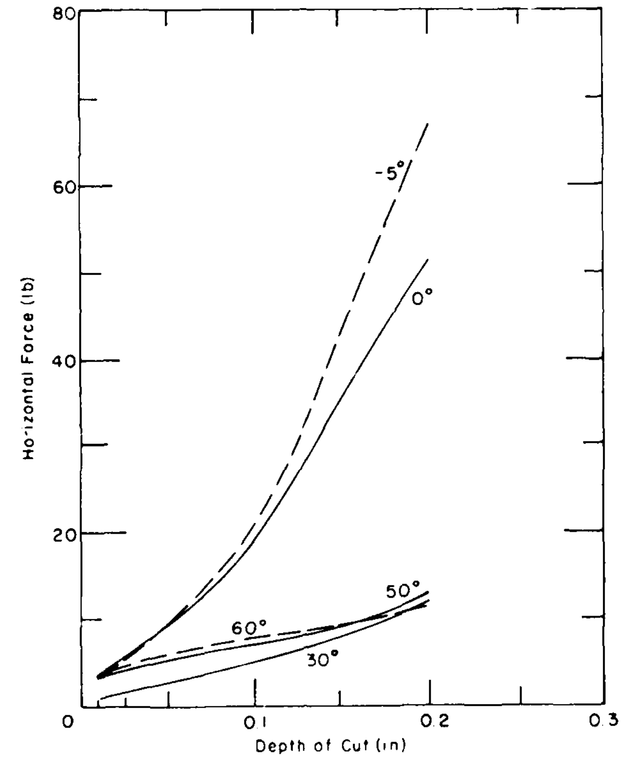
The effect of velocity on the horizontal force cannot be clearly discerned from the limited data. The 0 and –5° cutters do show an increase



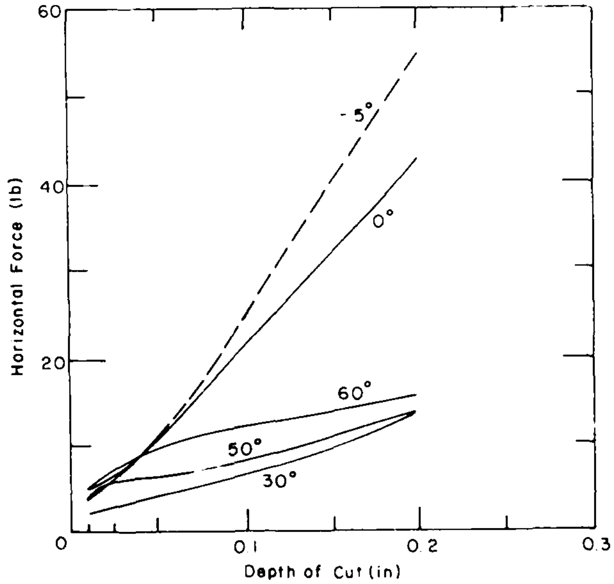
a. Velocity of 4.0 in./s; deepest cut first.



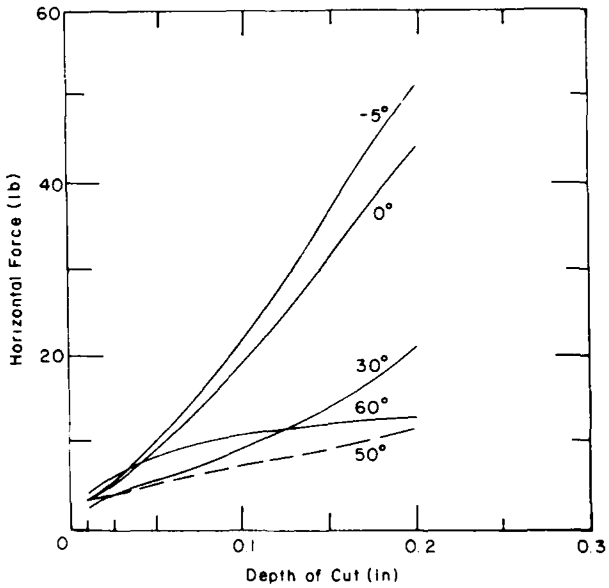
b. Velocity of 5.7 in./s; deepest cut first.



c. Velocity of 3.9 in./s; shallowest cut first.



d. Velocity of 10.1 in./s; shallowest cut first.



e. Velocity of 10.6 in./s; shallowest cut first.

Figure 9. Average horizontal force versus depth of cut. The dashed lines are used to help separate curves.

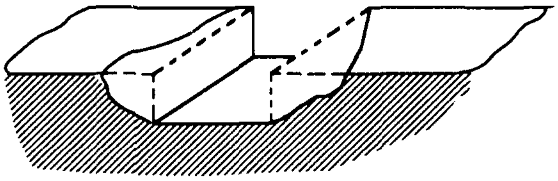
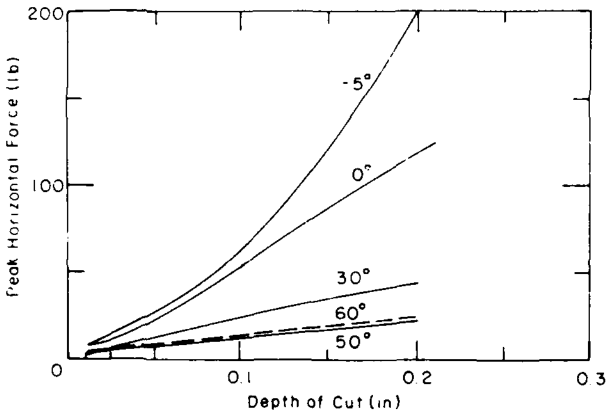
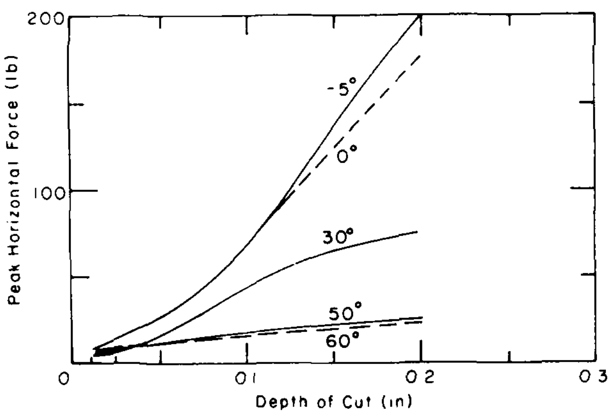


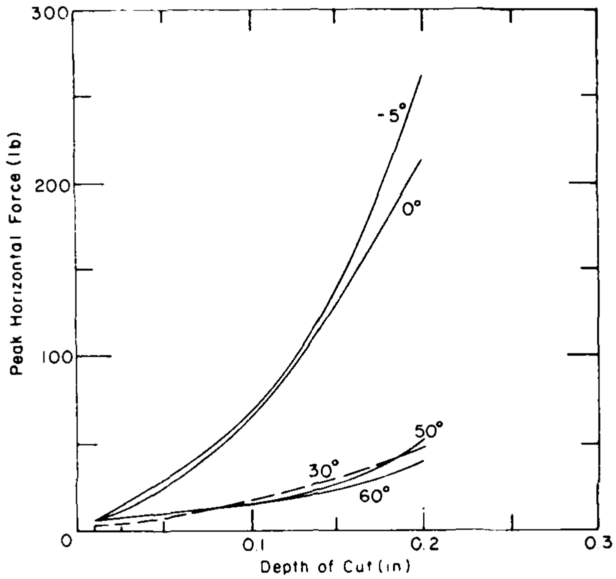
Figure 10. Typical cross sections of groove (solid line shows how it looks when the first cut is the deepest, dashed line when the last cut is the deepest).



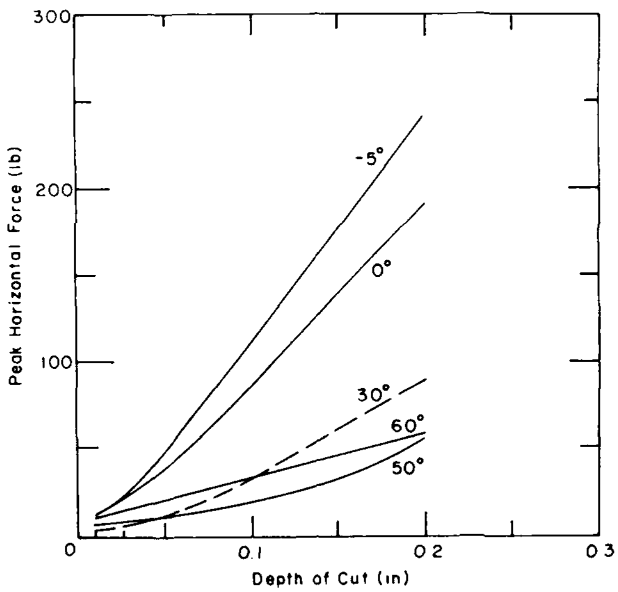
a. Velocity of 4.0 in. / s; deepest cut first.



b. Velocity of 5.7 in. / s; deepest cut first.



c. Velocity of 3.9 in. / s; shallowest cut first.



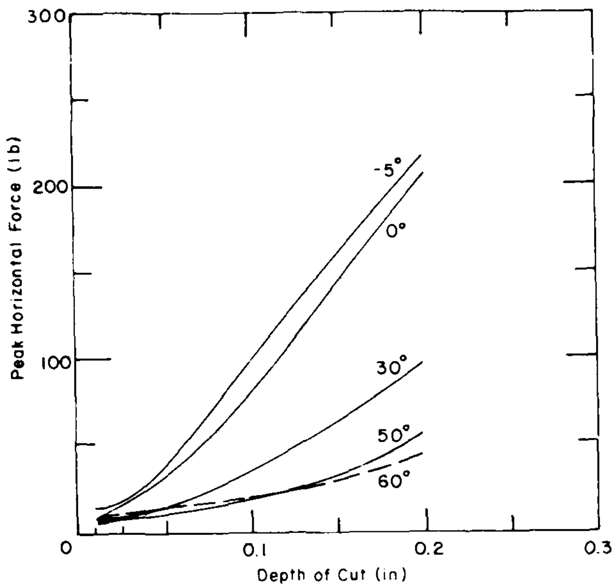
d. Velocity of 10.1 in. / s; shallowest cut first.

Figure 11. Peak horizontal forces versus depth of cut. The dashed lines are used to help separate the curves.

in force with decreasing velocity at the deeper cutting depths.

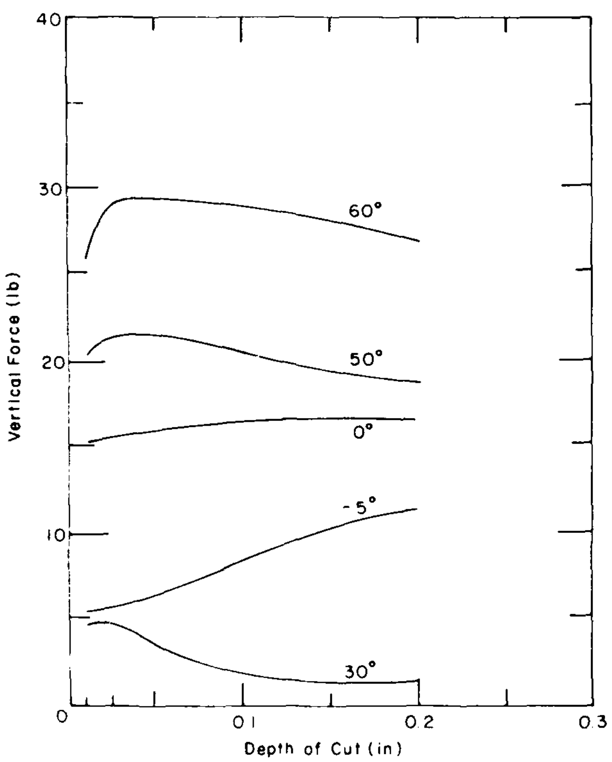
Peak horizontal force

Peak horizontal forces are of interest to the designer since they are the forces that a cutting tool and its holder must be strong enough to resist. For this investigation, the peak force represents the average of the five highest peaks over the length of a cutting run. The plots of the peak force versus depth of cut are shown in Figure 11. The –5 and 0° rake angle cutters produced the highest average peak forces at all depths of cut, with a maximum force in excess of 200 lb. In almost all cases, the 30° cutter force is consistently higher than the those of the 50 or 60°

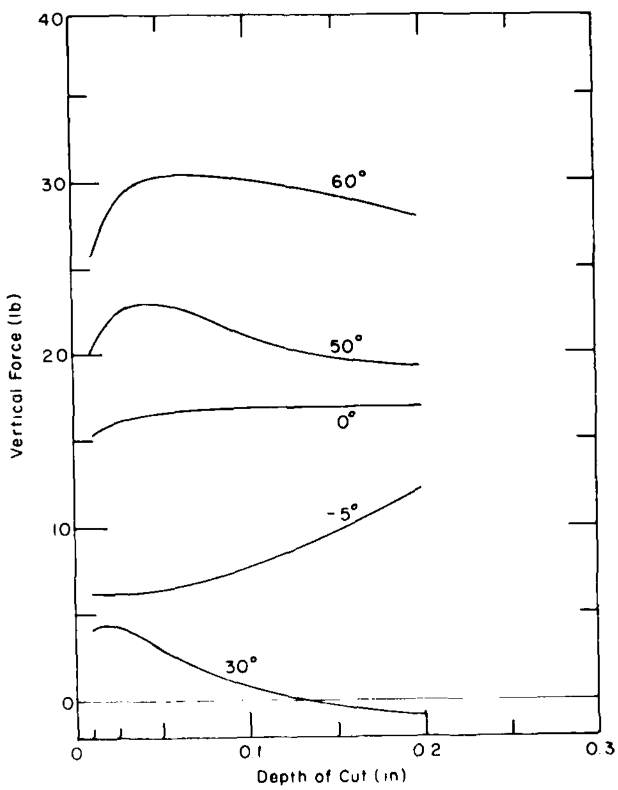


e. Velocity of 10.6 in. / s; shallowest cut first.

Figure 11 (cont'd). Peak horizontal forces versus depth of cut. The dashed lines are used to help separate the curves.

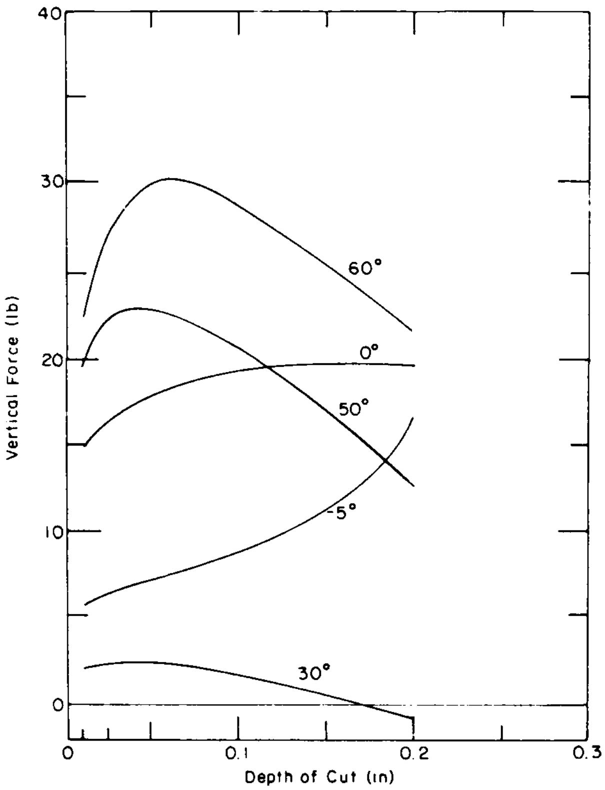


a. Velocity of 4.0 in. / s; deepest cut first.

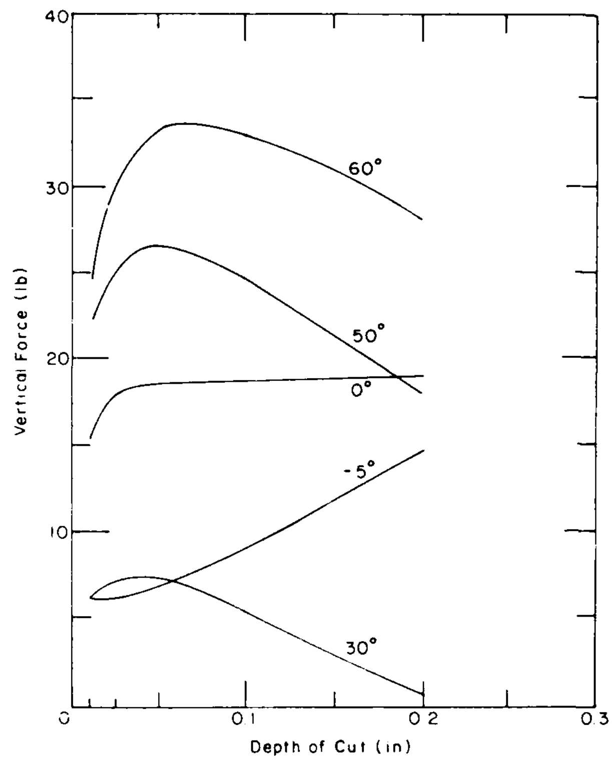


b. Velocity of 5.7 in. / s; deepest cut first.

Figure 12. Average vertical force versus depth of cut.

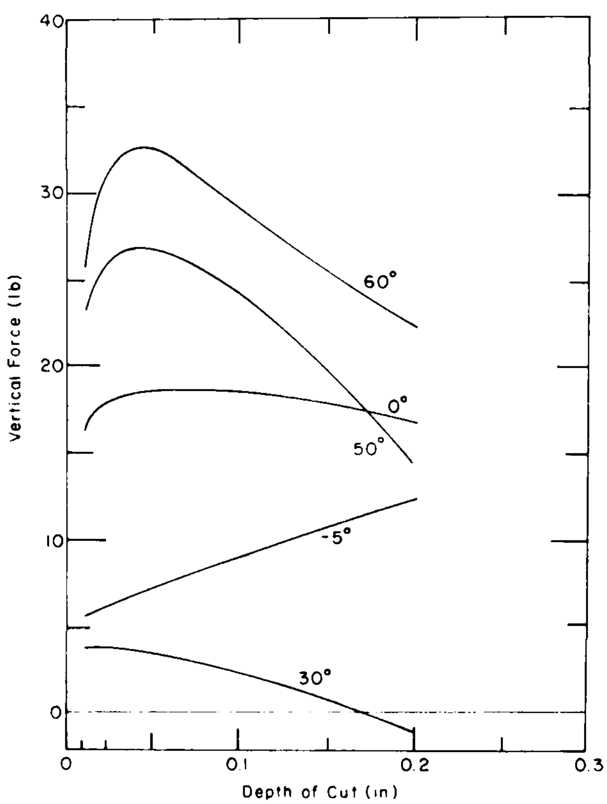


c. Velocity of 3.9 in. / s; shallowest cut first.



e. Velocity of 10.6 in. / s; shallowest cut first.

Figure 12 (cont'd).



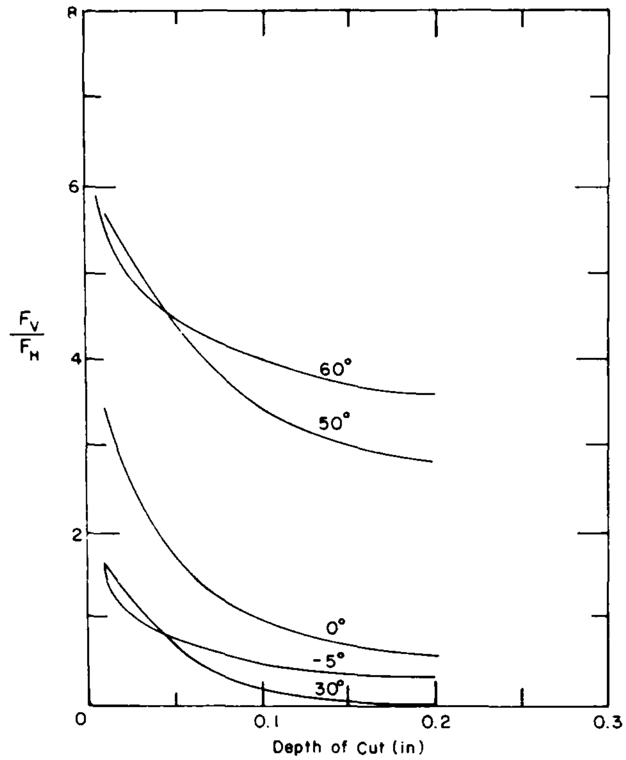
d. Velocity of 10.1 in. / s; shallowest cut first.

cutters at the greater depths of cut. At the 0.200-in. depth of cut, the 30° cutter has a peak force 4 to 6.7 times the average horizontal force (for example, compare Figures 9a and 11a).

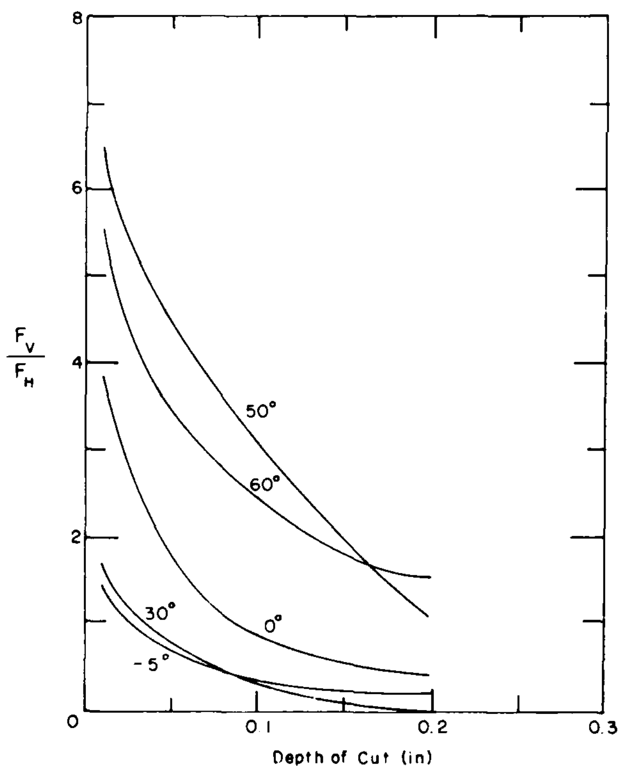
Vertical force

The vertical component of force is of interest to us since it could determine the amount of thrust that must be provided by the operator of a drill, for example, or by the weight of an excavating device. Figure 12 shows the plots of the average vertical component of force versus the depth of cut. The positive direction of force is up, towards the cutter. The curves are consistent, relative to each other for the same depth of cut sequence. The forces on the 50 and 60° rake angle cutters all peak around 0.025 to 0.050 in., then decrease with increased depths of cut. The curve for the 0° cutter stays relatively flat. It is interesting to note that the 30° rake angle cutter produces a negative force at the deepest cuts in three cases, i.e., it is being pulled into the material. Such an aggressive behavior may be desirable in some instances.

The surprising data are those for the 50 and 60° rake angle cutters. The 60° cutter produced



a. Average velocity of 5.7 in./s; deepest cut first.



b. Average velocity of 10.1 in./s; shallowest cut first.

Figure 13. Ratio of vertical to horizontal force versus depth of cut.

the highest vertical forces, with a maximum of [illegible] lb. At first we suspected errors in the testing technique or in the data reduction. However, each set of curves represents a different series of tests completed on different days. We thought it unlikely that the same errors in test procedure or data reduction could be consistently repeated. It is also evident that the depth of cut sequence has an effect on the shape of the curves for the 50 and 60° cutters. The effect of cutter velocity on the vertical force component is not clear from the data, at least in the range of velocities used here.

The ratio of the vertical to the horizontal forces with depth of cut is shown in Figure 13 for the two depth of cut sequences. Almost all of the curves have high values at the shallow depths and then approach a constant, lower value near the deepest cuts. The force ratio is an indication of the direction of the resultant force. Under similar conditions, with a rounded edged tool, a 15° rake angle and a 0.25-in. depth of cut, Peng (1958) obtained ratios that ranged from about 2 to 7.5, which are considerably higher than our results. The round edges used on his cutters may have accounted for this.

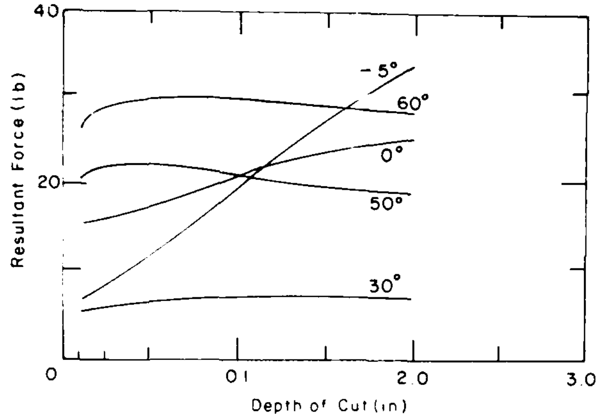
Resultant force

The resultant force plots versus cutting depth are shown in Figure 14. The 30, 50 and 60° cutters behave fairly consistently regardless of velocity or depth of cut sequence. The 30° cutter force rises to a maximum at the deepest cut. The 50 and 60° cutter forces peak around 0.050 in., then decrease with deeper cuts. The 0 and –5° cutter forces rise rapidly with increased cutting depth, particularly when the cutting sequence progresses from shallow to deep. The 30° cutter has the lowest resultant force in all cases.

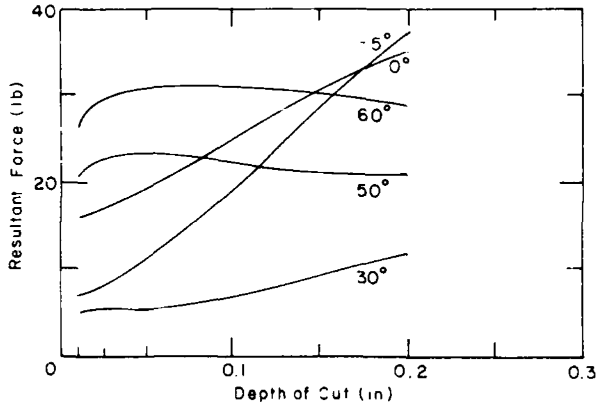
Average resultant force angles for one series of runs is shown in Figure 15. All runs used the same depth of cut sequence and had the same average velocity of 10 in./s. All of the angles decrease from the horizontal with increased cutting depths. It is difficult to explain the unexpected steep angles for the 50 and 60° rake angle cutters. The range of angles for this series was from –3 to 81°, with negative angles above the horizontal reference.

Specific energy

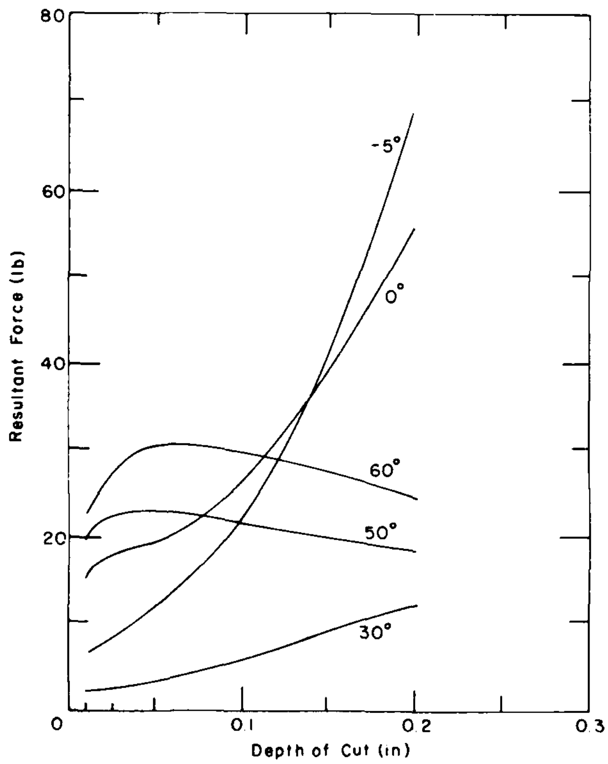
Specific energy is defined as the energy expended per unit volume of the material removed. It is based on the average horizontal force and an assumed cross-sectional area of cutter width by depth of cut. The plots of specific energy versus depth of cut are shown in Figure 16. The values



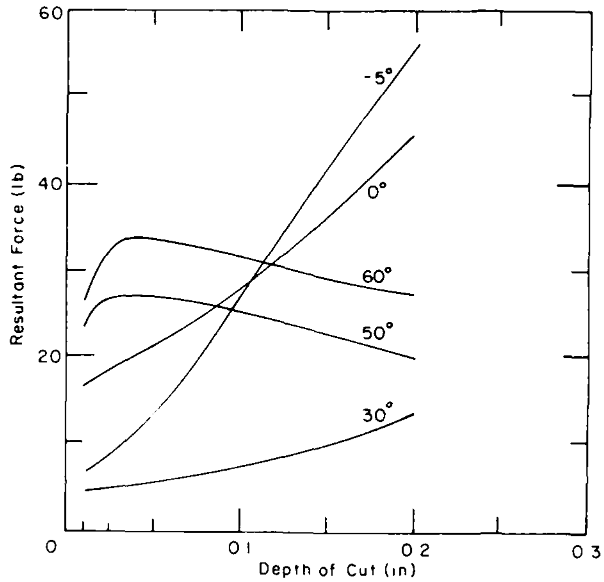
a. Velocity of 4.0 in. / s; deepest cut first.



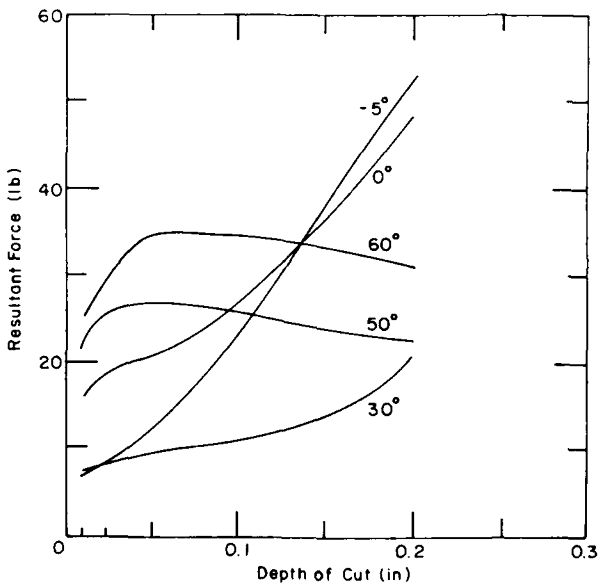
b. Velocity of 5.7 in. / s; deepest cut first.



c. Velocity of 3.9 in. / s; shallowest cut first.



d. Velocity of 10.1 in. / s; shallowest cut first.



e. Velocity of 10.6 in. / s; shallowest cut first.

Figure 14. Resultant force versus depth of cut.

are in the range found by past investigators (Peng 1952, Bailey 1967, Mazur 1974). The sharp increase in specific energy with a decrease in the depth of cut is not unusual. Shallow cuts are the least energy efficient, as the process is essentially a scraping action where more energy is used up in producing fine particles and overcoming friction. With deeper cuts, larger chips are formed with a resulting decrease in the ratio of surface area to volume. Proportionately less energy is used for crushing and overcoming friction.

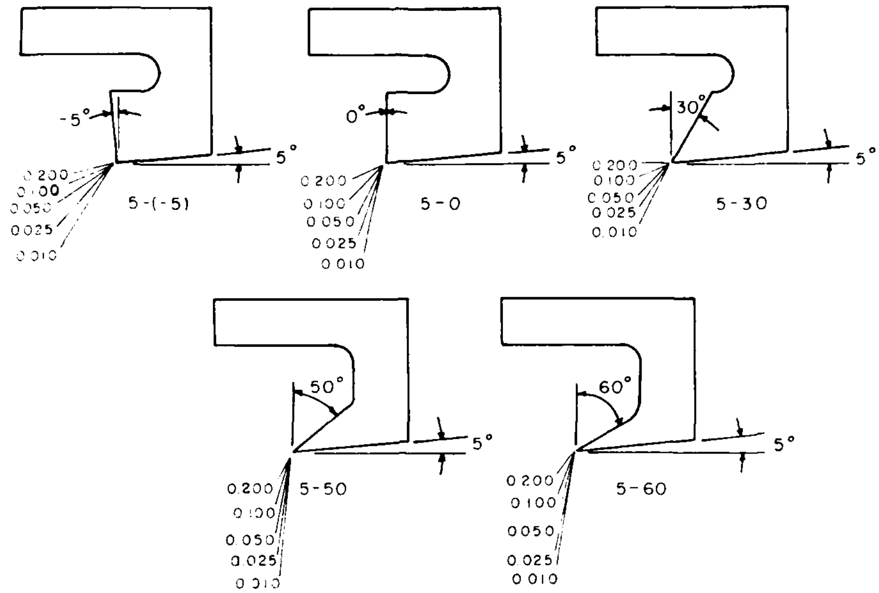
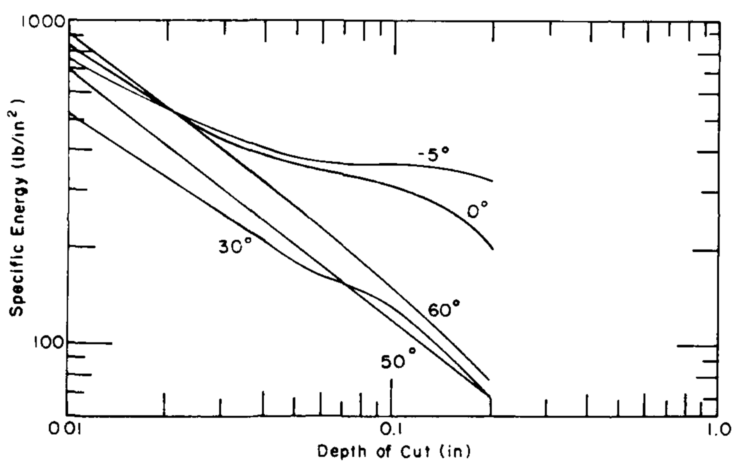
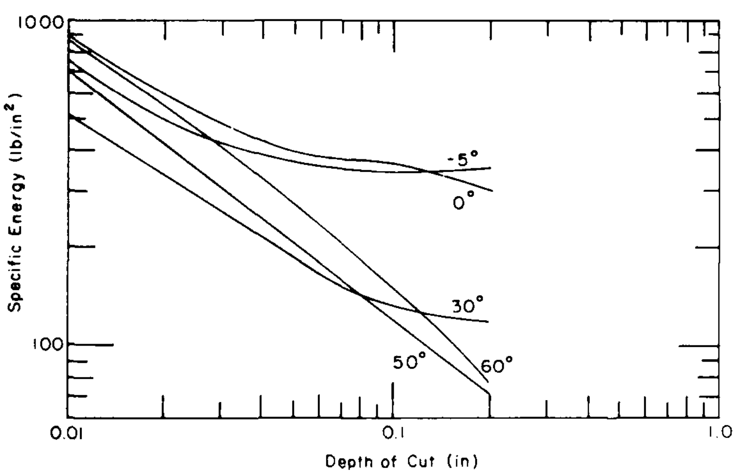


Figure 15. Average angle of resultant force for each cutter and depth of cut. Cutting sequence of 0.010 to 0.200 in.; velocity of 10 in. / s.

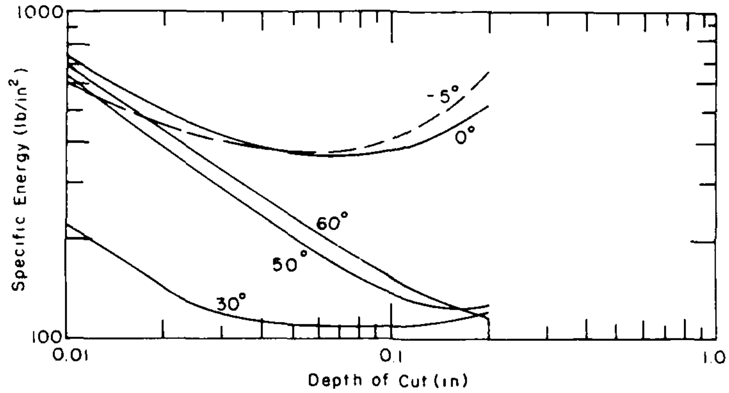


a. Velocity of 4.0 in. / s; deepest cut first.

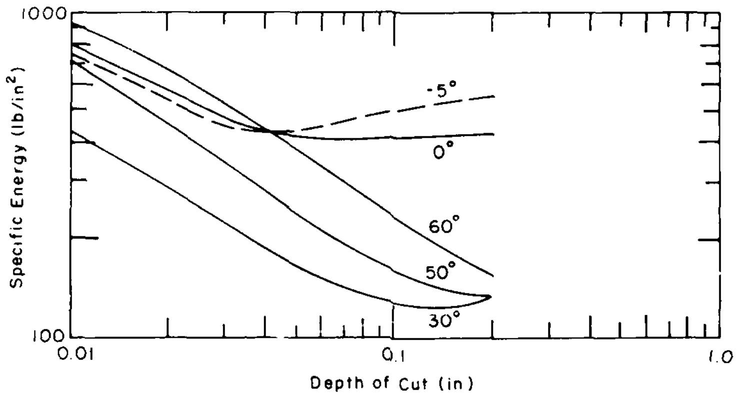


b. Velocity of 5.7 in. / s; deepest cut first.

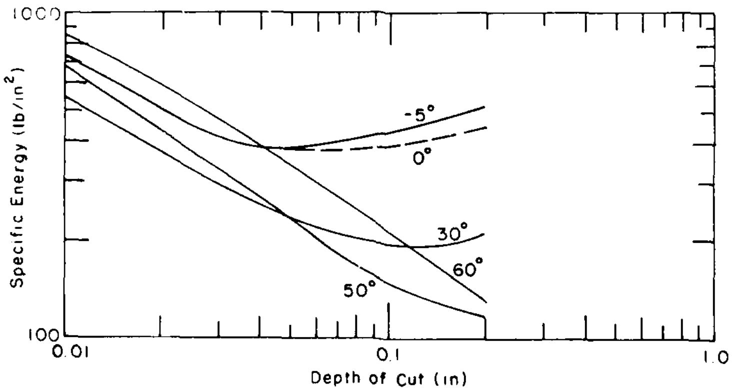
Figure 16. Specific energy versus depth of cut. The dashed lines are used to help separate curves.



c. Velocity of 3.9 in. / s; shallowest cut first.



d. Velocity of 10.1 in. / s; shallowest cut first.



e. Velocity of 10.6 in. / s; shallowest cut first.

Figure 16 (cont'd).

The 30° rake angle cutter has the lowest specific energy at the shallowest cuts, with the 50 and 60° rake angle cutters having values about the same or lower than the 30° cutter at the deepest cut. Unlike other investigators, we found that the specific energy of the 0 and –5° rake angle cutters tends to decrease with increased depths of cut to a minimum value, and then tends to level off or increase at greater depths of cut. In addition, it appears that there is a significant difference in the specific energy of the 0 and –5° cutters, depending upon whether the deepest cut is started from the surface or at the bottom of an existing groove. Apparently, when confined within an existing groove, the shear and friction forces are much higher, requiring higher horizontal forces and subsequently higher specific energy.

At the deepest cutting depth, the specific energy varied by a factor of about five from the lowest to the highest values over the range of the five rake angles. The 30, 50 and 60° cutters have significantly lower values than the 0 and –5° cutters in all tests.

It is generally accepted that adequately high strain rates to induce brittle behavior in frozen materials are desirable from an energy expenditure point of view, although the effect of strain rates on specific energy is not entirely clear. It apparently depends upon the type of failure—tension, compression or shear—and temperature. Haynes et al. (1975) found a slight increase in specific energy with increased strain rates up to 10^{-1} s^{-1} and constant specific energy levels thereafter, up to a strain rate 10^{1} s^{-1}, in compression tests on frozen silt. They found a slight decrease in specific energy with increased strain rates in tension tests.

The strain rates in our tests are obviously difficult to determine but a very rough estimate can be made by counting the major peaks on a typical test trace and assuming that each peak represents a major chip. From typical runs at 10 in./s, with a 0.200-in. cutting depth, 30 to 60 major chips per second have been observed, which corresponds to a time between failures of 0.015 to 0.030 seconds. Assuming a failure strain of 1%, we can calculate a strain rate of about 10^{0} to 10^{1} s^{-1}. Since the load rate is in reality quite unsteady, the time to failure is most likely several times faster than the average time to failure might indicate. Realistically, the actual strain rate is probably in the neighborhood of 10^{1} to 10^{2} s^{-1}.

SUMMARY AND CONCLUSIONS

The scope of these tests on cutting tools for natural lake ice was limited to the effects on the horizontal component of force, the vertical component of force and the specific energy of varying the cutter rake angle, the depth of cut and the velocity of cutting. Mostly tests were conducted within a groove cut by earlier tests. The action of a cutter in ice is essentially a series of impacts that dislodge large chips of various sizes, combined with fines from local crushing and scraping between impacts. A digital oscilloscope was employed to determine average and peak forces in these tests. Varying the parameters affected the cutter forces and specific energy, but not always as expected.

The sequence of cuts used, shallow to deep or vice versa, has a significant effect on the cutter force components. We observed a 70 to 100% increase in the horizontal component of force with deeper cuts when the sequence was from shallow to deep or when succeeding passes were confined to a previously cut groove.

The maximum average horizontal force was 67 lb with a –5° rake angle cutter. The maximum average peak horizontal force was in excess of 200 lb. The 30, 50 and 60° cutters produced the lowest horizontal forces.

The maximum average vertical force was 33 lb with a 60° rake angle cutter. The 30° cutter was the only one to produce a negative force, i.e., the cutter was pulled into the ice. It also produced the lowest force in most instances.

The 30, 50 and 60° cutters had significantly lower specific energy values than the 0 and –5° cutters in all tests. The 0 and –5° cutter specific energies were strongly affected by the depth of cut sequence. The strain rates for these tests were estimated to be 10^{1} to 10^{2} s^{-1}, which should have assured brittle behavior.

The effect of velocity on the cutter forces was not clearly evident, at least in the range of velocities employed. Future tests should include the effect of higher velocities. The effect of tool wear on cutter forces should also be examined since it is well known that dull tools can significantly increase the energy expended in fracturing brittle materials.

Although the scope of these tests was quite limited, we hope that these results will help fill a small void in the databank of experimental information needed to formulate a rational, empirical theory for designing parallel motion ice-cutting tools.

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APPENDIX A: CUTTER DYNAMOMETER DESIGN

A circular ring can be used to independently measure a vertical and a horizontal force with appropriately placed strain gauges. A more practical shape, although less sensitive, is to make the outer surface octagonal (Fig. A1), which provides more rigidity in the horizontal direction and also provides flat fastening surfaces. Strain gauges 1, 2, 3 and 4 detect the vertical strains and 5, 6, 7 and 8 detect the horizontal strains. No exact stress–strain solutions exist for this configuration but reasonable approximations can be obtained from

$$\varepsilon_{center} \approx 0.7 \frac{VR}{Ebt^2} \quad \text{(A1)}$$

$$\varepsilon_{45°} \approx 1.4 \frac{HR}{Ebt^2} \quad \text{(A2)}$$

$$\sigma_v \approx 3.7 \frac{VR^3}{Ebt^3} \quad \text{(A3)}$$

$$\sigma_h \approx 3.7 \frac{HR^3}{Ebt^3} \quad \text{(A4)}$$

where R = mean ring radius
E = modulus of elasticity
b = width of ring
t = thickness of ring
σ_v = vertical deflection attributable to V (see Fig. A1)
σ_h = horizontal deflection attributable to H (see Fig. A1)
ε_{center} = strain at center
$\varepsilon_{45°}$ = strain on the 45° face
V = vertical component of force
H = horizontal component of force.

An even more stable configuration with adequate sensitivity can be obtained by extending the ring as in Figure A2, which is the design that we used. Equations A1–A4 can still be used but will not include the bending effects if the extended length becomes large.

The sensitivity of the dynamometer turned out to be 0.5 mV/V at a full scale of 300 lb, which was lower than expected. This was mainly ascribable to the low gauge factor of the strain gauges used.

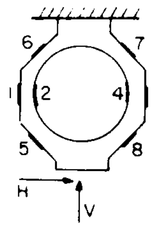

Figure A1. Octagonal ring dynamometer.

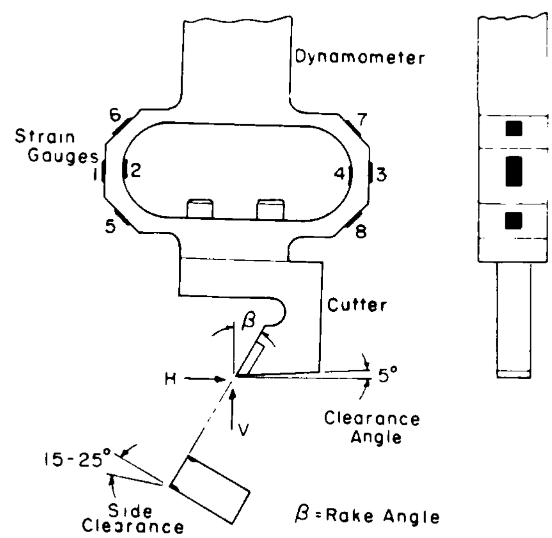

Figure A2. Extended octagonal ring dynamometer.

APPENDIX B: DATA REDUCTION

A Nicolet 4094 series digital oscilloscope was used for data reduction and analysis. The arithmetic mean of the horizontal and vertical forces and the average of the five highest horizontal peak forces recorded during a run were found and reported in the body of the report.

Analog data on the three tape recorder channels (horizontal force, vertical force and tool velocity) were digitized and stored on floppy disks for permanent record and later analysis. The original data were sampled at 2000 points per second on the Nicolet oscilloscope's 4562 plug-in-module, which uses 16-bit A/D converters. On the ±4-V full scale setting this allowed 0.122 mV resolution, far more resolution than the original tape recording justified. The sampling rate of 2 kHz satisfies our data analysis needs. Sharing the nearly 16,000 points available between two channels allowed a continuous signal of 3.97 seconds to be analyzed. Actual records varied in length from about 2 to slightly over 4 seconds. The three channels were digitized in two steps. First, horizontal and vertical force and then horizontal force and velocity were digitized and stored on floppy disk. Digitizing the three channels together would have meant sharing the available memory among four channels at a 1-kHz sampling rate. We originally felt that this sampling rate was too slow, but in retrospect, little information would have been lost.

In applying the Nyquist criterion, we see frequencies below 1 kHz will not be aliased. A preliminary analysis of the data with a HP 5420A digital signal analyzer showed the 2 kHz to be sufficient. Allowing eight samples per cycle, we should get good waveform reproduction up to 250 Hz. Although this was not the intent of the digitization process, the reproduced data appeared very similar to the original analog signals. To test the sampling process, several early tests were digitized at faster sampling rates and the arithmetic mean, the five high peaks, and the reproduced shape compared to the 2-kHz sampling rate. Although the faster sampling rates did not allow the entire test to be captured, the reproduced waveshape and the high peaks at both 5-kHz and 10-kHz sampling rates compared favorably with the slower sampling rate. Also there was no significant difference in the arithmetic means between the sampling rates when appreciable lengths of data were included.

In most instances the arithmetic mean reported in the body of the report includes the entire length of the test. In only a few instances did a test run over 4 seconds. In these instances, however, a sufficient length of data could be included and a good average reported.

The programs used to analyze the data are interactive in that they require operator intervention to set start and stop times. This slowed the process considerably, but avoided the problem of defining the length of the test for computer interpretation. Observation of the velocity was helpful in this.

APPENDIX C: EXPERIMENTAL DATA

Cutter 5-30   3 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
1	0.200	10.71	69.77	-0.65	5.25	107
2	0.100	6.42	29.95	2.02	5.23	128
3	0.050	4.28	12.23	3.31	5.30	171
4	0.025	3.59	7.08	4.38	5.28	287
5	0.010	2.59	4.49	4.37	5.33	518
6	0.200	9.86	60.62	-0.27	5.16	99
7	0.100	6.53	32.33	2.01		131
8	0.050	4.26	12.95	3.19	5.17	170
9	0.025	3.57	8.26	3.93		286
10	0.010	2.57	4.73	3.94	5.21	514
11	0.200	12.91	80.65	-1.18	5.16	129
12	0.100	7.00	30.28	1.46		140
13	0.050	4.66	15.11	3.13	5.22	186
14	0.025	3.66	8.22	4.96		293
15	0.010	2.52	4.64	4.52	5.19	504
16	0.200	13.77	87.70	-0.87	5.27	138
17	0.100	* 18.30	* 89.15	-1.76		366
18	0.050	4.65	16.13	2.90	5.28	186
19	0.025	3.60	8.73	4.17		288
20	0.010	2.38	4.56	3.86	5.32	476

*Omitted data for averaging

Cutter 5-50   8 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
21	0.200	7.12	26.73	20.37	5.60	71
22	0.100	6.94	16.79	21.62	5.54	139
23	0.050	5.22	8.46	25.67	5.70	209
24	0.025	4.42	7.46	22.95	5.70	354
25	0.010	3.37	5.91	19.81	5.65	674
26	0.200	6.69	24.58	19.55	5.22	67
27	0.100	5.93	15.84	20.89		119
28	0.050	5.18	10.58	22.36	5.60	207
29	0.025	4.46	8.24	22.22		357
30	0.010	3.55	6.14	20.25	5.59	710
31	0.200	6.73	25.16	19.62	5.56	67
32	0.100	5.84	15.95	21.08		117
33	0.050	4.93	9.84	22.36	5.60	197
34	0.025	4.21	7.87	21.77		337
35	0.010	3.80	6.97	19.98	5.60	760
36	0.200	7.34	26.36	18.16	5.58	73
37	0.100	6.14	17.72	20.42		123
38	0.050	4.90	11.09	21.68	5.59	196
39	0.025	4.20	8.36	21.68		336
40	0.010	3.45	6.30	20.15	5.60	690

Cutter 5-60 10 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
41	0.200	7.39	18.03	28.46	5.54	74
42	0.100	7.39	15.16	29.72	5.76	148
43	0.050	6.56	10.71	30.41	5.76	262
44	0.025	5.84	9.36	28.81	5.70	467
45	0.010	4.11	6.60	24.76	5.76	822
46	0.200	8.46	24.52	26.77	5.56	85
47	0.100	7.66	15.62	29.77		153
48	0.050	6.74	12.32	29.88	5.52	270
49	0.025	5.89	10.07	28.98		471
50	0.010	4.44	7.38	25.95	5.58	888
51	0.200	7.44	18.82	28.92	5.58	74
52	0.100	7.44	14.31	30.66		149
53	0.050	6.90	12.70	30.46	5.67	276
54	0.025	6.22	10.75	29.34		498
55	0.010	4.55	8.07	24.42	5.67	910
56	0.200	7.92	26.18	27.60	5.61	79
57	0.100	7.29	15.80	29.91		146
58	0.050	6.77	12.10	30.52	5.67	271
59	0.025	5.72	9.76	29.07		458
60	0.010	4.42	7.18	26.20	5.81	884

Cutter 5-0 10 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
61	0.200	36.96	161.46	18.35	6.22	370
62	0.100	19.74	65.90	16.68	6.31	395
63	0.050	10.99	28.43	16.64	6.35	440
64	0.025	7.50	15.62	16.17	6.37	600
65	0.010	4.80	8.56	13.77	6.32	960
66	0.200	34.74	217.71	15.58	5.44	347
67	0.100	17.82	60.59	17.05		356
68	0.050	9.31	27.91	16.60	5.57	372
69	0.025	6.56	14.60	16.69		525
70	0.010	4.53	8.06	15.46	5.59	906
71	0.200	27.42	157.23	17.55	5.58	274
72	0.100	18.12	77.72	17.07		362
73	0.050	9.31	27.61	16.91	5.64	372
74	0.025	5.93	13.54	16.17		474
75	0.010	4.36	8.14	16.37	5.69	472
76	0.200	22.70	156.89	16.62	5.59	227
77	0.100	16.75	61.66	17.15		335
78	0.050	8.85	28.65	19.68	5.71	354
79	0.025	5.82	14.06	15.67	5.72	466
80	0.010	4.28	8.14	16.07		856

Cutter 5-(-5)   11 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
81	0.200	38.62	209.80	11.82	6.23	386
82	0.100	17.42	67.21	7.69	6.27	384
83	0.050	9.22	26.06	6.09	6.22	369
84	0.025	5.70	14.43	6.04	6.38	456
85	0.010	3.99	8.02	6.14	6.39	798
86	0.200	42.22	241.29	14.49	5.43	422
87	0.100	17.02	64.34	8.12		340
88	0.050	9.07	26.72	6.49	5.63	363
89	0.025	5.53	14.59	6.07	5.60	442
90	0.010	3.46	7.59	6.52		692
91	0.200	34.42	172.22	12.87		344
92	0.100	18.20	69.90	8.34		364
93	0.050	8.97	29.02	6.69	5.61	359
94	0.025	5.63	15.18	6.52		450
95	0.010	3.31	7.64	6.12	5.63	662
96	0.200	25.67	172.35	10.07	5.57	257
97	0.100	14.76	61.40	7.74		295
98	0.050	8.97	25.76	6.69	5.69	359
99	0.025	5.49	14.75	5.39		439
100	0.010	4.13	8.55	5.87	5.59	826

Cutter 5-30   20 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
1a	0.200	6.34	31.44	1.55	3.65	63
2a	0.100	8.26	27.84	2.32		165
3a	0.050	5.60	12.32	3.96	3.71	224
4a	0.025	4.26	7.55	5.66		341
5a	0.010	2.82	4.23	5.60	3.73	564
6a	0.200	7.54	45.44	1.24	3.65	75
7a	0.100	6.25	25.16	2.06		125
8a	0.050	4.29	11.66	3.38		172
9a	0.025	3.40	6.60	4.66		272
10a	0.010	2.57	4.19	3.99		514
11a	0.200	7.07	40.51	1.30		71
12a	0.100	6.33	25.88	1.85	3.79	127
13a	0.050	4.14	11.31	3.25	3.80	166
14a	0.025	3.49	7.03	4.44		279
15a	0.010	2.54	4.49	4.74	3.77	508
16a	0.200	6.98	46.35	1.24	3.85	70
17a	0.100	5.95	26.24	1.82		119
18a	0.050	3.89	10.54	3.24	3.90	156
19a	0.025	3.24	7.00	4.62		259
20a	0.010	2.19	4.24	4.42	3.87	438

Cutter 5-50 20 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
21a	0.200	6.68	23.42	18.45	3.83	67
22a	0.100	5.80	14.07	20.20		116
23a	0.050	4.89	8.29	21.23		196
24a	0.025	4.14	6.39	21.20		331
25a	0.010	3.40	5.09	20.28		680
26a	0.200	6.30	20.92	19.49	3.75	63
27a	0.100	5.72	14.08	20.95		114
28a	0.050	4.98	8.49	21.69	3.80	199
29a	0.025	4.38	6.60	21.69		350
30a	0.010	3.57	5.36	20.70		714
31a	0.200	6.75	21.91	18.96	3.94	68
32a	0.100	5.99	14.10	20.43		120
33a	0.050	5.05	8.60	21.71		202
34a	0.025	4.19	6.91	21.34		335
35a	0.010	3.44	5.35	20.45		688
36a	0.200	7.19	26.06	17.75	4.02	72
37a	0.100	5.89	15.19	20.10		118
38a	0.050	4.92	8.47	20.77	4.02	197
39a	0.025	4.11	6.58	20.75		329
40a	0.010	3.36	5.27	19.53	4.05	672

Cutter 5-60 20 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
41a	0.200	8.21	27.19	26.16	3.99	82
42a	0.100	6.84	14.07	29.01		137
43a	0.050	6.30	10.16	29.40		252
44a	0.025	5.71	8.59	28.39		457
45a	0.010	4.39	6.47	25.85		878
46a	0.200	7.83	23.78	26.77	4.04	78
47a	0.100	7.16	14.22	29.17		143
48a	0.050	6.45	10.61	29.75	4.05	258
49a	0.025	5.82	8.52	28.86		466
50a	0.010	4.53	6.83	26.43	4.10	906
51a	0.200	7.51	20.66	27.63	4.06	75
52a	0.100	7.28	14.38	28.85		146
53a	0.050	6.45	10.11	29.38	4.09	258
54a	0.025	5.65	8.51	31.65		452
55a	0.010	4.34	6.68	25.45	4.13	868
56a	0.200	7.73	20.71	26.91	4.11	77
57a	0.100	7.41	13.82	28.20		148
58a	0.050	6.46	10.10	28.16	4.10	258
59a	0.025	5.61	8.49	27.20		449
60a	0.010	4.32	6.50	25.11	4.18	864

Cutter 5-0   20 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
61a	0.200	18.42	111.75	15.54	3.93	184
62a	0.100	15.56	46.39	16.23		311
63a	0.050	8.75	21.84	15.78		350
64a	0.025	6.10	11.50	16.16		488
65a	0.010	3.94	7.26	15.19		788
66a	0.200	16.62	111.04	15.90	4.06	166
67a	0.100	15.28	53.29	16.45		306
68a	0.050	9.10	21.58	16.20	4.00	364
69a	0.025	6.10	11.84	16.03		488
70a	0.010	4.16	8.06	15.23	4.11	832
71a	0.200	22.63	107.21	16.21	3.97	226
72a	0.100	16.53	58.36	16.78		331
73a	0.050	8.72	22.43	15.90	4.12	349
74a	0.025	6.00	11.86	15.25		480
75a	0.010	4.34	7.64	16.00	4.14	868
76a	0.200	21.14	139.63	16.99	4.14	211
77a	0.100	16.19	53.31	16.53		324
78a	0.050	8.38	20.83	15.27	4.17	335
79a	0.025	5.66	12.24	14.44		453
80a	0.010	4.09	8.25	14.30	4.18	818

Cutter 5-(-5)   20 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
81a	0.200	37.62	184.41	12.92	4.18	376
82a	0.100	18.74	60.91	8.11		375
83a	0.050	9.21	23.22	6.14		368
84a	0.025	6.00	13.73	5.84		480
85a	0.010	3.55	7.21	5.20		710
86a	0.200	32.90	195.19	11.03	4.14	329
87a	0.100	18.40	62.95	8.55		368
88a	0.050	9.30	27.80	6.68	4.15	372
89a	0.025	6.04	12.97	6.15		483
90a	0.010	3.73	7.50	5.67	4.15	746
91a	0.200	24.64	204.20	9.81	4.13	246
92a	0.100	16.91	61.96	8.14		338
93a	0.050	9.61	25.41	6.58	4.22	384
94a	0.025	5.96	12.66	5.58		477
95a	0.010	3.75	7.85	5.40	4.26	750
96a	0.200	33.19	199.78	11.66	4.14	332
97a	0.100	18.22	62.09	8.52		364
98a	0.050	9.08	25.39	6.29	4.26	363
99a	0.025	5.87	13.75	5.67		470
100a	0.010	3.56	7.51	5.36	4.26	712

Cutter 5-30 27 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
1b	0.010	1.19	2.37	1.94	3.76	238
2b	0.025	1.78	3.81	2.05		143
3b	0.050	2.86	7.85	2.24		114
4b	0.100	5.79	16.62	1.62		116
5b	0.200	15.73	53.15	-1.14		157
6b	0.010	1.02	1.97	1.74	3.78	204
7b	0.025	1.42	3.39	1.77		114
8b	0.050	2.30	6.60	2.01	3.80	92
9b	0.100	4.18	17.52	1.30		836
10b	0.200	7.78	42.38	-0.48	3.74	78
11b	0.010	1.12	2.33	2.05	3.83	224
12b	0.025	1.79	4.10	2.21		143
13b	0.050	2.99	7.73	2.49	3.82	120
14b	0.100	5.74	19.43	1.87		115
15b	0.200	11.44	48.90	-0.50	3.81	114
16b	0.010	1.19	2.47	2.27	3.88	238
17b	0.025	2.03	4.33	2.58		162
18b	0.050	3.23	7.55	2.81	3.90	129
19b	0.100	5.81	17.34	2.03		116
20b	0.200	13.37	47.12	-0.50	3.92	134

Cutter 5-50 27 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
21b	0.010	3.10	5.19	16.99		620
22b	0.025	4.45	7.00	22.57		356
23b	0.050	5.69	9.62	22.82		228
24b	0.100	7.74	16.05	20.13		155
25b	0.200	14.26	57.56	10.95	3.97	143
26b	0.010	3.20	5.20	20.32	3.91	640
27b	0.025	3.95	6.74	22.44		316
28b	0.050	5.08	9.08	22.89	3.93	203
29b	0.100	6.88	15.67	20.54		138
30b	0.200	12.43	49.54	13.41	3.93	124
31b	0.010	3.30	5.28	20.66	3.98	660
32b	0.025	4.03	7.04	22.54		322
33b	0.050	5.04	9.38	22.36	4.00	202
34b	0.100	6.96	15.73	20.37		139
35b	0.200	14.17	55.73	11.80	3.90	142
36b	0.010	3.02	4.81	19.51	4.01	604
37b	0.025	3.87	6.30	21.55		310
38b	0.050	4.59	8.11	21.98	4.04	184
39b	0.100	5.84	13.85	20.64		117
40b	0.200	10.57	44.64	14.88	4.01	106

Cutter 5-60 27 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
41b	0.010	3.04	5.67	20.63		608
42b	0.025	4.72	7.78	28.27		378
43b	0.050	6.20	10.32	30.13		248
44b	0.100	8.77	18.04	28.12		175
45b	0.200	12.58	45.26	19.62	3.99	126
46b	0.010	3.06	5.03	21.42	3.98	612
47b	0.025	4.88	7.94	28.74		390
48b	0.050	5.99	10.19	30.80	4.06	240
49b	0.100	7.52	14.16	28.93		150
50b	0.200	11.16	35.68	22.52	4.02	112
51b	0.010	3.53	5.86	23.67	4.00	706
52b	0.025	4.67	7.57	28.17		374
53b	0.050	5.87	9.56	30.08	4.09	235
54b	0.100	7.45	14.96	29.08		149
55b	0.200	11.42	37.56	21.98	4.03	114
56b	0.010	3.55	6.04	23.42	4.07	710
57b	0.025	4.51	7.51	23.31		361
58b	0.050	5.78	10.02	29.09	4.08	231
59b	0.100	7.73	14.35	28.28		155
60b	0.200	11.28	37.51	21.96	4.02	113

Cutter 5-0 27 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
61b	0.010	3.54	9.33	14.29		708
62b	0.025	5.61	11.55	17.56		449
63b	0.050	8.96	23.79	17.41		358
64b	0.100	19.08	64.54	18.04	4.01	382
65b	0.200	50.54	229.57	17.51		505
66b	0.010	3.66	7.99	14.25	3.72	732
67b	0.025	5.72	12.77	17.16		458
68b	0.050	9.26	24.51	17.22	3.59	370
69b	0.100	20.02	62.58	17.33		400
70b	0.200	56.50	215.75	20.82	3.46	565
71b	0.010	3.54	8.11	14.90	3.63	708
72b	0.025	5.37	11.45	16.90		430
73b	0.050	8.73	24.38	16.99	3.62	349
74b	0.100	17.99	76.73	23.26		360
75b	0.200	53.95	204.02	19.96	3.60	540
76b	0.010	3.84	8.35	15.66	3.72	768
77b	0.025	5.68	12.35	17.09		454
78b	0.050	9.07	25.69	16.76	3.68	363
79b	0.100	18.49	64.38	17.41		370
80b	0.200	49.11	211.43	20.32	3.68	491

Cutter 5-(-5)   27 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
81b	0.010	3.03	6.73	5.62		606
82b	0.025	5.46	12.51	6.85		437
83b	0.050	9.52	26.55	7.53		381
84b	0.100	20.91	67.24	8.60	3.77	418
85b	0.200	59.56	259.24	11.29		596
86b	0.010	2.66	6.39	5.12	3.75	532
87b	0.025	4.97	13.20	6.26		398
88b	0.050	8.91	32.04	6.86	3.74	356
89b	0.100	20.21	69.72	8.81		404
90b	0.200	68.13	243.28	18.31	3.64	681
91b	0.010	3.16	8.24	5.82	3.79	632
92b	0.025	5.38	14.15	6.35		430
93b	0.050	9.55	26.66	6.98	3.80	382
94b	0.100	20.63	63.71	8.84		413
95b	0.200	70.37	257.13	18.56	3.67	704
96b	0.010	3.16	8.42	6.22	3.79	632
97b	0.025	5.29	12.91	6.28		423
98b	0.050	9.49	30.24	6.83	3.85	380
99b	0.100	20.84	72.28	9.05		417
100b	0.200	69.36	287.12	18.52	3.74	694

Cutter 5-30   31 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
1c	0.010	2.32	4.48	3.83	10.01	464
2c	0.025	3.22	6.53	3.70		258
3c	0.050	4.69	12.90	4.05		188
4c	0.100	7.71	35.70	2.16		154
5c	0.200	15.81	88.85	-2.02		158
6c	0.010	2.30	4.46	4.02	10.09	460
7c	0.025	3.17	6.38	3.83		254
8c	0.050	4.21	14.34	3.41	9.96	168
9c	0.100	6.48	33.46	2.35		130
10c	0.200	11.37	98.10	-0.19	9.87	114
11c	0.010	2.31	4.47	3.80		462
12c	0.025	3.00	6.67	3.66		240
13c	0.050	3.83	11.78	3.29	9.76	153
14c	0.100	5.78	26.78	2.11		116
15c	0.200	11.31	77.94	-0.14	9.91	113
16c	0.010	1.80	3.94	3.17	10.02	380
17c	0.025	2.74	5.78	3.60		219
18c	0.050	3.76	11.35	3.24	10.29	150
19c	0.100	6.10	31.52	1.99		122
20c	0.200	15.33	92.67	-1.41	10.15	153

Cutter 5-50 31 Dec. 1981

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
21c	0.010	3.59	6.37	22.64		718
22c	0.025	4.81	8.09	26.45		385
23c	0.050	5.86	10.17	26.50		234
24c	0.100	7.49	17.80	24.41	10.12	150
25c	0.200	11.72	51.29	17.49		117
26c	0.010	3.41	6.08	22.88	10.82	682
27c	0.025	4.60	7.79	26.39		368
28c	0.050	5.93	9.93	26.38	10.06	237
29c	0.100	7.90	21.54	23.84		158
30c	0.200	13.17	54.40	14.51	10.01	132
31c	0.010	3.49	6.53	23.59	10.13	698
32c	0.025	4.66	7.73	26.37		373
33c	0.050	5.81	9.93	26.90	10.09	232
34c	0.100	8.06	18.81	24.41		161
35c	0.200	14.77	58.19	14.77	10.01	148
36c	0.010	3.72	6.45	23.47	10.19	744
37c	0.025	5.50	7.99	25.74		440
38c	0.050	6.13	10.39	26.48	10.11	245
39c	0.100	8.31	18.38	24.06		166
40c	0.200	15.39	66.99	11.88	10.01	154

Cutter 5-60 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
41c	0.010	4.31	9.65	23.71	9.89	862
42c	0.025	7.57	14.00	32.38		606
43c	0.050	9.95	18.05	32.72		398
44c	0.100	14.47	54.02	24.44		289
45c	0.200	16.00	60.86	23.06		160
46c	0.010	4.52	10.33	25.27	10.05	904
47c	0.025	7.32	14.49	31.69		586
48c	0.050	9.26	19.19	32.55	9.67	370
49c	0.100	11.18	25.37	31.00		224
50c	0.200	16.43	56.44	20.21	9.98	164
51c	0.010	4.84	11.10	26.96	9.83	968
52c	0.025	7.31	16.25	32.05		585
53c	0.050	9.31	18.26	32.53	9.99	372
54c	0.100	11.36	25.77	31.04		227
55c	0.200	14.90	60.79	23.63	9.99	149
56c	0.010	4.79	11.17	26.44	10.18	958
57c	0.025	6.77	14.28	30.27		542
58c	0.050	9.12	17.82	32.14	10.07	365
59c	0.100	11.15	22.29	30.12		223
60c	0.200	14.22	58.68	23.43	10.10	142

Cutter 5-0 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
61c	0.010	4.64	10.96	16.57	10.23	928
62c	0.025	6.92	20.05	18.52		554
63c	0.050	11.05	47.55	18.96		442
64c	0.100	23.31	82.83	19.70		466
65c	0.200	44.00	212.47	16.91		440
66c	0.010	4.05	11.34	15.80	10.26	810
67c	0.025	6.35	20.58	18.09		508
68c	0.050	10.17	30.27	18.25	10.14	407
69c	0.100	19.56	85.68	17.80		391
70c	0.200	40.40	170.84	17.14	9.88	404
71c	0.010	4.11	10.66	15.74	10.18	822
72c	0.025	5.94	19.72	17.29		475
73c	0.050	10.14	40.13	18.38	10.13	406
74c	0.100	19.57	86.50	17.83		391
75c	0.200	43.60	195.82	16.85	9.85	436
76c	0.010	4.28	12.15	17.04	10.19	856
77c	0.025	6.35	19.89	18.30		508
78c	0.050	10.31	36.88	18.57	10.11	412
79c	0.100	20.85	78.97	19.10		417
80c	0.200	41.53	189.02	16.87	9.91	415

Cutter 5-(-5) 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
81c	0.010	3.71	9.67	5.47	10.27	742
82c	0.025	5.53	23.35	5.88		442
83c	0.050	10.15	46.91	6.75		406
84c	0.100	24.71	125.06	8.46		494
85c	0.200	52.43	228.46	11.10		524
86c	0.010	3.65	11.13	5.34	10.11	730
87c	0.025	6.27	21.65	6.26		502
88c	0.050	11.01	45.53	7.02	10.09	440
89c	0.100	26.44	99.99	9.11		529
90c	0.200	57.89	243.32	12.94	9.68	579
91c	0.010	3.82	10.04	5.67	10.14	764
92c	0.025	6.22	23.61	6.41		498
93c	0.050	10.67	45.06	7.09	10.10	427
94c	0.100	23.49	115.81	9.05		470
95c	0.200	54.48	237.83	12.80	9.68	545
96c	0.010	3.60	12.79	5.66	10.23	720
97c	0.025	6.12	21.12	6.16		490
98c	0.050	10.98	46.86	7.00	10.13	439
99c	0.100	25.21	104.39	9.20		504
100c	0.200	54.54	258.62	13.07	9.74	545

Cutter 5-30 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
1d	0.010	2.71	5.02	6.71	10.66	542
2d	0.025	4.11	8.12	7.50		355
3d	0.050	5.48	14.16	7.33	10.59	219
4d	0.100	8.54	34.51	5.33		171
5d	0.200	18.30	94.35	0.80	10.44	183
6d	0.010	2.66	5.29	5.80	10.69	532
7d	0.025	3.99	7.68	6.90		319
8d	0.050	5.62	13.43	7.16	10.68	225
9d	0.100	9.56	37.48	5.28		191
10d	0.?00	22.26	91.66	0.69	10.54	223
11d	0.010	3.03	5.53	6.52	10.76	606
12d	0.025	4.49	8.92	7.88		359
13d	0.050	6.49	15.39	7.98	10.67	260
14d	0.100	10.56	37.15	5.79		211
15d	0.200	21.88	89.80	1.01	10.56	219
16d	0.010	2.53	5.30	5.76	10.82	506
17d	0.025	3.72	7.48	6.42		298
18d	0.050	5.71	16.15	7.07	10.69	228
19d	0.100	9.33	37.15	5.32		187
20d	0.200	21.70	98.30	1.26	10.61	217

Cutter 5-50 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
21d	0.010	3.40	6.98	22.30	10.57	680
22d	0.025	4.50	8.09	25.60		360
23d	0.050	5.71	16.18	26.80	10.69	228
24d	0.100	7.38	18.64	24.96		148
25d	0.200	11.67	58.28	17.99	10.59	117
26d	0.010	3.71	7.19	22.55	10.73	742
27d	0.025	4.78	8.84	25.50		382
28d	0.050	6.20	10.69	26.53	10.74	248
29d	0.100	7.78	18.08	24.48		156
30d	0.200	13.40	56.33	16.98	10.66	134
31d	0.010	3.35	6.28	21.82	10.83	670
32d	0.025	4.39	9.10	25.16		351
33d	0.050	5.51	10.60	26.31	10.78	220
34d	0.100	7.00	17.50	24.32		140
35d	0.200	10.81	48.21	18.30	10.71	108
36d	0.010	3.47	7.26	22.09	10.82	694
37d	0.025	4.50	8.22	25.39		360
38d	7.350	5.52	9.94	26.20	10.78	221
39d	0.100	7.35	17.76	24.07		147
40d	0.200	10.83	53.09	18.40	10.81	108

Cutter 5-60 3 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
41d	0.010	4.13	8.80	24.52	10.63	826
42d	0.025	6.29	12.86	30.73		503
43d	0.050	8.45	17.00	33.36	10.62	338
44d	0.100	10.55	18.50	32.84		211
45d	0.200	13.27	38.01	27.90	10.62	133
46d	0.010	4.12	9.15	24.59	10.86	824
47d	0.025	6.39	16.62	28.07		511
48d	0.050	8.13	14.80	33.84	10.75	325
49d	0.100	10.33	18.68	33.81		207
50d	0.200	12.37	38.05	28.97	10.70	124
51d	0.010	4.45	9.38	24.85	10.82	890
52d	0.025	6.49	14.34	30.02		519
53d	0.050	8.10	15.61	32.55	10.79	324
54d	0.100	10.17	19.99	31.83		203
55d	0.200	13.17	44.00	27.17	10.64	132
56d	0.010	4.35	10.61	24.93	10.87	870
57d	0.025	6.43	12.66	31.26		514
58d	0.050	8.32	15.48	33.82	10.84	333
59d	0.100	10.68	19.60	33.17		214
60d	0.200	13.83	42.50	28.32	10.71	138

Cutter 5-0 4 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
61d	0.010	3.60	7.97	14.23	10.46	720
62d	0.025	5.44	14.29	18.47		435
63d	0.050	9.00	32.29	19.15	10.32	360
64d	0.100	19.88	67.29	19.74		398
65d	0.200	45.90	187.73	18.66	9.93	459
66d	0.010	3.77	12.53	16.11	10.53	754
67d	0.025	5.29	14.29	17.96		423
68d	0.050	8.75	30.26	17.96	10.41	350
69d	0.100	18.05	74.00	18.06		361
70d	0.200	42.09	179.97	19.15	10.41	421
71d	0.010	3.39	7.98	14.73	10.49	678
72d	0.025	5.68	14.05	18.02		454
73d	0.050	9.72	32.40	18.46	10.49	389
74d	0.100	19.77	75.43	19.11		395
75d	0.200	47.34	183.64	18.74	10.11	473
76d	0.010	3.87	10.87	16.15	10.62	774
77d	0.025	5.69	15.34	17.51		455
78d	7.350	9.54	29.10	18.42	10.50	382
79d	0.100	19.42	80.22	18.75		388
80d	0.200	41.42	234.65	19.79	10.20	414

Cutter 5-(-5)   4 Jan. 1982

Run No.	Depth of cut (in.)	Horizontal Force (lb)	Peak Horizontal Force (lb)	Vertical Force (lb)	Velocity (in./s)	Specific Energy (lb/in.^2)
81d	0.010	3.88	8.60	5.99	10.54	776
82d	0.025	5.83	17.05	6.10		466
83d	0.050	10.12	37.55	7.17	10.38	405
84d	0.100	22.32	88.37	9.15		446
85d	0.200	49.65	188.13	13.45	10.11	497
86d	0.010	3.75	19.77	6.39	10.69	750
87d	0.025	5.57	20.97	6.11		446
88d	0.050	9.46	36.92	6.89	10.55	378
89d	0.100	22.31	91.31	9.23		446
90d	0.200	52.77	238.13	16.16	10.14	528
91d	0.010	3.30	9.65	6.08	10.61	660
92d	0.025	5.29	18.94	6.23		423
93d	0.050	9.54	37.21	7.06	10.59	382
94d	0.100	20.04	105.55	8.93		400
95d	0.200	53.19	229.75	15.33	10.04	532
96d	0.010	3.54	8.46	6.55		708
97d	0.025	5.69	18.03	6.36		455
98d	0.050	9.19	38.75	7.18	10.57	368
99d	0.100	20.93	83.02	8.94		419
100d	0.200	49.21	207.21	14.69	10.34	492

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Experiments on the cutting process in ice / by Herbert T. Ueda and John Kalafut. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1989.

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