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ENGINEERING RESEARCH INSTITUTE  
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REPORT NO. 3

EFFECT OF SIDE RAKE ANGLE ON TOOL LIFE IN TURNING TITANIUM  
(HIGH-SPEED-STEEL TOOLS)

By

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Project M993

U. S. ARMY, ORDNANCE CORPS  
CONTRACT NO. DA-20-018-ORD-11918

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## SUMMARY SHEET

- I. Engineering Research Institute, University of Michigan, Ann Arbor, Michigan.
- II. U. S. Army, Ordnance Corps.
- III. Project No. TB4-15  
Contract DA-20-018 ORD-11918, RAD No. ORDTB-1-12045.
- IV. Report No. WAL 401/109-3
- V. Priority No. - None
- VI. Investigation of machinability of titanium-base alloys.
- VII. Object:

The object is to investigate the machinability of commercially pure titanium and three alloys of titanium.

### VIII. Summary:

Turning tests were made with 18-4-1 high-speed steel tools ground to the shape 0,Var,6,6,6,15,0.010. The rake angles studied varied between -8 degree and 40 degrees. Cutting speed tool life curves were determined for each of several rake angles in the above range. All cuts were made dry with a feed of 0.006 ipr. and a depth of 0.050 inch. Similar tests were carried out on SAE 1045 hot-rolled steel, type 304 stainless steel, grade Ti 150A titanium and grade RC 130B titanium.

### XI. Conclusions:

The preliminary nature of these tests and the dependence of interpretation of the results upon the outcome of other tests yet to be conducted makes it inadvisable to speculate on general application of the results reported herein.

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EFFECT OF SIDE RAKE ANGLE ON TOOL LIFE IN TURNING TITANIUM  
(HIGH-SPEED-STEEL TOOLS)

One of the more important factors of any metal cutting setup is the life of the cutting tools as influenced by variations in cutting speed, tool shape, size of cut, tool material, and cutting fluids. These variables are being studied separately in the titanium machining program. This report presents the results of a study of the influence of both cutting speed and tool side rake angle when cutting with 18-4-1 high-speed-steel tools. Reports on the effect of other variables follow later.

WORK MATERIALS

The overall program was set up to include machining studies of four grades of titanium: Ti 75A, Ti 150A, Ti 150B, and RC 130B. Hot-rolled SAE 1045 steel and type 304 stainless steel were added to the test group to be carried through the same testing program. This provides a basis for comparing the performance of titanium with metals for which machining practice has become fairly well established. Only the Ti 150A and the RC 130B titanium were available for the early part of the program. Results for the Ti 75A and Ti 150B will be given in supplementary reports.

PROCEDURE

The general procedure involved determining the tool life curve in turning for each material for each of several tool side rake angles. A tool life curve is determined by plotting the results of several tool life tests conducted at different cutting speeds. A tool life test consists of operating a tool at constant speed and size of cut until ultimate breakdown failure occurs and observing the elapsed cutting time. The elapsed time to total failure is known as the tool life. The tool life in minutes and the corresponding cutting speed in fpm are plotted on logarithmic coordinates.



The resulting points can be represented by a straight line which in turn can be represented by an equation of the form  $VT^n = C$ , where  $n$  is the slope of the line and  $C$  is a proportionality constant. When summarized in this manner the original data are readily analyzed to evaluate the effects of pertinent variables.

### TEST CONDITIONS

For this phase of the program, the size of cut was fixed at 0.050 inch depth of cut and the feed at 0.006 ipr. The tool material selected for the tests was 18-4-1 high speed steel marketed as "Blue Chip" by the Firth-Sterling Steel Company. The tools were in the form of 1/2-inch square by 4-inch long tool bits. Only those tools with hardness readings between 63.0 and 64.5 Rc were accepted for testing.

The tool shape conformed with the ASA signature O,Var.,6,6,6,15,0.010, wherein the side rake angle was varied in increments of 4 to 8° from -8° up to and including 40°.

The work materials were in the form of 3-inch diameter bars except for the SAE 1045 steel, which was in 4-inch diameter bars. These bars were mounted in a 14-inch swing American "Pacemaker" lathe with one end held in a four-jaw chuck and the other end against a live center. The lathe was equipped with a Reliance Electric Company "V-S" Drive, making it possible to maintain constant cutting speed at any work diameter. All tests were run without a cutting fluid.

### TEST RESULTS

#### Tool Life versus Rake Angle

The test results are summarized in Figs. 1-12 inclusive. Figures 1-4 show the effect of side rake angle on tool life at constant cutting speed. Figure 1 is a curve for RC 130B titanium. It shows the tool life in minutes for a cutting speed of 48 fpm as affected by tool side rake angle. It will be noted that tool life increases as the rake angle is increased from -8° up to an optimum in the vicinity of 30°. It then drops off very rapidly as the rake angle is further increased to 40°.

The data points in Fig. 1 were obtained from the tool-life curves in Figs. 13-20 inclusive. The cutting speed of 48 fpm gives a 60-minute or

1-hour tool life with the optimum rake angle of  $32^\circ$  as shown in Fig. 19. The other data points in Fig. 1 are the tool lives at the same speed as obtained from the other tool-life curves in Figs. 13-20.

Similar curves showing the effect of rake angle on tool life are shown for Ti 150A, SAE 1045 steel and 304 stainless steel in Figs. 2, 3, and 4 respectively. In every case, the optimum is in the vicinity of  $30^\circ$ .

It was concluded that the optimum is  $28^\circ$  for the type 304 stainless steel and  $32^\circ$  for the three other materials.

The tool life drops off precipitously as the rake angle is increased beyond the optimum, so it is somewhat hazardous to attempt to operate in this range, particularly since slight reduction in rigidity of the setup can cause crumbling of the cutting edge, thus making it impossible to realize full advantage of the optimum rake angle. Since it may be desirable to operate somewhat below the optimum rake angle, the slope of the curves in the approach to the optimum takes on particular significance.

It will be noted that the tool life for the Ti 150A and the stainless steel drops off very rapidly as the rake angle is decreased from the optimum, while it decreases more slowly with the other two materials. Thus rigid specification of the rake angle is less important in the case of the 1045 steel and the RC 130B titanium.

The cutting speeds shown in Figs. 1-4 are particularly significant, since they give similar performance in cutting each of the four work materials. These speeds are summarized in Table I.

TABLE I

CUTTING SPEED FOR ONE-HOUR TOOL LIFE AT OPTIMUM RAKE ANGLE

Work Material	Cutting Speed	
	<u>fpm</u>	<u>%</u>
RC 130B	48	25
Ti 150A	74	39
304 Stainless	99	53
SAE 1045	187	100

Cutting Speed versus Rake Angle

The cutting speed, tool life curves, Figs. 13-47 inclusive, are relatively flat (i.e.,  $n$  is small), so it is possible to get an exaggerated impression of the importance of rake angle by considering only the tool life at constant speed. Therefore the cutting speed for a 1-hour tool life ( $V_{60}$ ) at each rake angle is plotted for each material in Figs. 5-8 inclusive. It will be noted that the resulting curves show relatively broad optimums for all four materials and that the percentage change in cutting speed over the entire range of rake angles is relatively small except in the case of the SAE 1045 steel. Thus it may be concluded that standard tool shapes may be used satisfactorily on titanium with only a relatively small sacrifice in production rate over what could be obtained at optimum conditions.

It should be emphasized that the rake angle referred to as the side rake angle in these tests is substantially the effective slope of the top of the tool in the direction of chip flow. Thus if it were decided to use a  $30^\circ$  effective rake angle on the teeth of a face mill cutting entirely on a  $45^\circ$  chamfer, then the radial and axial rake angles must be such as to produce a slope of  $30^\circ$  away from the chamfer, since the chip will flow in this direction.

Slope of Tool Life Curve versus Rake Angle

The slope of the tool life curve is an empirical indication of the relative effectiveness of temperature and abrasiveness in a metal cutting combination. The flatter the curve (i.e., the smaller the value of the slope  $n$ ), the greater the influence of temperature. Similarly, temperature decreases in importance and abrasiveness increases in dominance as the slope approaches  $45^\circ$  or  $n$  approaches a value of 1.0. Figures 9-12 inclusive show corresponding values of the slope  $n$  for each material at the several rake angles. The slope decreases for rake angles in the region of the optimum. This should be interpreted as the result of decreased abrasiveness accompanying the decrease in strain hardening which results from larger rake angles. The increased slope at rake angles beyond the optimum represents a virtual increase in abrasiveness brought about by superficial crumbling or fracture of the cutting edge.

Original Data and Observations

All original test data are plotted in Figs. 13-47. The following is a description of the sequence of events leading up to tool failure:

I. SAE 1045 Steel (Hot Rolled). At the start of cut, a long, straight, silver colored chip forms. The chip then begins curling slightly and although the degree of spiraling varies, it is obvious that the chip is

no longer straight. In due time, the curl gets much smaller and the chip forms in tight little spirals which consistently break off and then reform. Up to this point, the surface finish is quite consistent, the chip does not discolor, the shoulder of the work at the tool point has not changed, and the nose of the cutting tool does not show a red glow. A point is reached where the surface finish begins to change, the chip has a yellowish tinge, and it appears to be straightening (i.e., the small spiral disappears). Suddenly the nose of the tool becomes very red, a noise probably caused by rubbing can be heard, the chip turns blue, and the shoulder of the work at the tool point undergoes a definite change in shape in addition to being burnished. Failure occurs almost instantly at this point.

II. Type 304 Stainless Steel. During the initial cutting stage, a long, straight silver colored chip forms. The cut itself presents a much noisier condition than was encountered with the SAE 1045 steel. The chip begins losing its straight formation and starts to form a slight spiral. In time the spiral decreases, but it does not get nearly as small as that which occurred on SAE 1045 steel. A slight change in surface finish can then be noticed and the chip formation that follows this event becomes quite inconsistent (that is, it curls, then becomes straight, then curls, etc.). This is followed by a very noticeable change in surface finish, at which time the nose of the tool turns red. As the chip is removed it has a definite pattern of discoloration; the portion nearest the work is much darker than the remainder. The shoulder of the work changes rapidly (becomes broad and burnished). Failure occurs immediately at this point.

III. Ti 150A. From the instant the cut starts, the chip is silver colored and curled in a very irregular ribbon-like formation. It does not form the long, straight chip so noticeable in the turning of the steels. Surface finish is very consistent. These conditions prevail up to a point just before tool failure. At this point, the finish begins changing and the chip color changes from silver to yellow. Since the chip curls back towards the work, the area between chip and tool face is exposed and it is very easy to see a red glow at the nose of the tool. At this stage, the contact area between chip and tool is very small. The red glow at the nose of the tool increases in intensity and the chip becomes a dark yellow in color for a very short time: then the material being removed appears to be in a molten state. As it cools it forms a chip which becomes blue and then purple in color and very tight and irregular in shape. At the same time this event is taking place, the shoulder changes shape and tool failure occurs. The blue color is a reliable criterion to use as the point of tool failure.

IV. RC 130B. During the initial cutting stage, the chip is silver-colored and has a slight spiral shape. It is not as long and straight as the chip formed in turning the steels, but it is not at all like the tightly curled ribbon-like chip formed by Ti 150A. There is a noticeable noise present from the beginning of the cut. The chip formation then becomes

similar to that encountered with Ti 150A, that is, irregular and ribbon-like. Following this period, the chip breaks up into small, irregular pieces. A red glow can be observed between the chip and tool face at the nose of the tool. Suddenly, the tip of the tool becomes very red, a whining noise occurs, the surface finish changes, the shoulder changes shape, and there is a slight discoloration of the chip (silver to yellow). At this point the tool fails almost instantly.

#### Tool Wear versus Time

Figures 48 and 49 show the progress of tool wear as a function of elapsed time during typical tool life tests. Figure 48 gives the results obtained when cutting Ti 150A at a constant speed of 75 fpm with a feed of 0.006 ipr and a depth of cut of 0.050 inch. The speed was selected to give a life of 12 minutes and the tool failed at 11.9 minutes. The cut was stopped at intervals no greater than 1 minute and the width of the worn area beneath the cutting edge was measured with a toolmaker's microscope. The results show that the wear increased rapidly to about 0.007 inch during the first minute of cutting and progressed at a much slower rate up to about 0.015 inch, after which the tool became unstable and wear progressed rapidly up to a maximum of 0.052 inch. This is typical of the performance of high-speed-steel tools when cutting ductile metals. The similarity to performance when cutting materials other than titanium is supported by the tool wear curve for SAE 1045 steel shown in Fig 49. Figure 50 shows pictures made of the cutting tools as they appeared halfway through the wear tests and again at failure.

#### CONCLUSIONS

Interpretation of the results of these tests and their application to commercial practice will be undertaken at the completion of the entire program. A final summary report will be devoted to this purpose.

Such conclusions as have been made in the manuscript of this report are not likely to be modified by results from the later phases of the program.

# TOOL LIFE vs. SIDE RAKE ANGLE

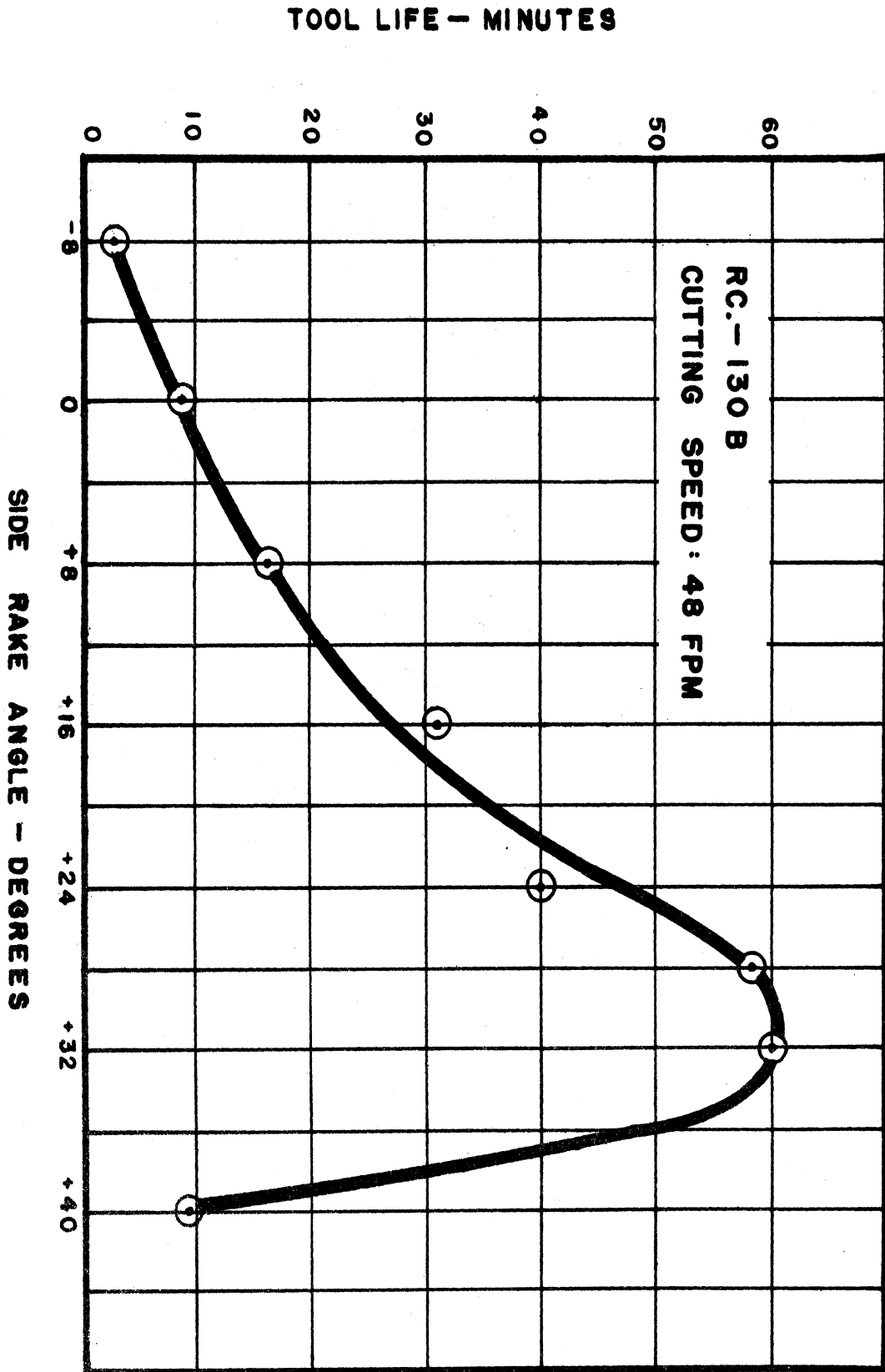


FIG. 1

# TOOL LIFE vs. SIDE RAKE ANGLE

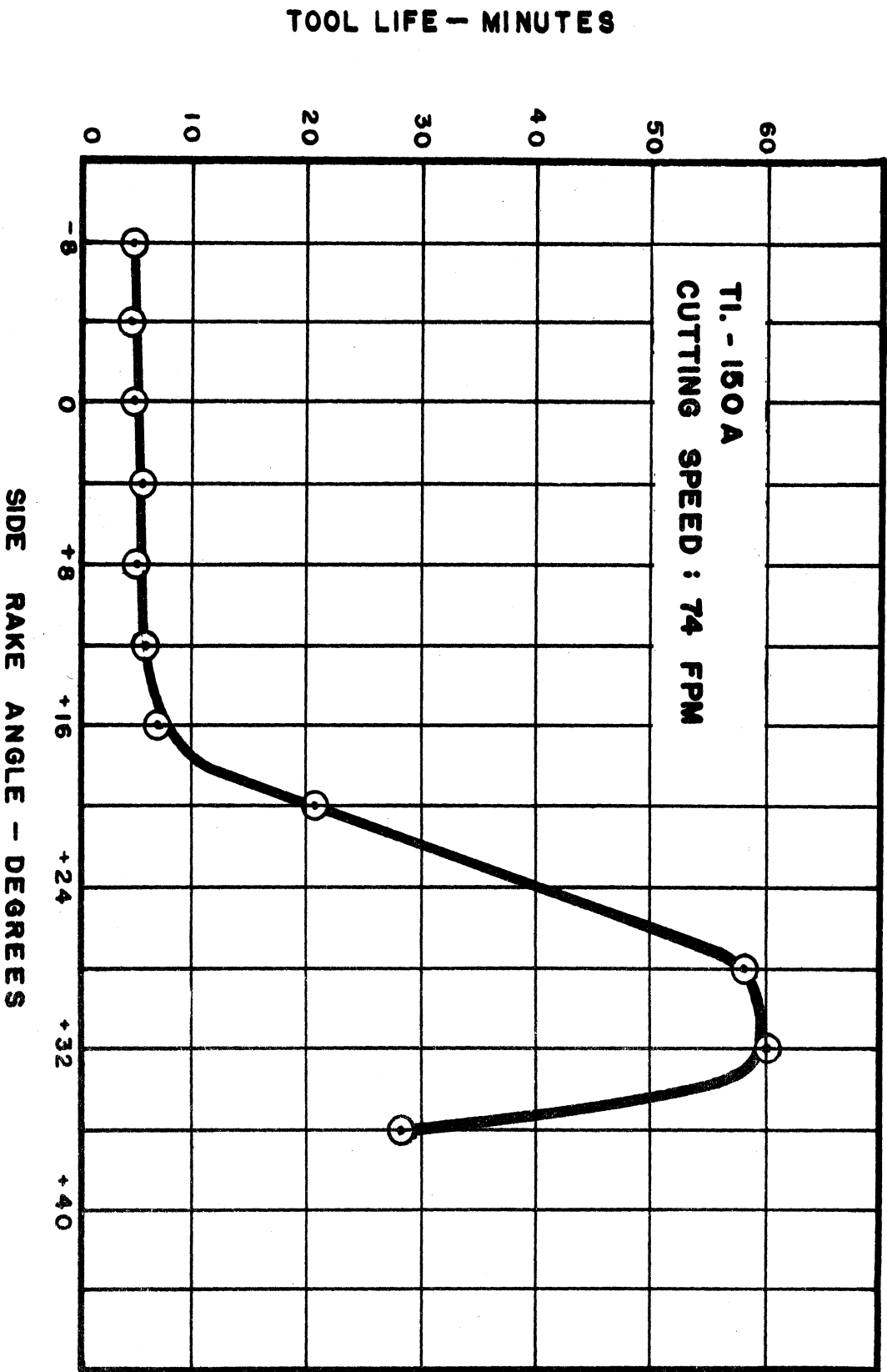


FIG. 2

# TOOL LIFE VS. SIDE RAKE ANGLE

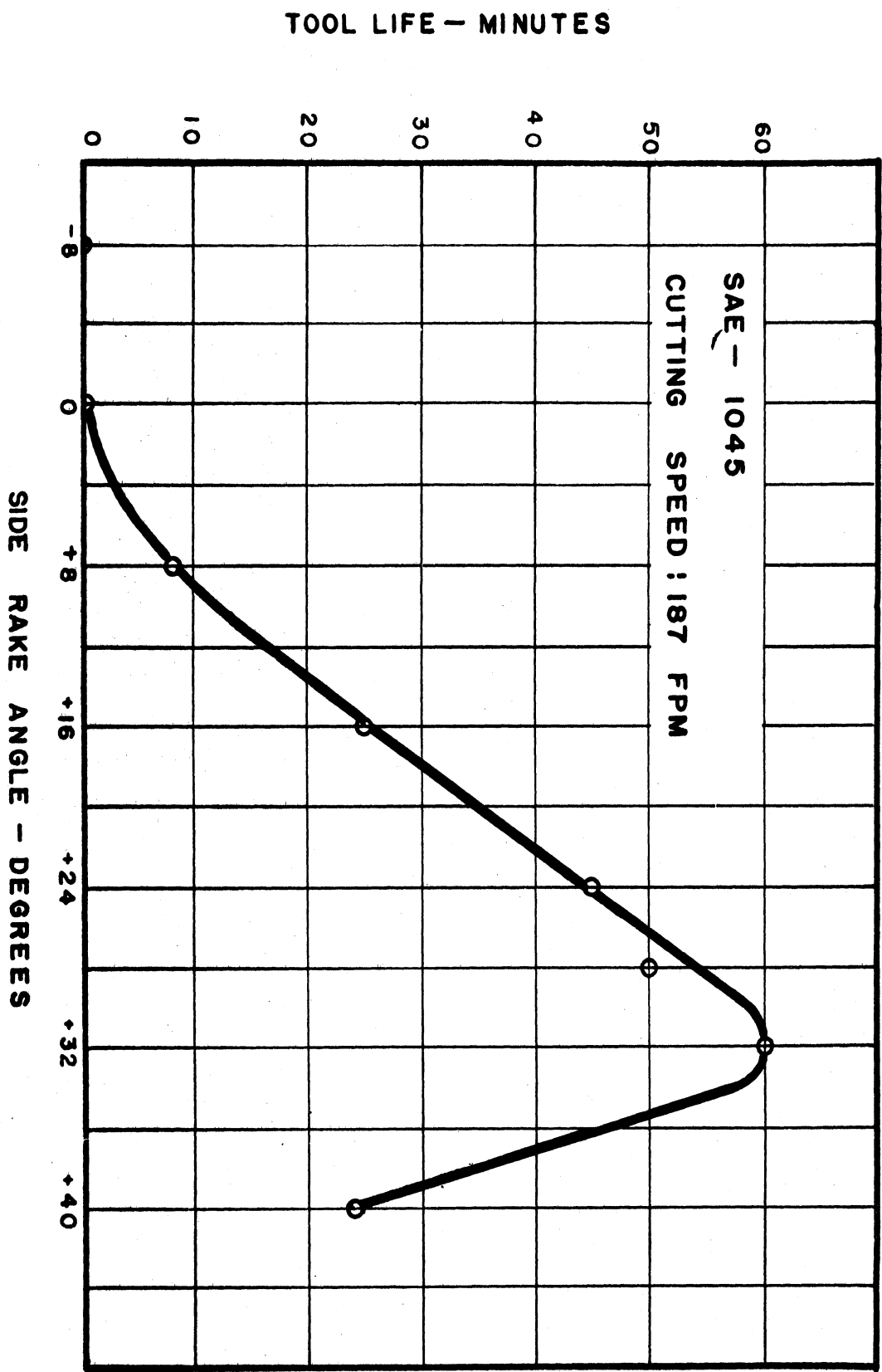


FIG. 3



# TOOL LIFE vs. SIDE RAKE ANGLE

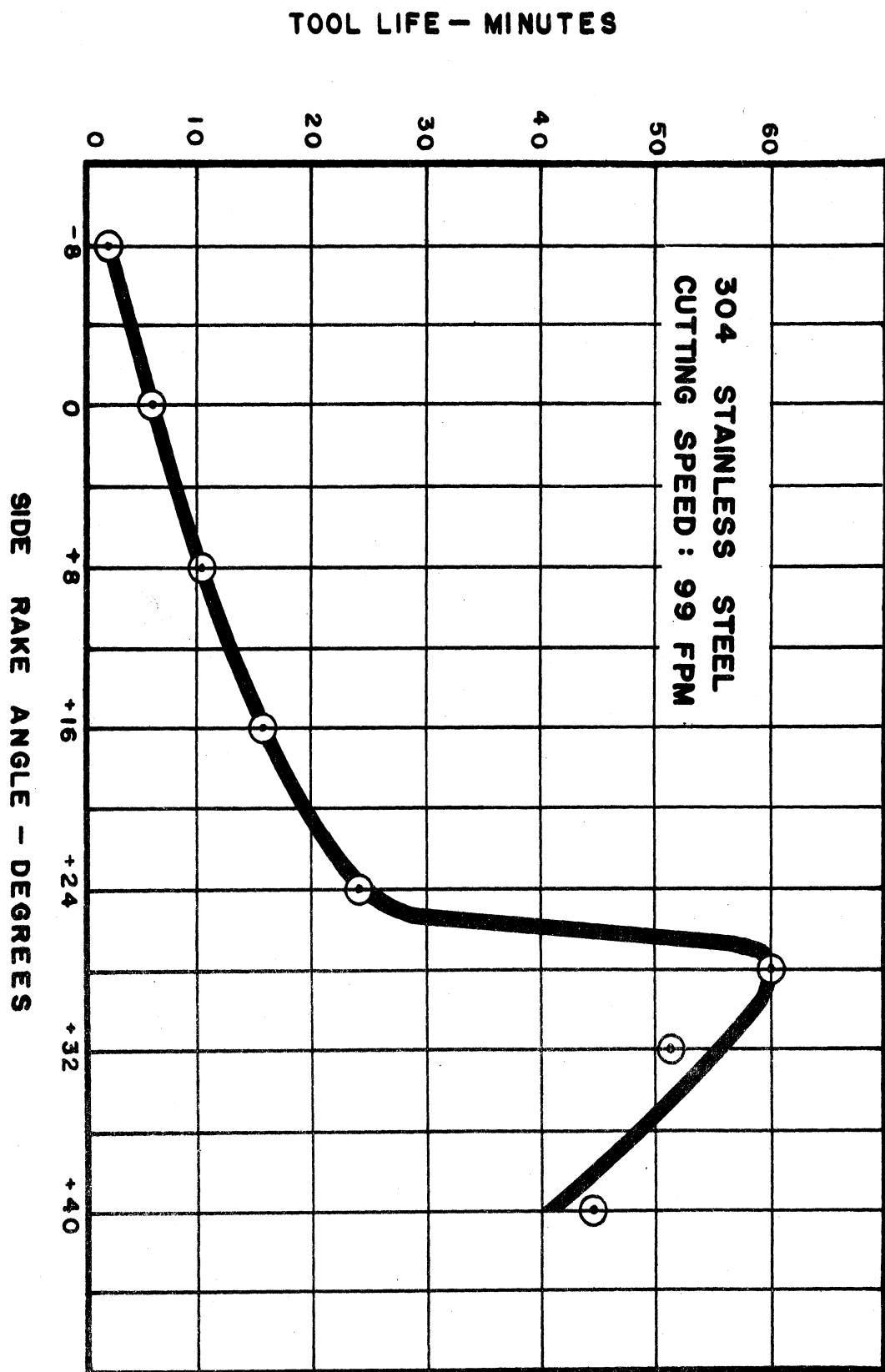
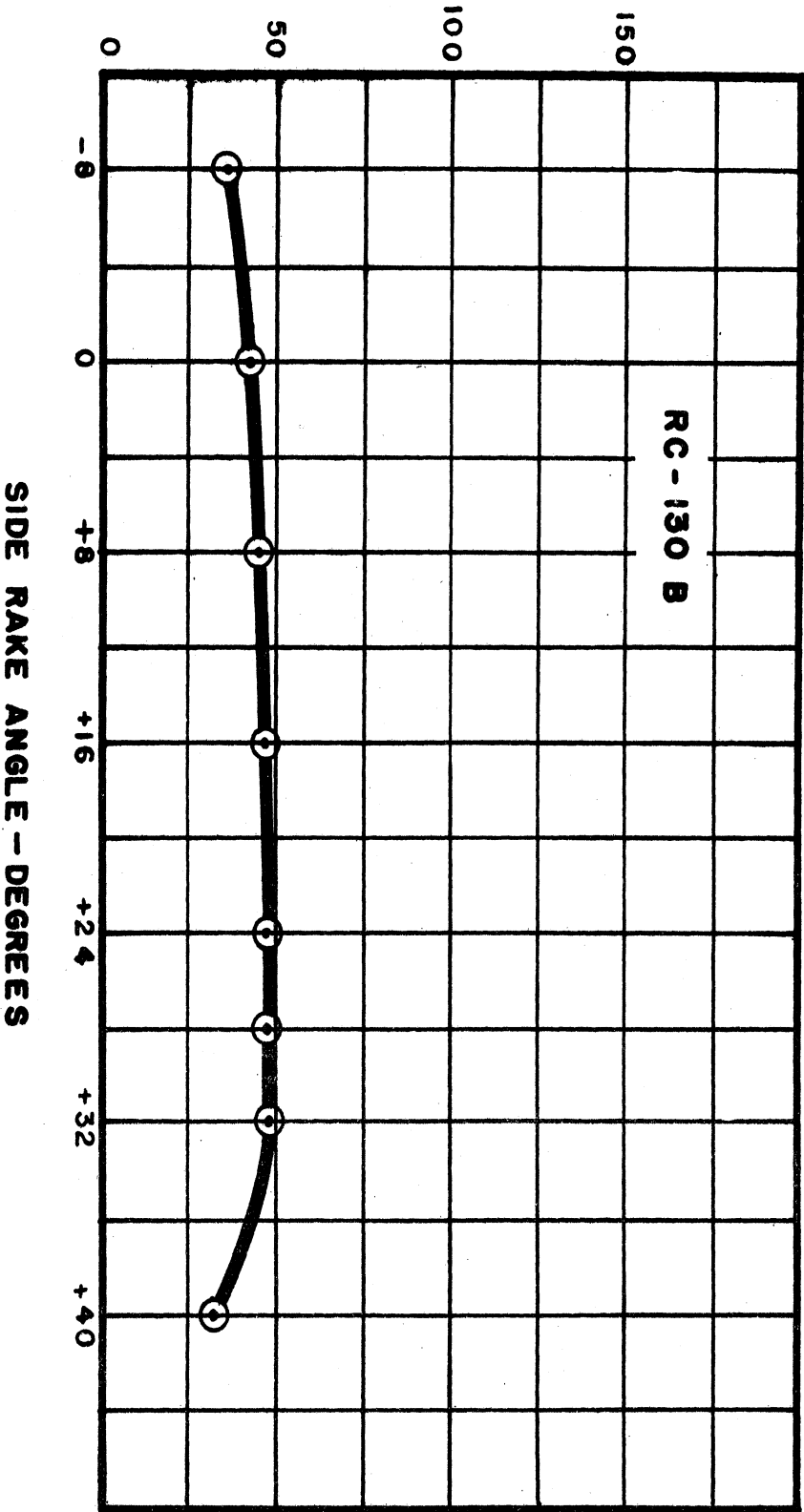


FIG. 4

**V<sub>60</sub>**  
**CUTTING SPEED - F.P.M.**



**CUTTING SPEED vs. SIDE RAKE ANGLE**

**FIG. 5**

V60  
CUTTING SPEED - F.P.M.

CUTTING SPEED vs. SIDE RAKE ANGLE

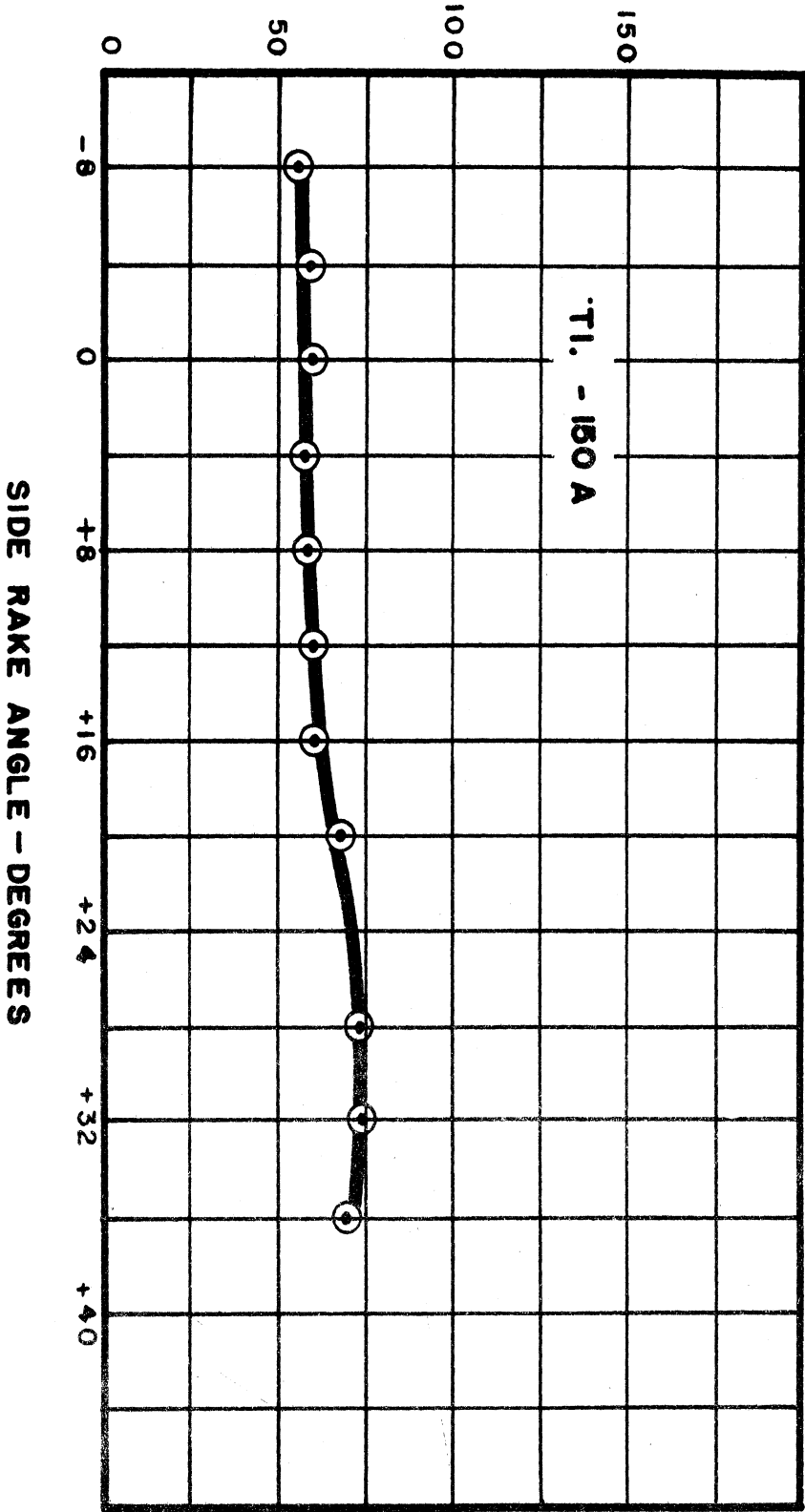


FIG. 6

$V_{60}$   
CUTTING SPEED - F.P.M.

CUTTING SPEED vs. SIDE RAKE ANGLE

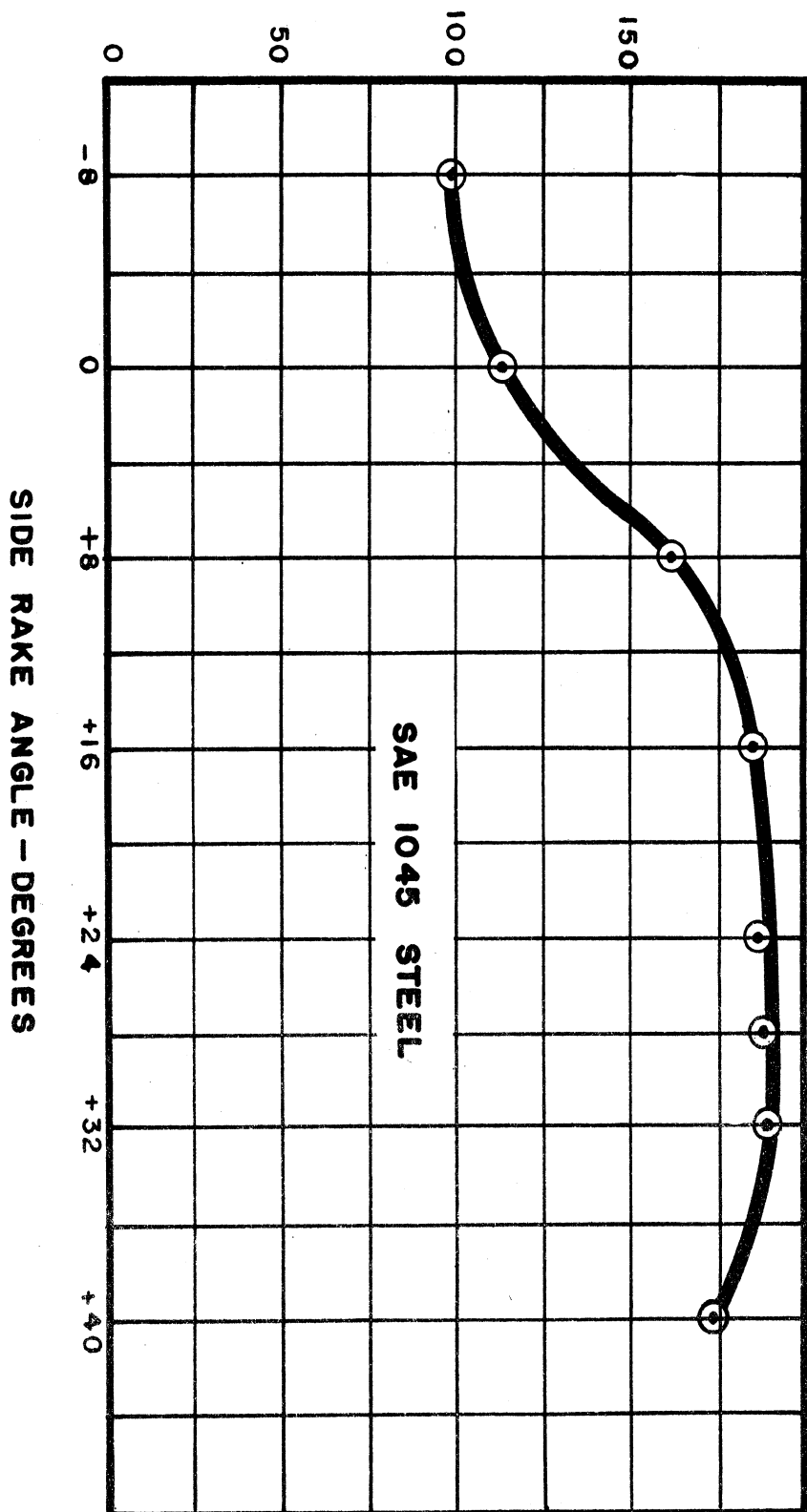


FIG. 7

V60  
CUTTING SPEED - F.P.M.

# CUTTING SPEED vs. SIDE RAKE ANGLE

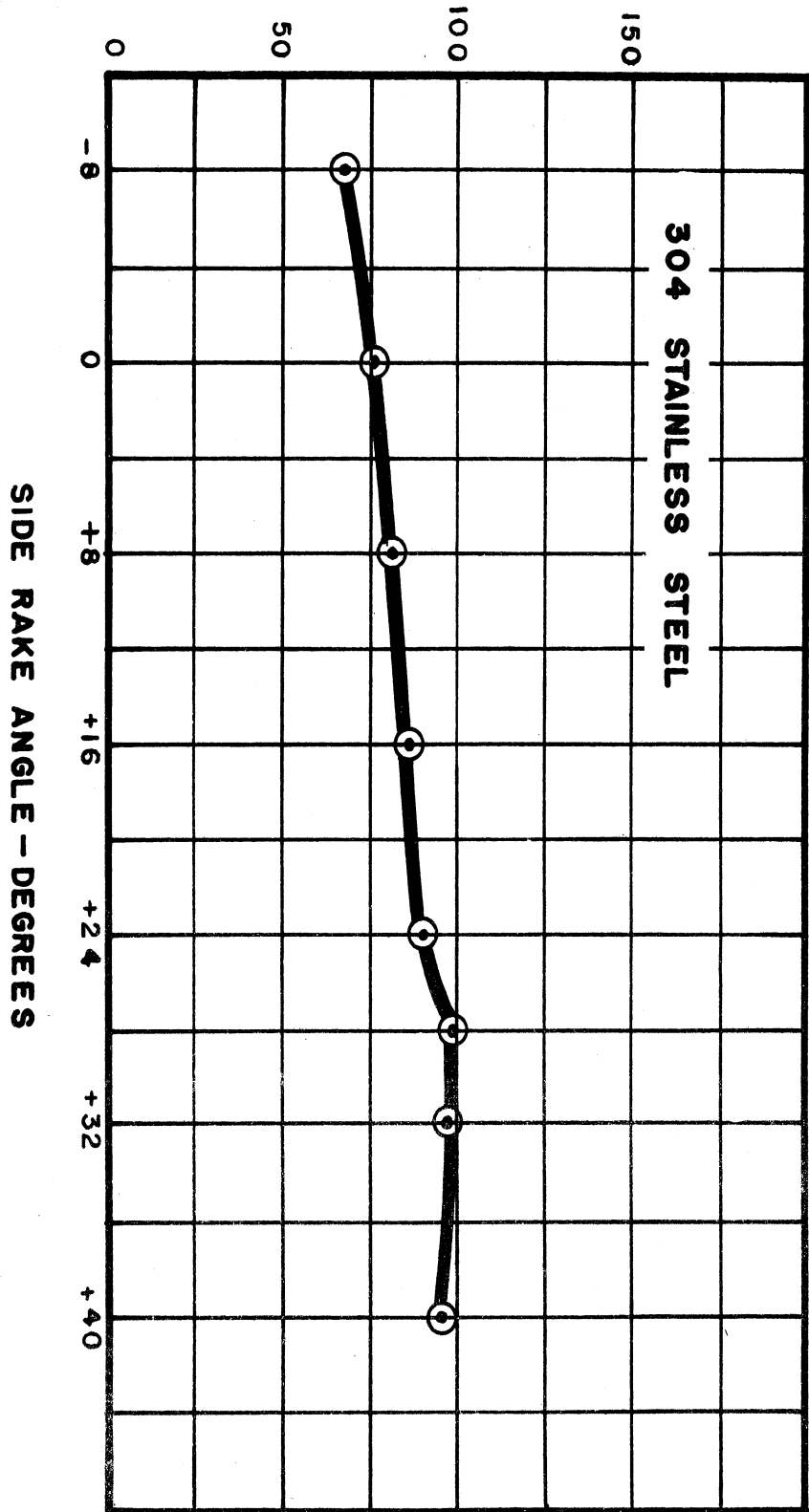


FIG. 8

# SLOPE OF TOOL - LIFE LINE vs. SIDE RAKE ANGLE

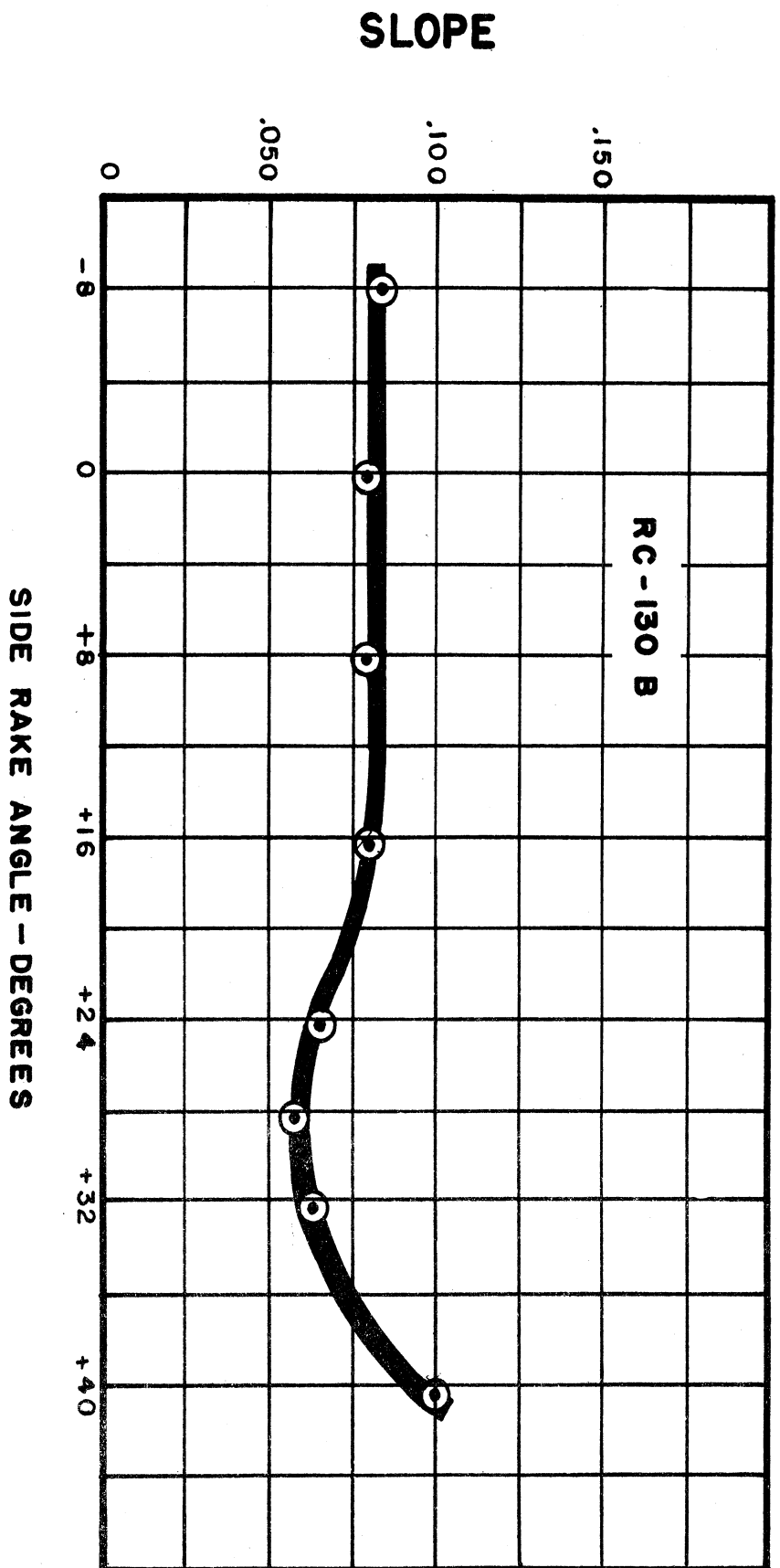


FIG. 9

# SLOPE OF TOOL-LIFE LINE vs. SIDE RAKE ANGLE

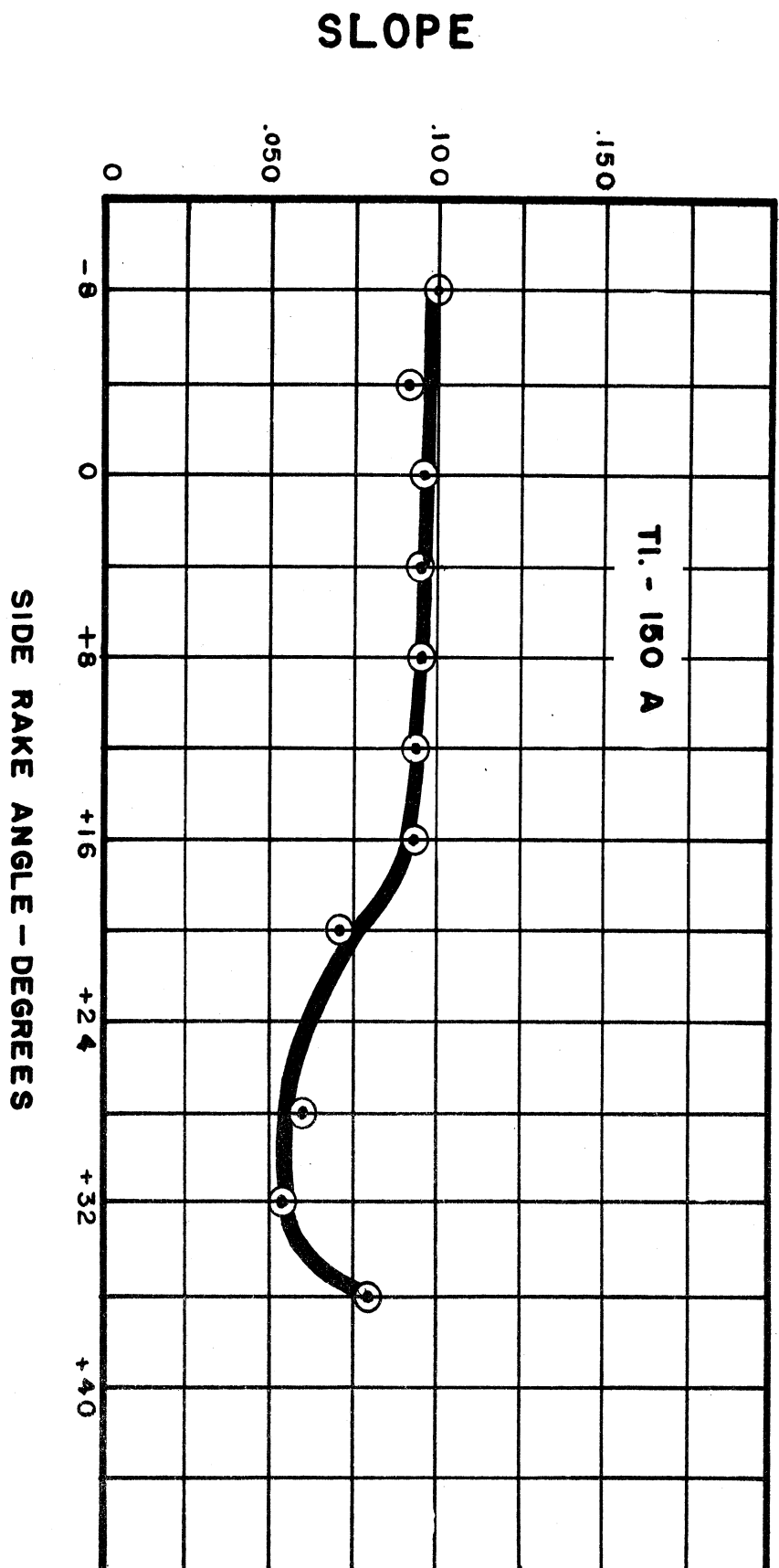


FIG. 10

# SLOPE OF TOOL - LIFE LINE vs. SIDE RAKE ANGLE

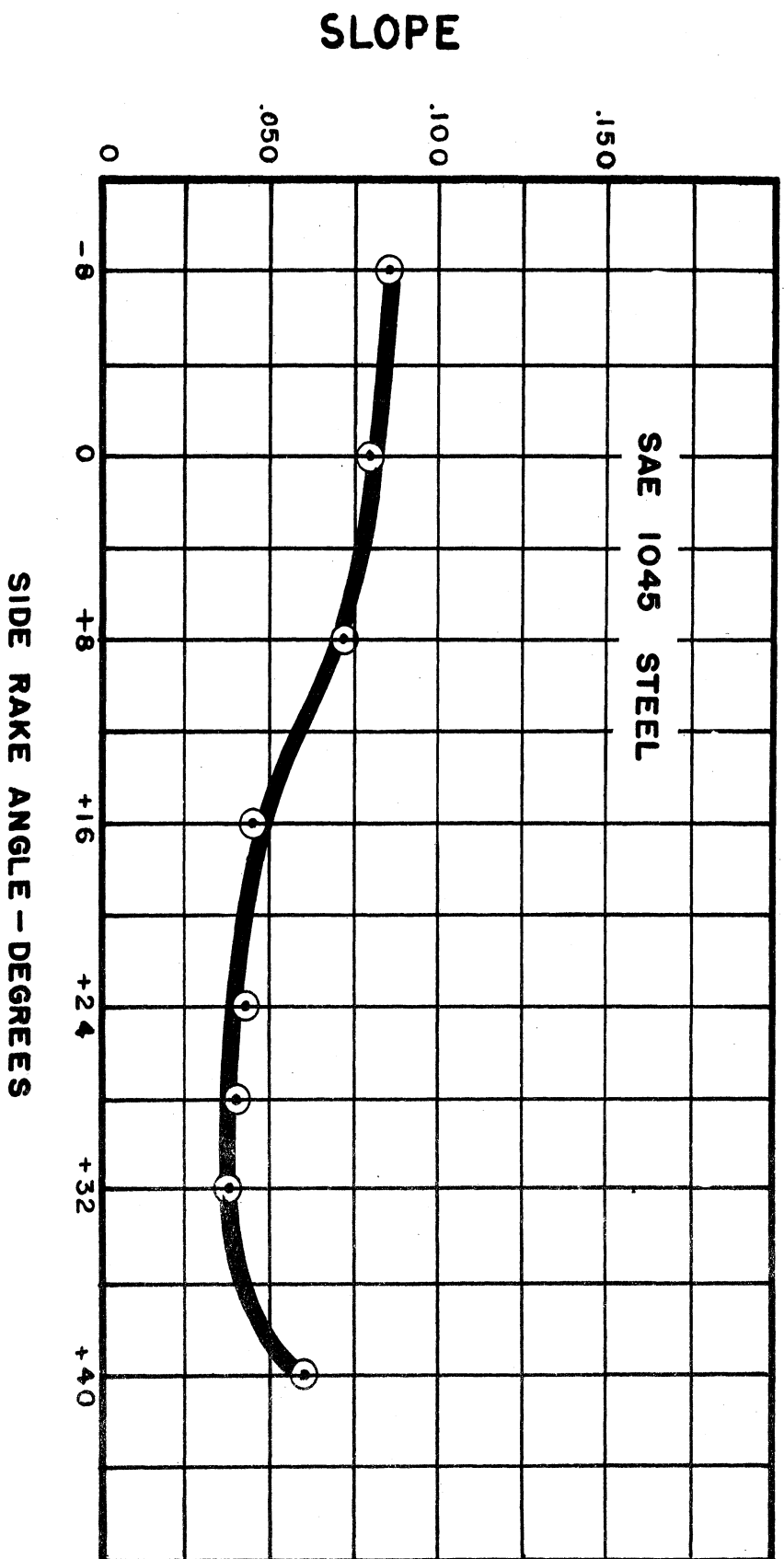


FIG. 11



# SLOPE OF TOOL-LIFE LINE VS. SIDE RAKE ANGLE

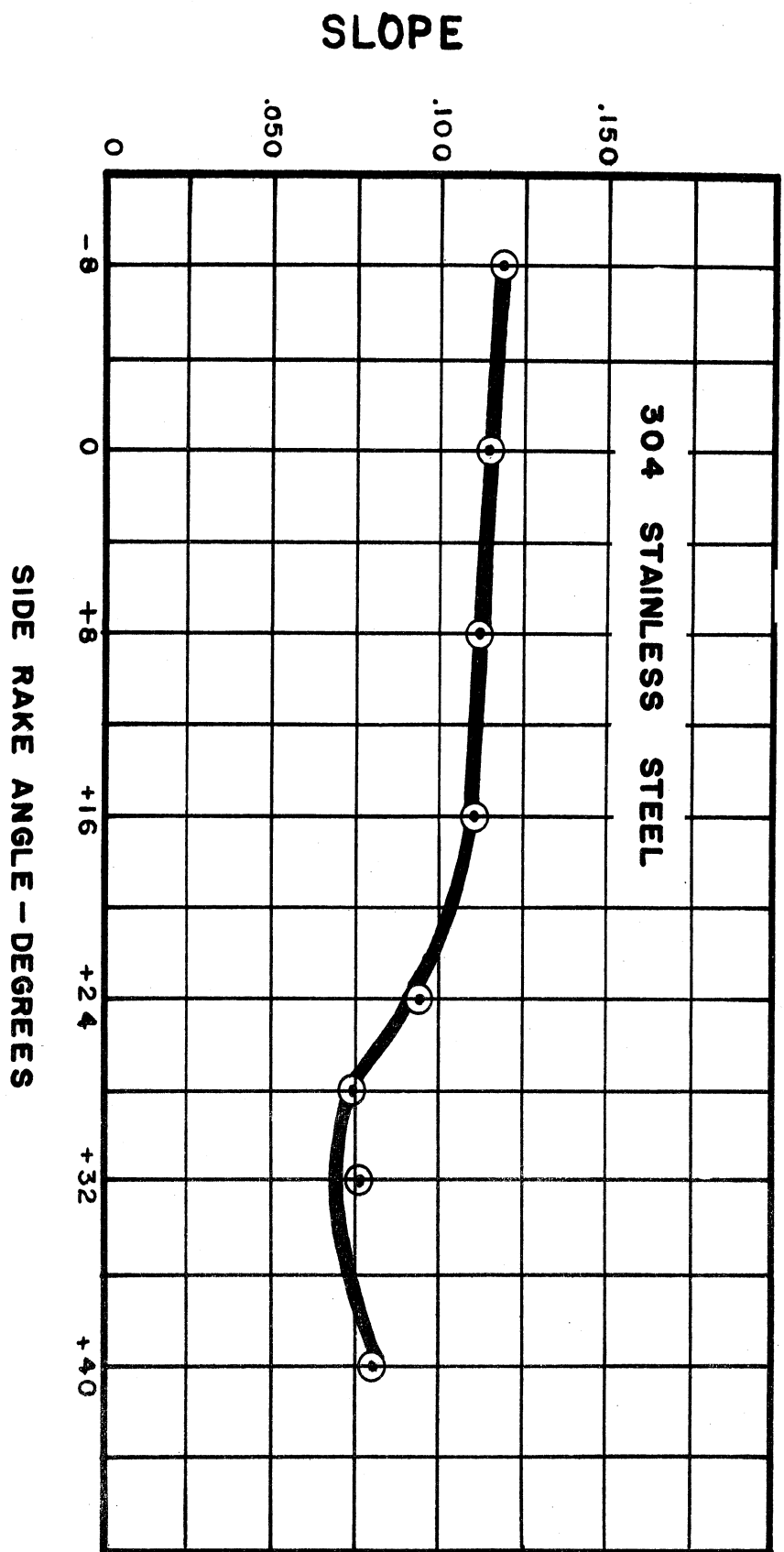


FIG. 12

# CUTTING SPEED — TOOL LIFE

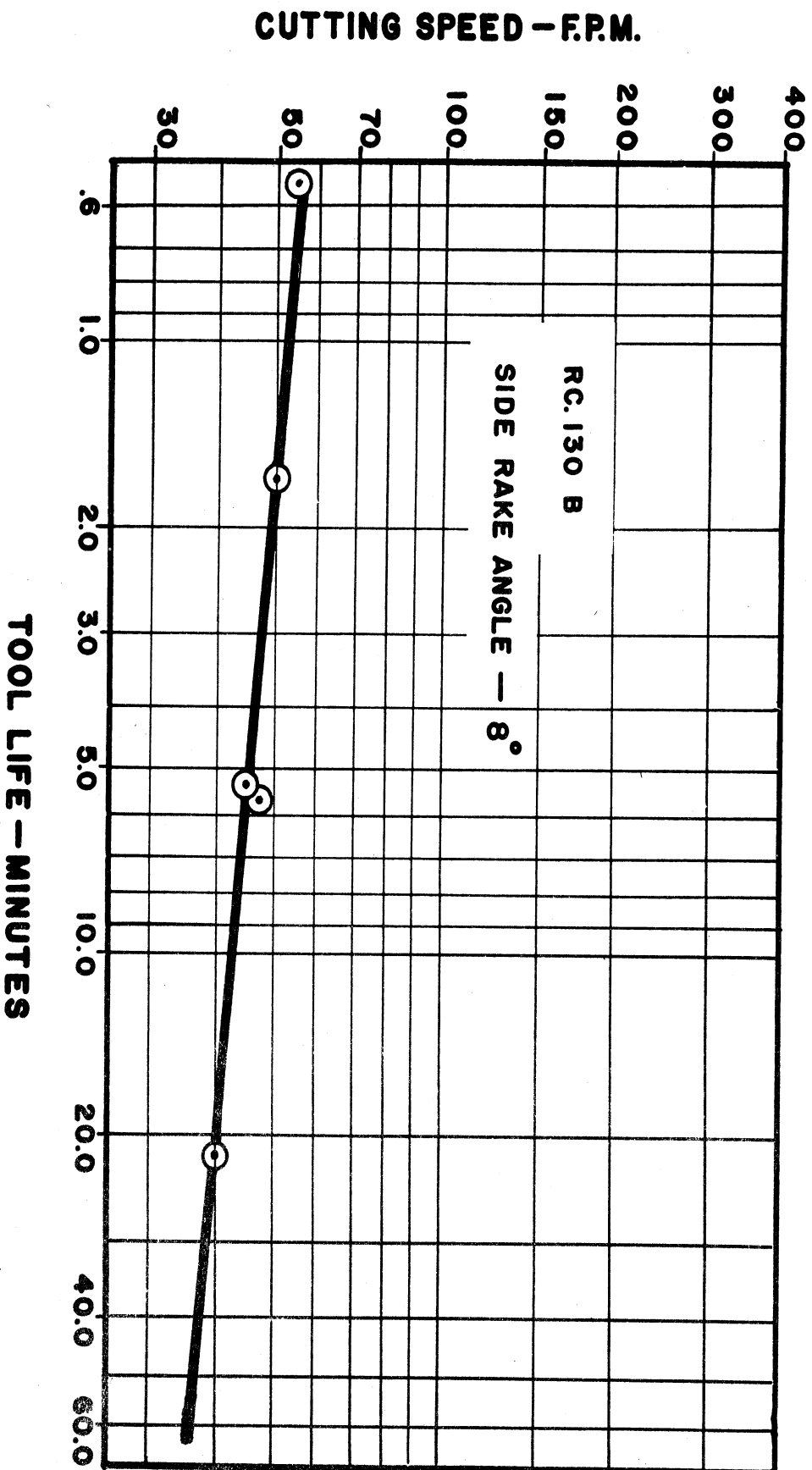


FIG. 13

# CUTTING SPEED — TOOL LIFE

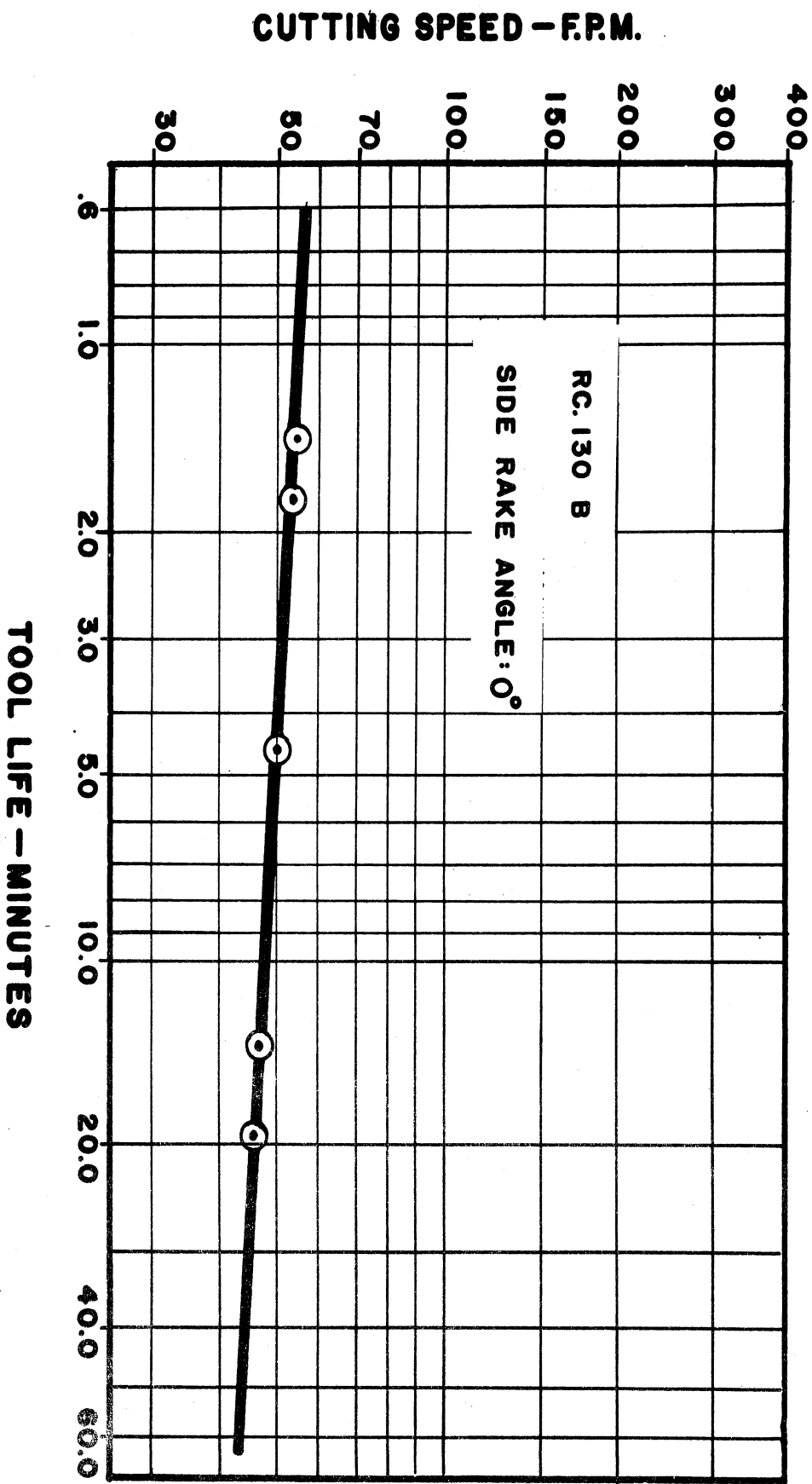


FIG. 14

# CUTTING SPEED — TOOL LIFE

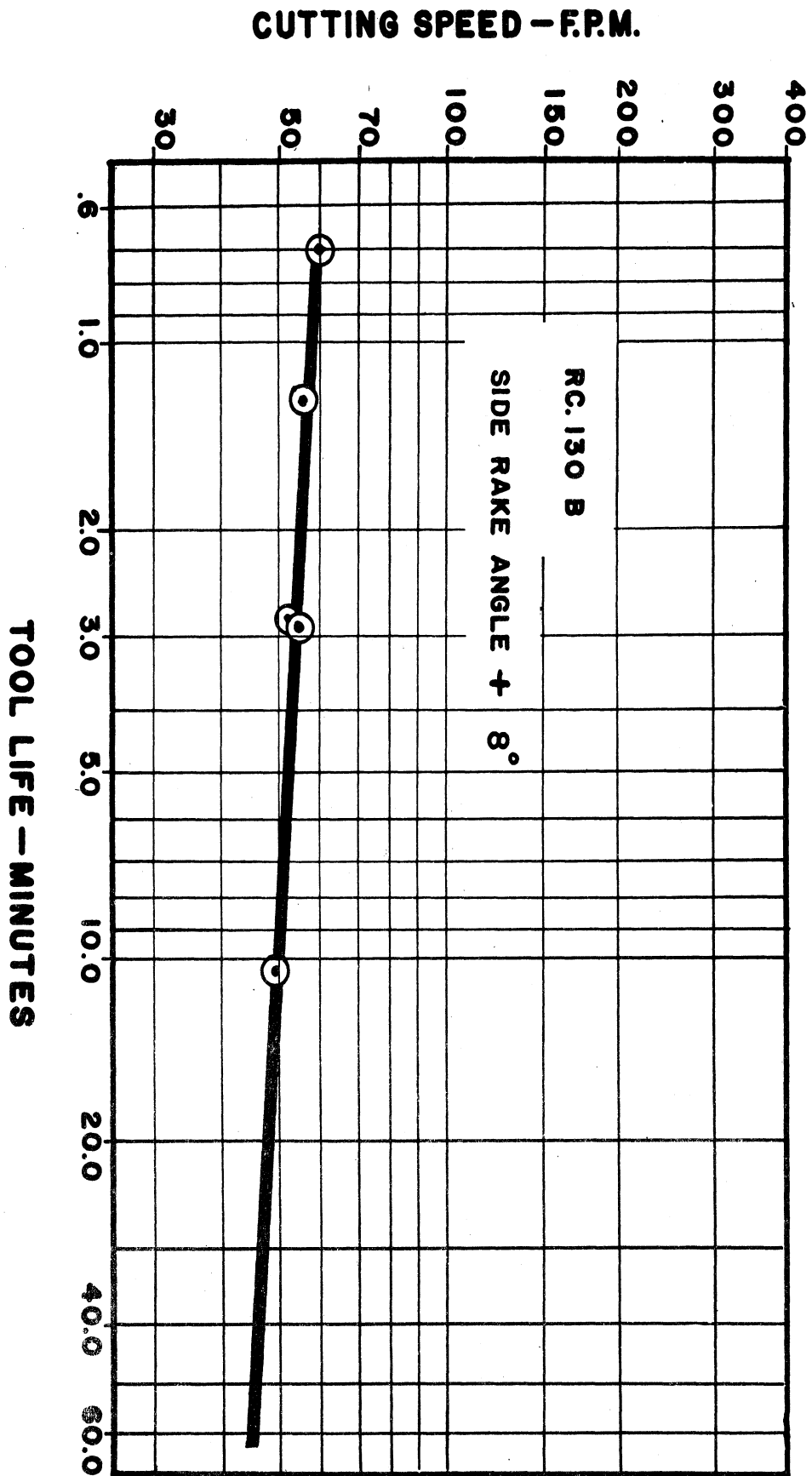


FIG. 15

# CUTTING SPEED — TOOL LIFE

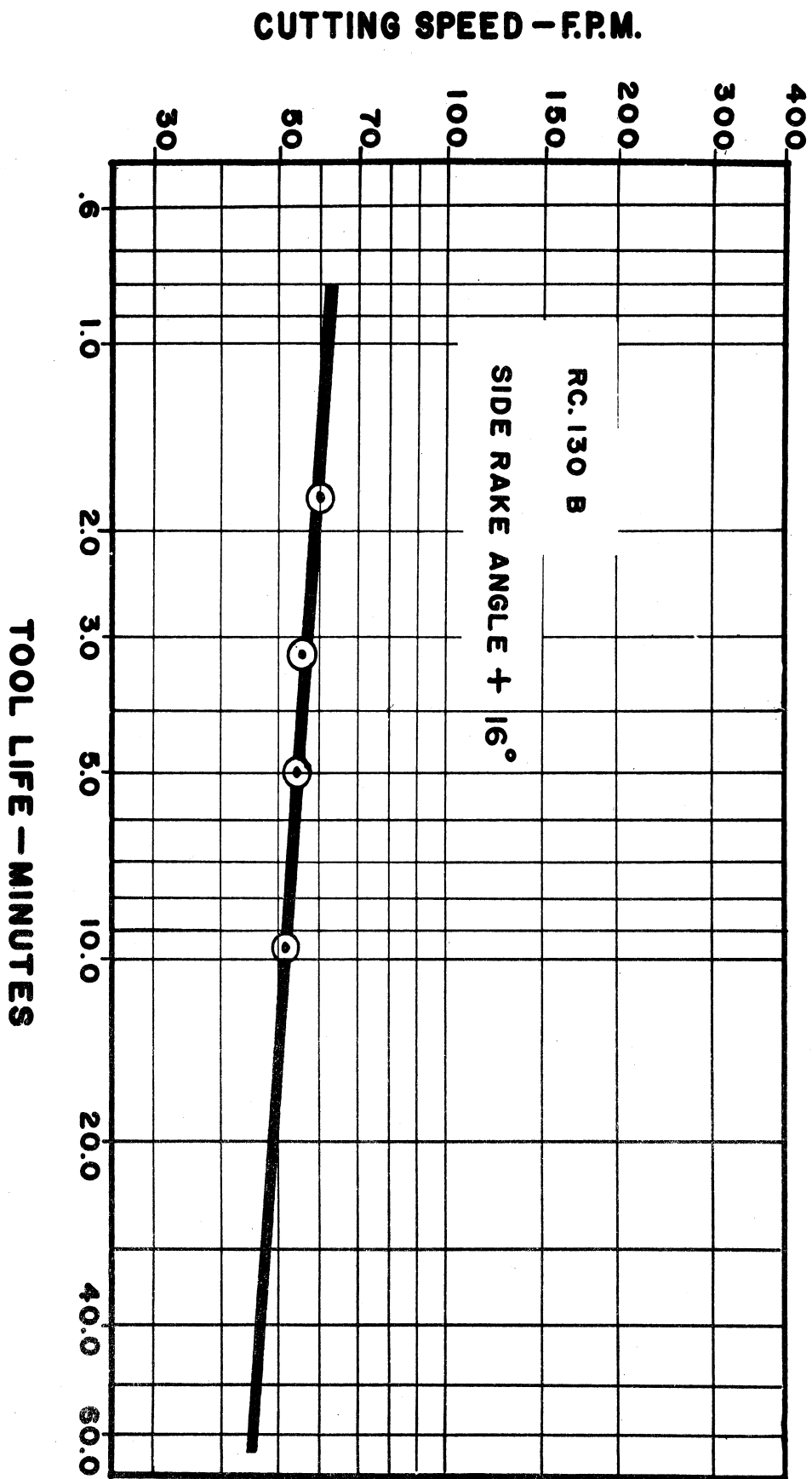


FIG. 16

# CUTTING SPEED — TOOL LIFE

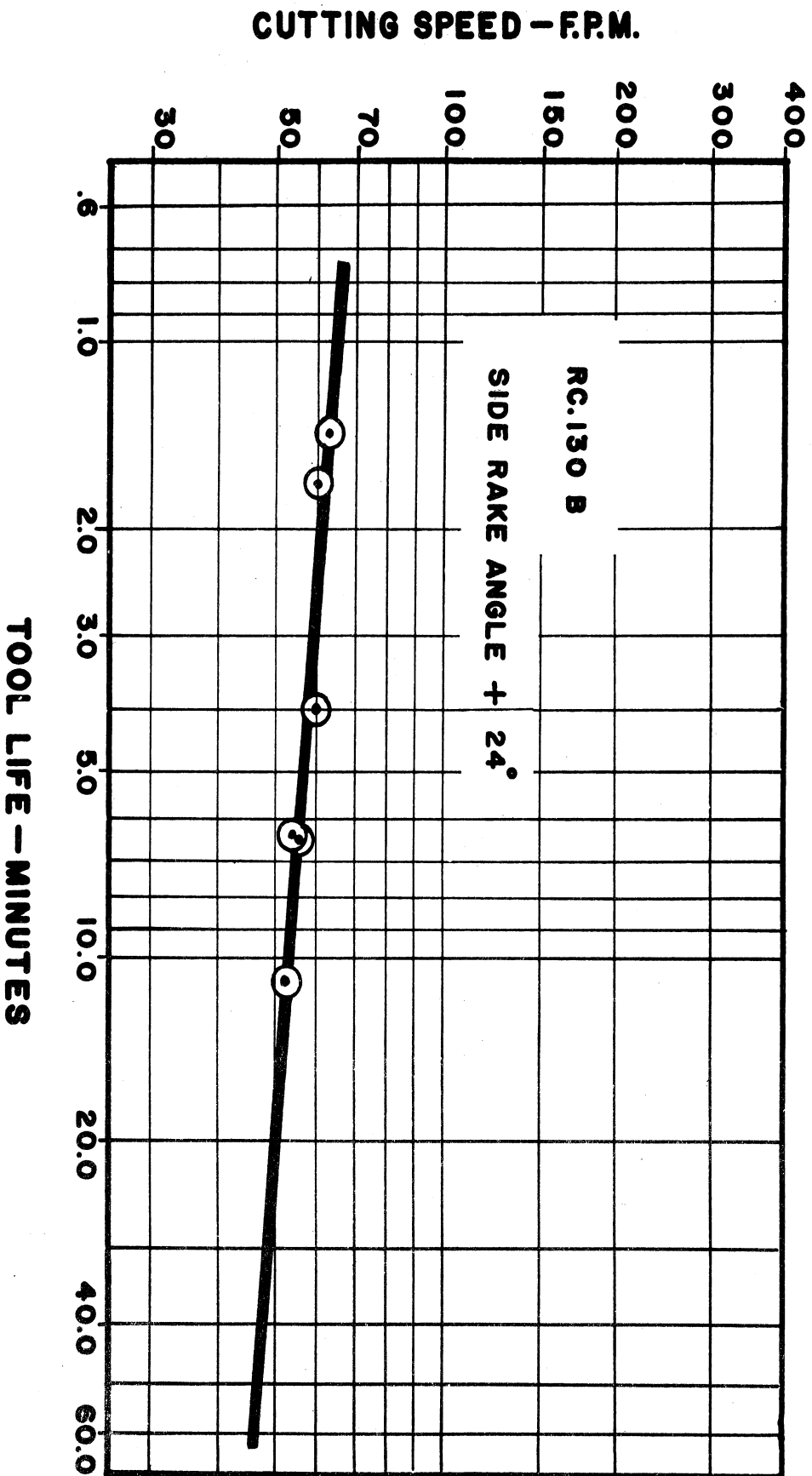


FIG. 17

# CUTTING SPEED — TOOL LIFE

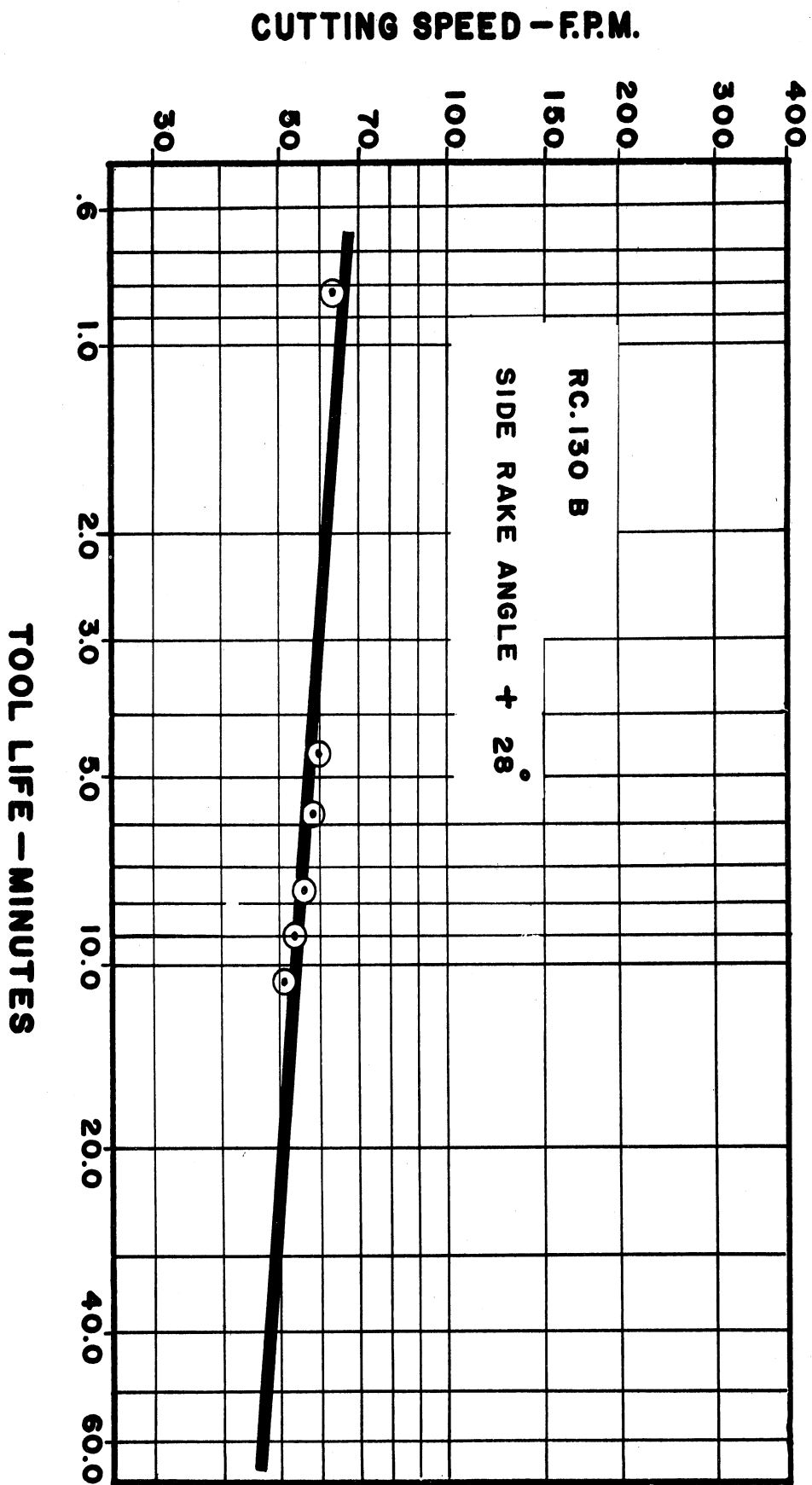


FIG. 18

# CUTTING SPEED — TOOL LIFE

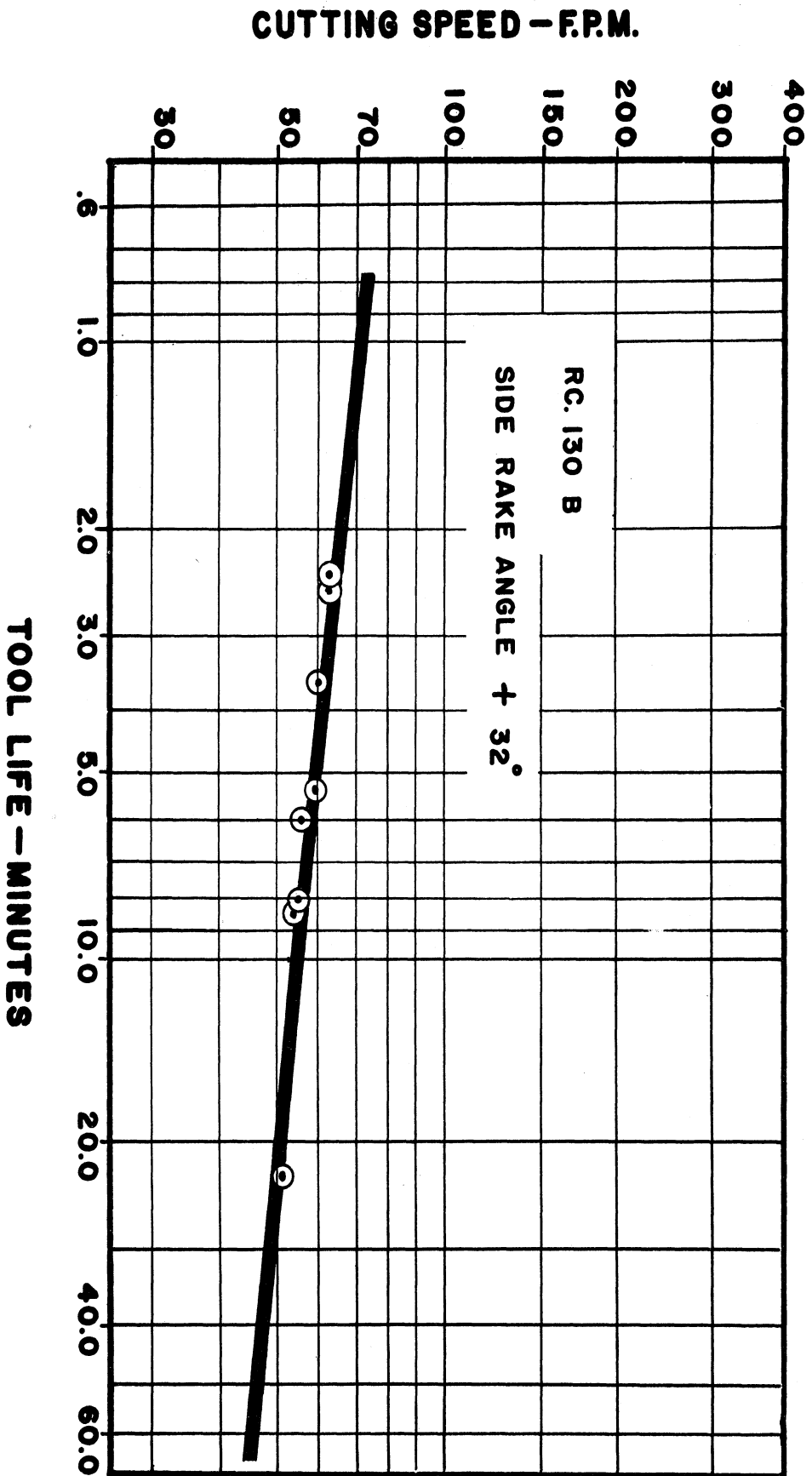


FIG. 19



# CUTTING SPEED — TOOL LIFE

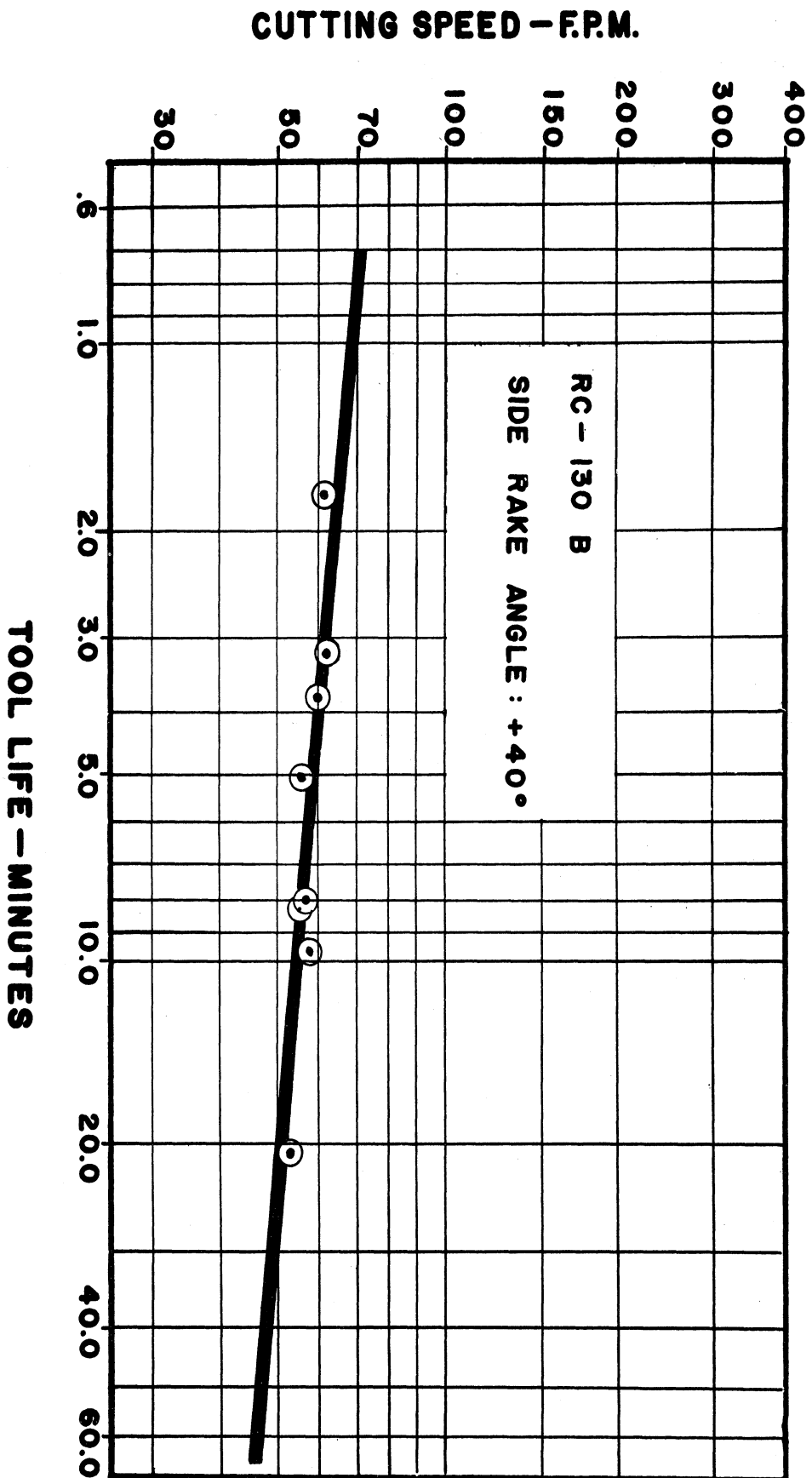


FIG. 20

# CUTTING SPEED — TOOL LIFE

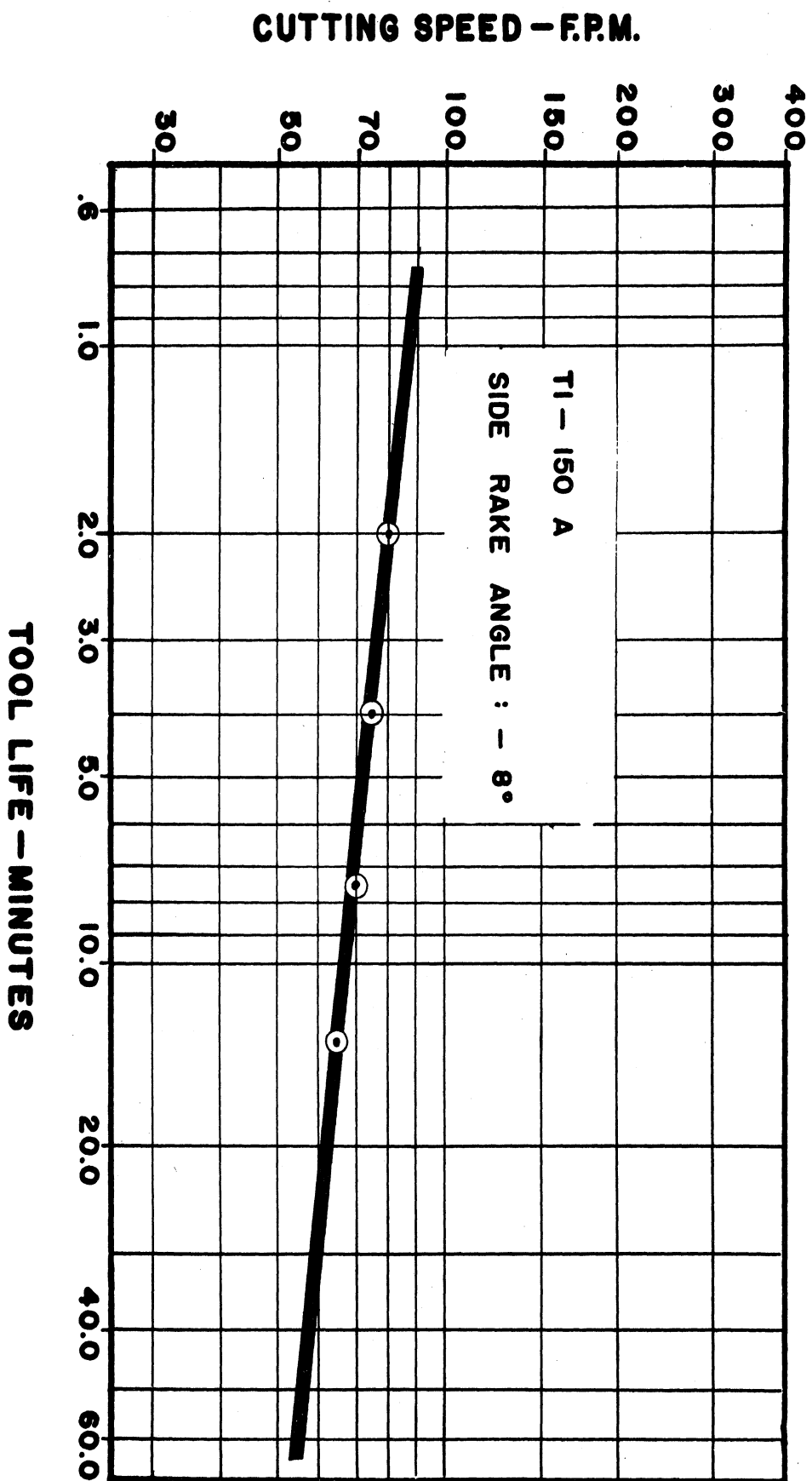


FIG. 21

# CUTTING SPEED — TOOL LIFE

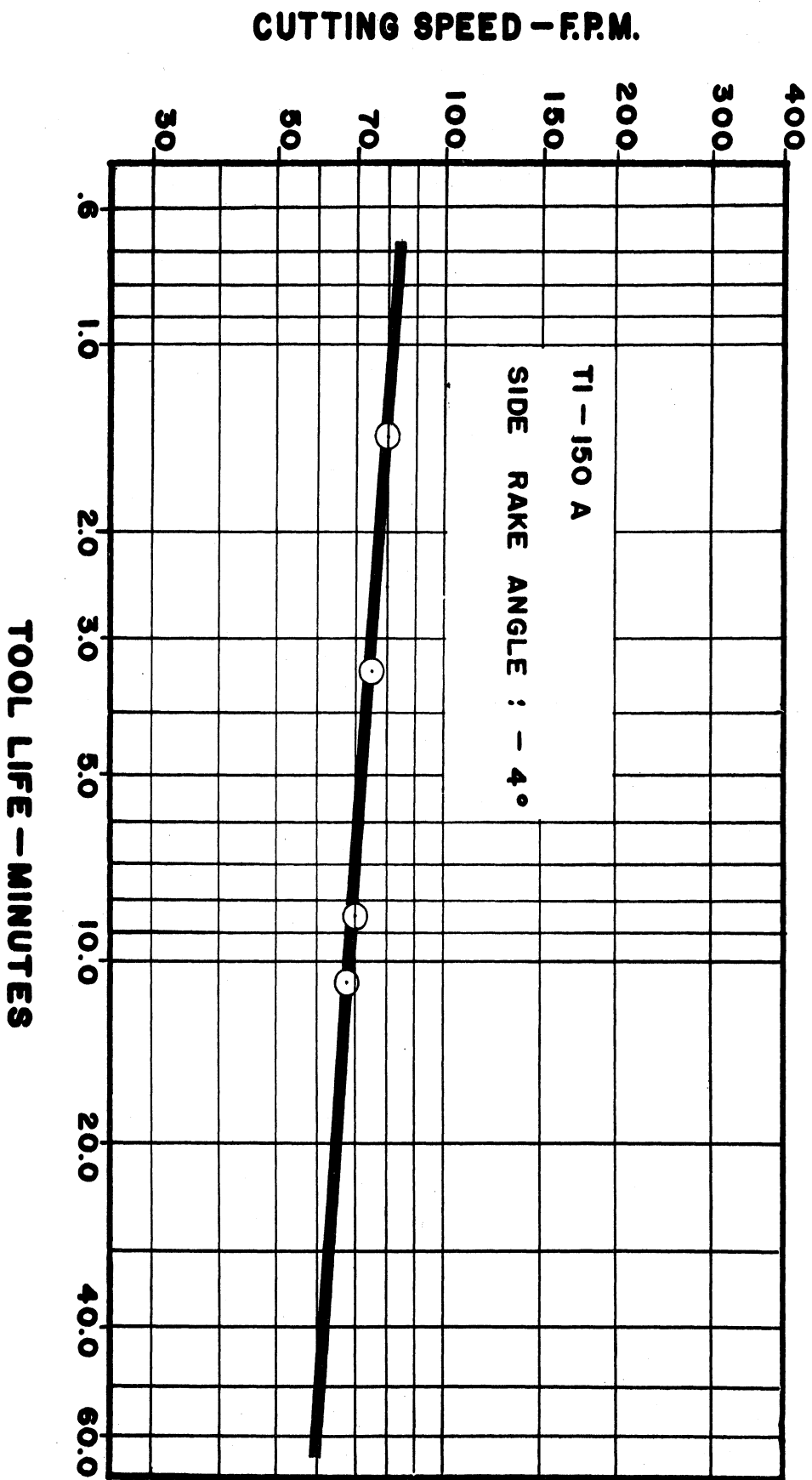


FIG. 2.2

# CUTTING SPEED — TOOL LIFE

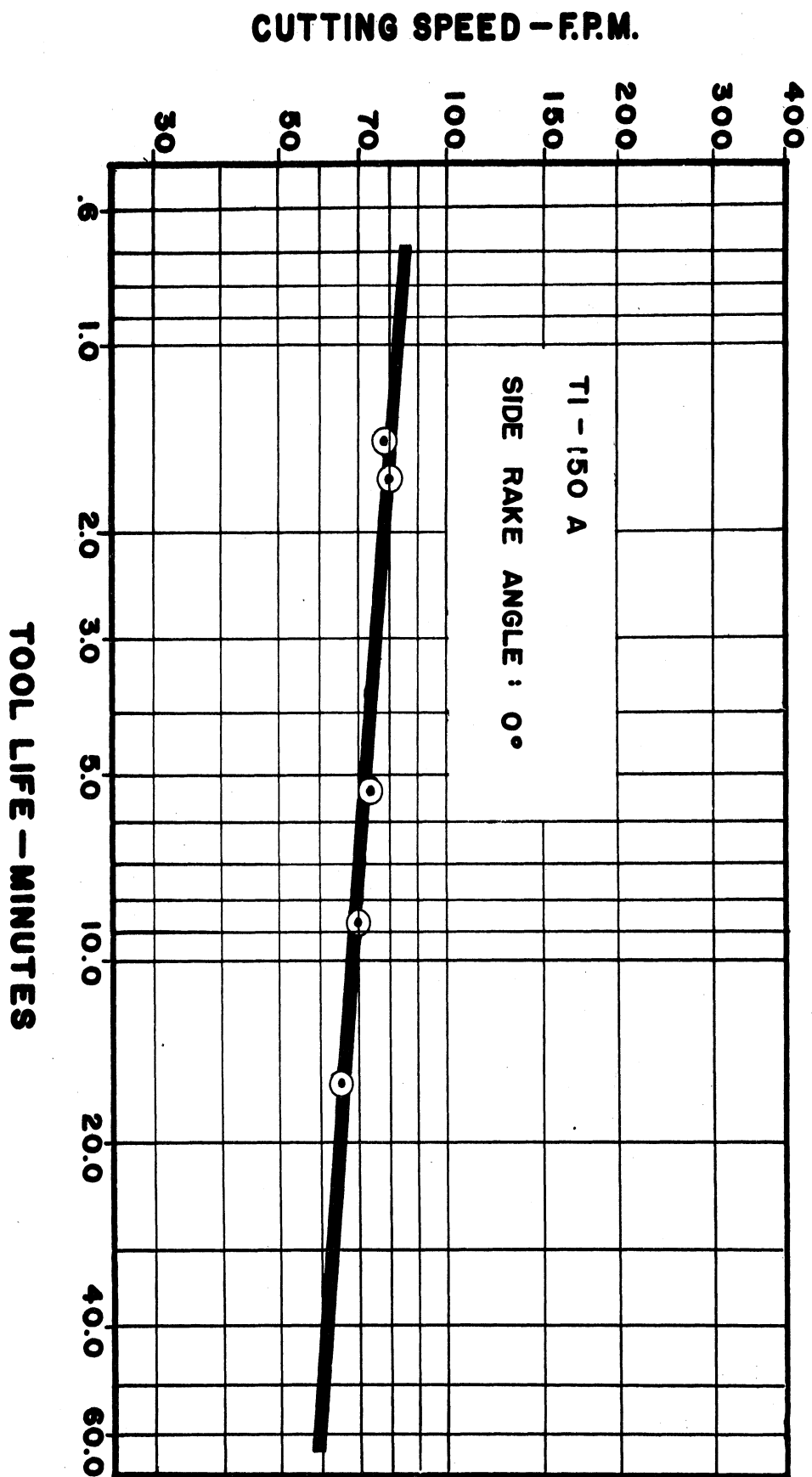


FIG. 23

# CUTTING SPEED — TOOL LIFE

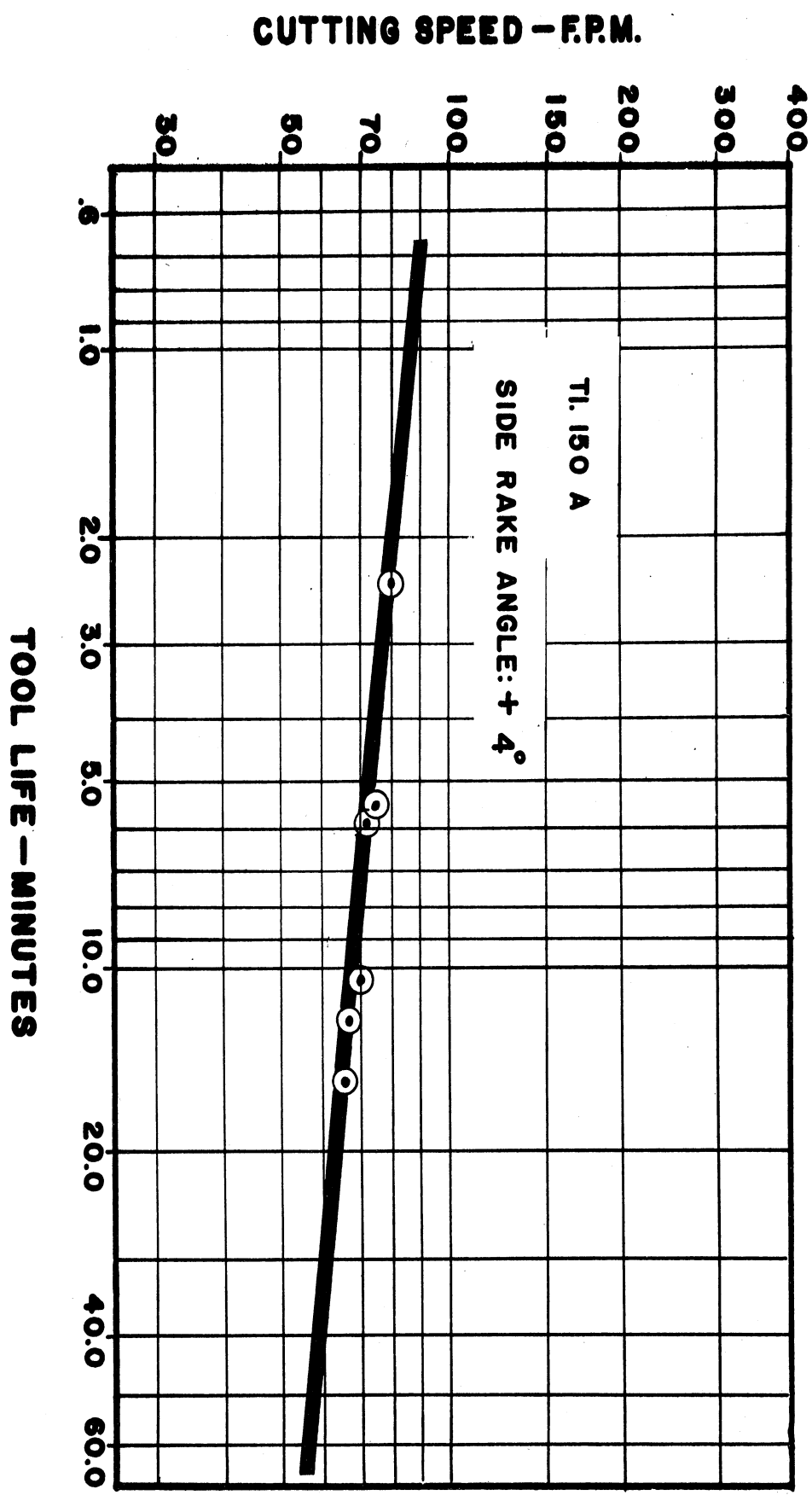


FIG. 24

# CUTTING SPEED — TOOL LIFE

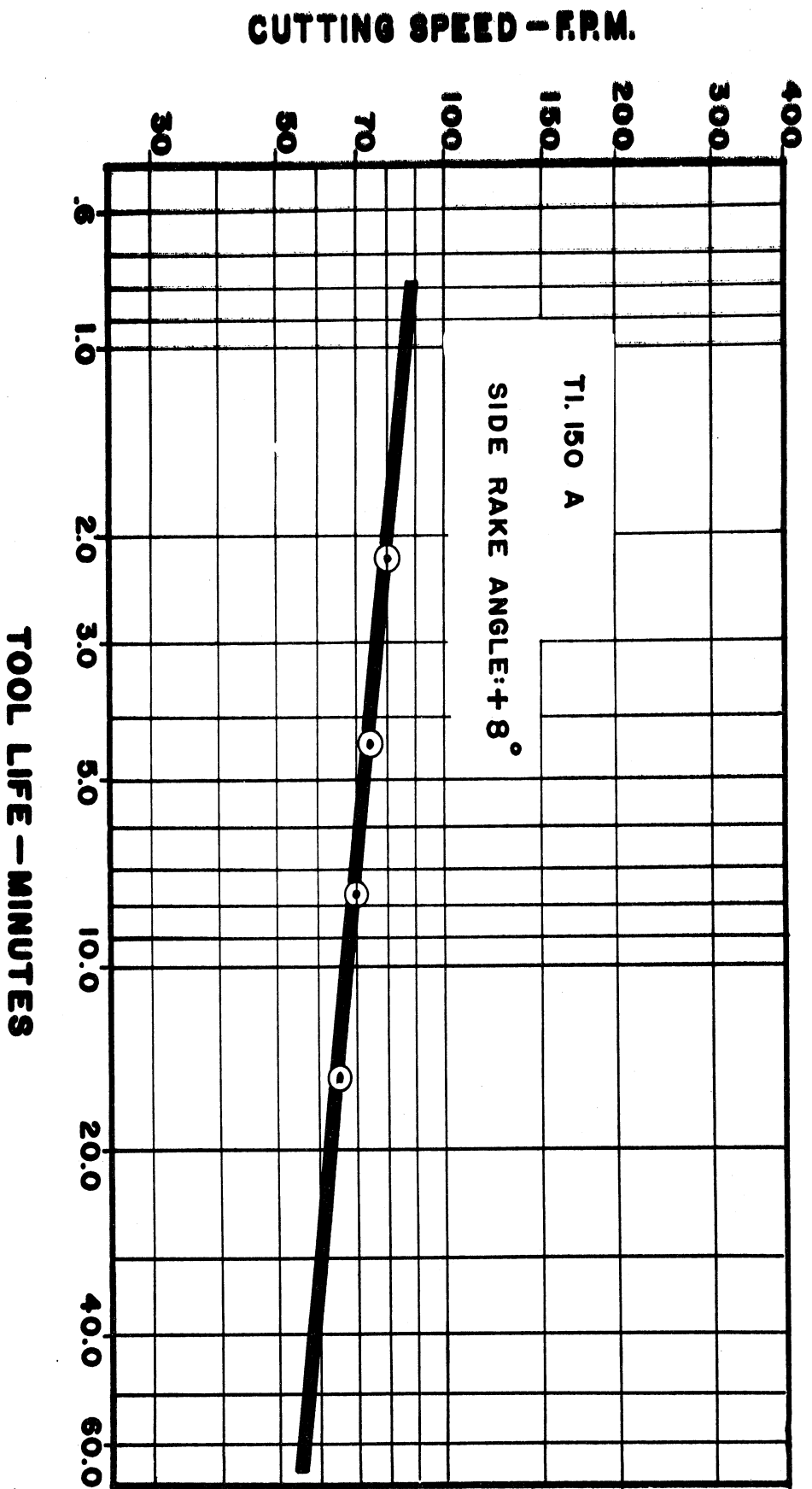


FIG. 25

# CUTTING SPEED — TOOL LIFE

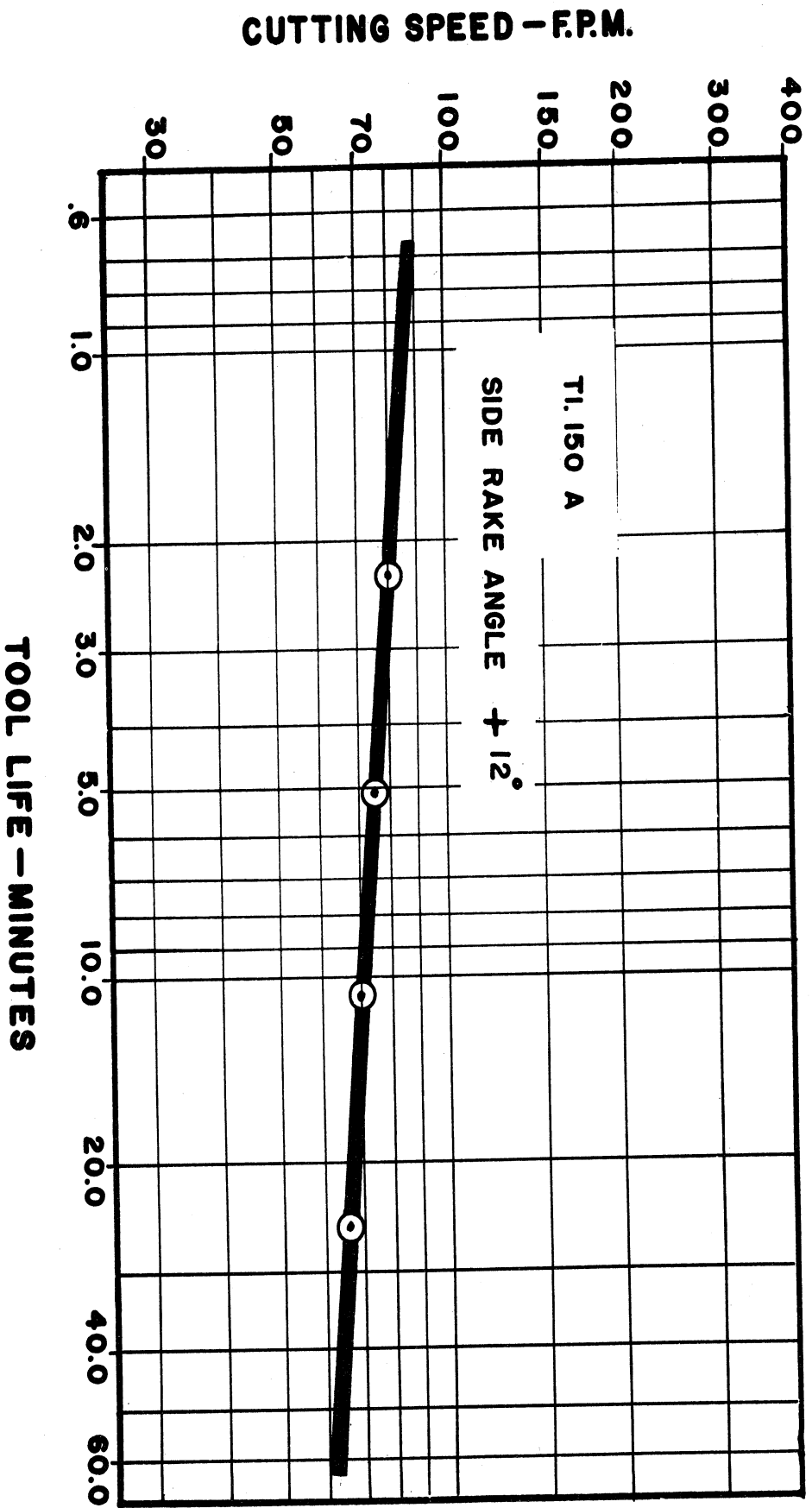


FIG. 26

# CUTTING SPEED — TOOL LIFE

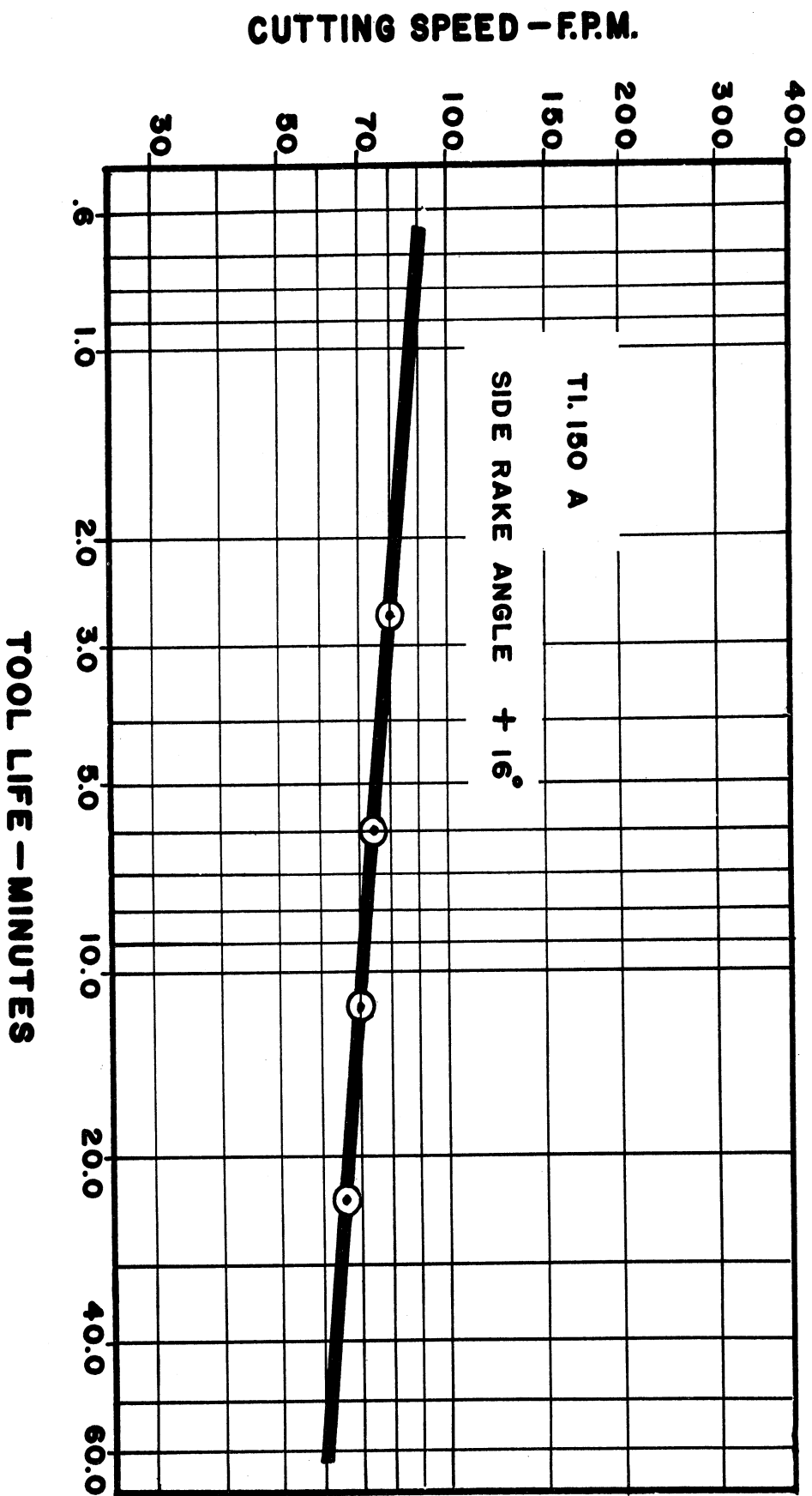


FIG. 27



# CUTTING SPEED — TOOL LIFE

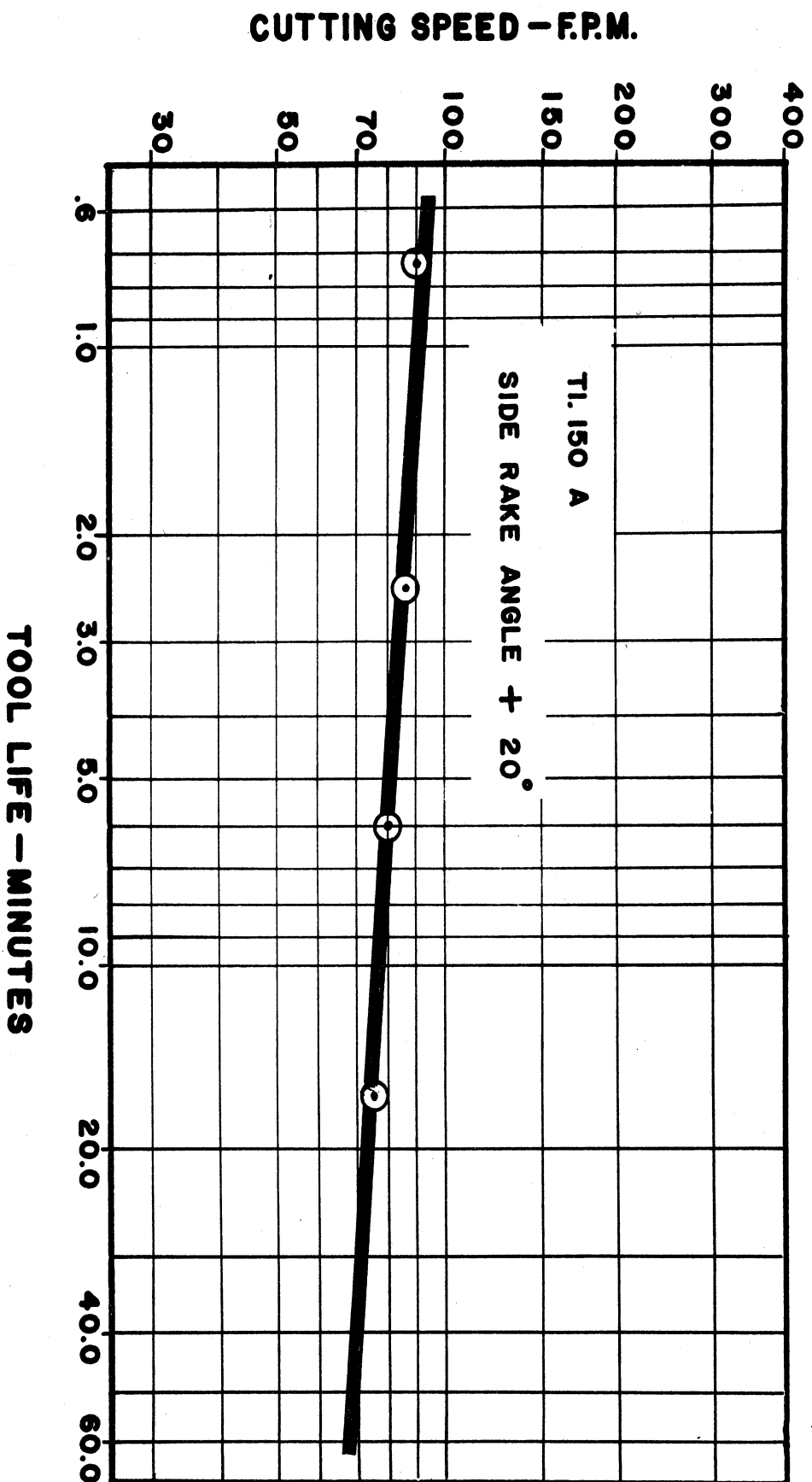


FIG. 28

# CUTTING SPEED — TOOL LIFE

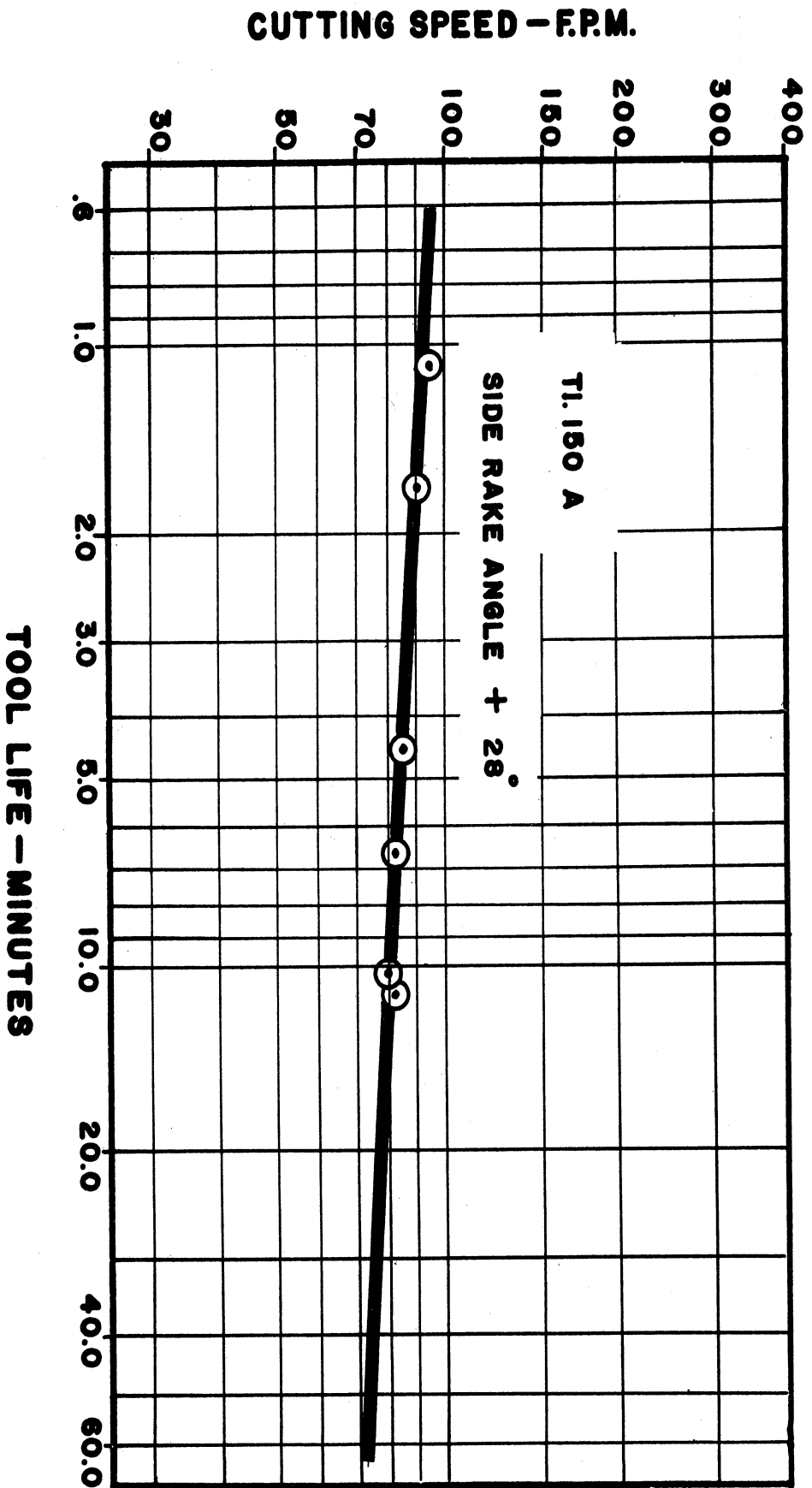


FIG. 29

# CUTTING SPEED — TOOL LIFE

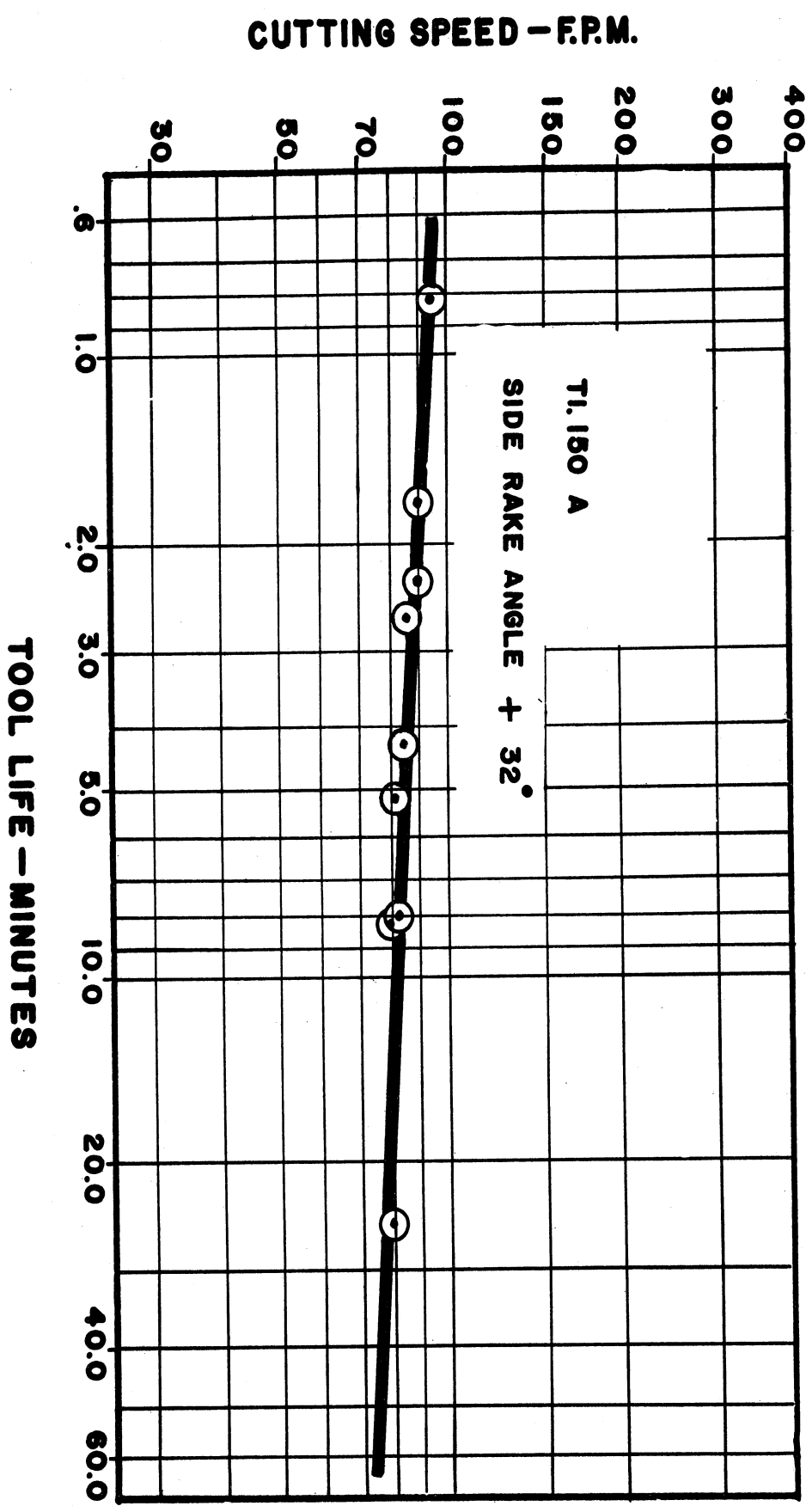


FIG. 30

# CUTTING SPEED — TOOL LIFE

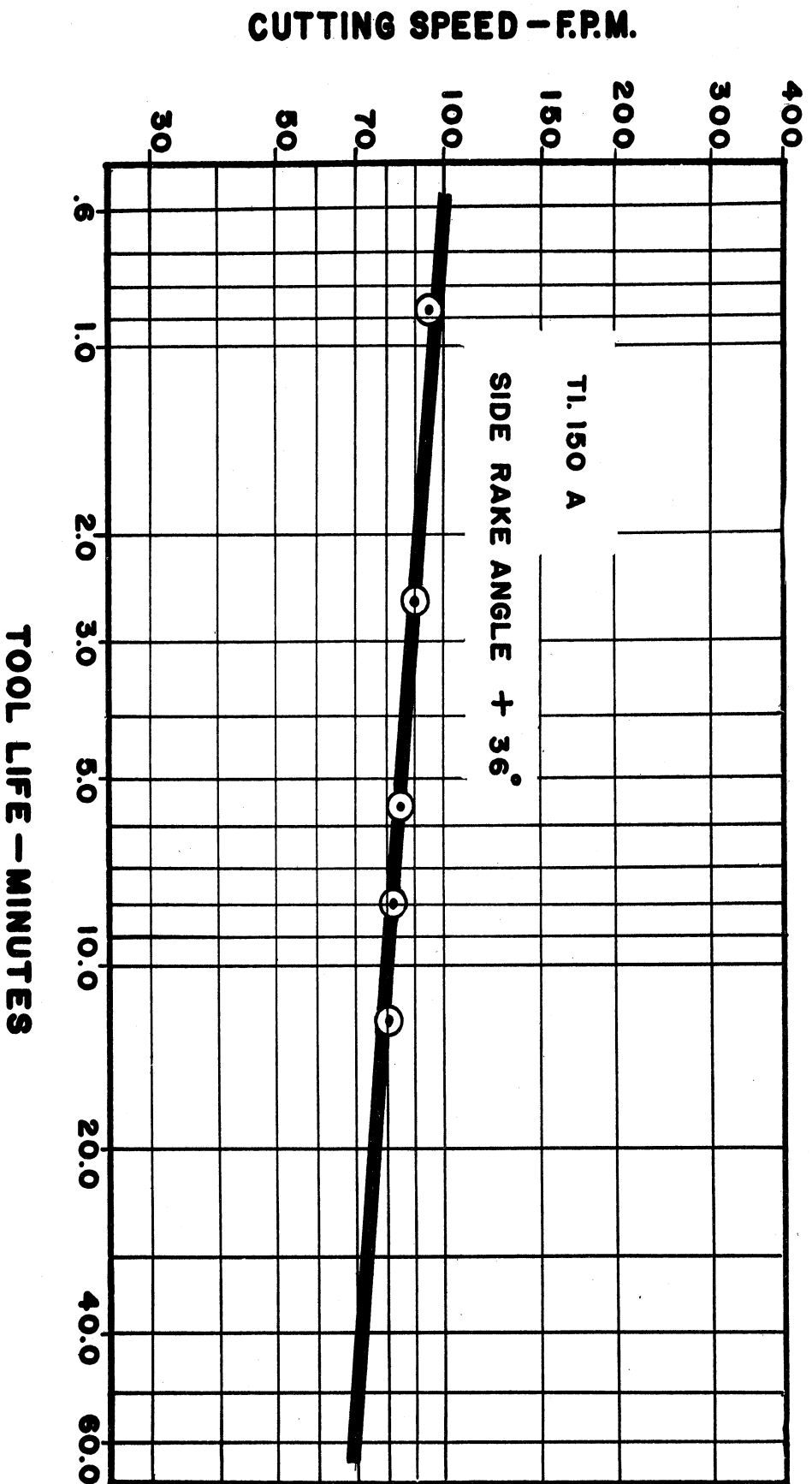


FIG. 31

# CUTTING SPEED — TOOL LIFE

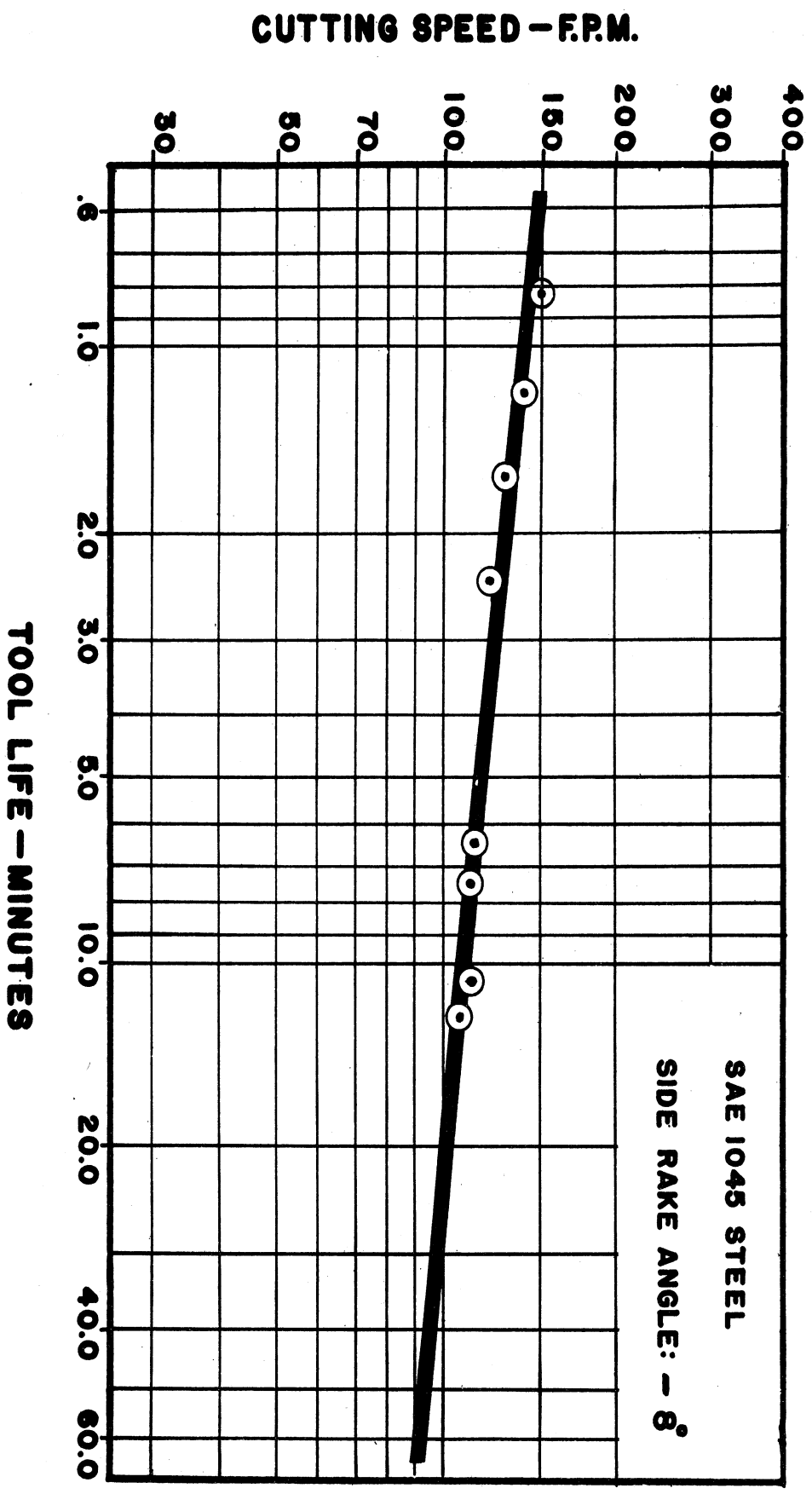


FIG. 32

# CUTTING SPEED — TOOL LIFE

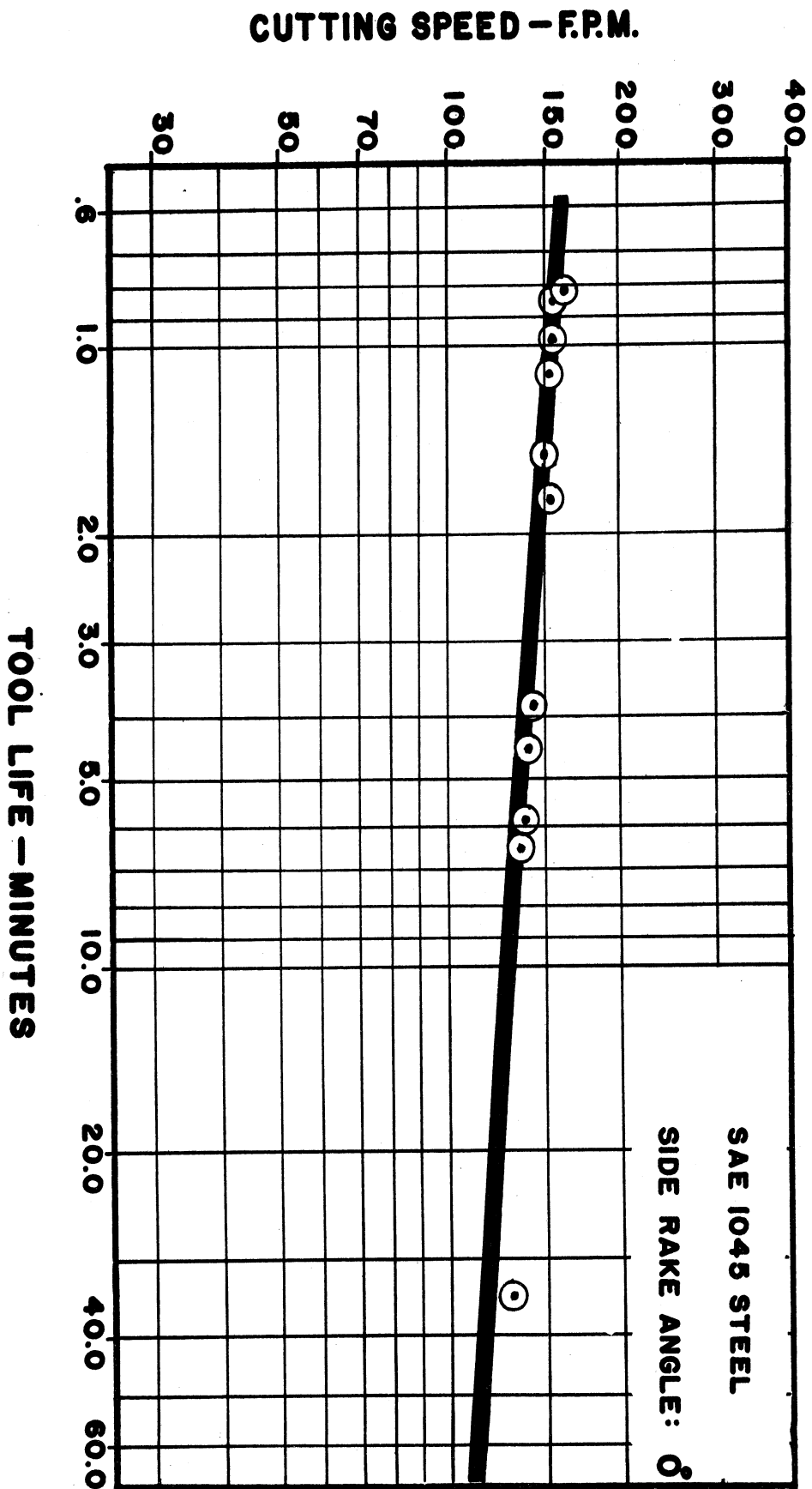


FIG. 33

# CUTTING SPEED — TOOL LIFE

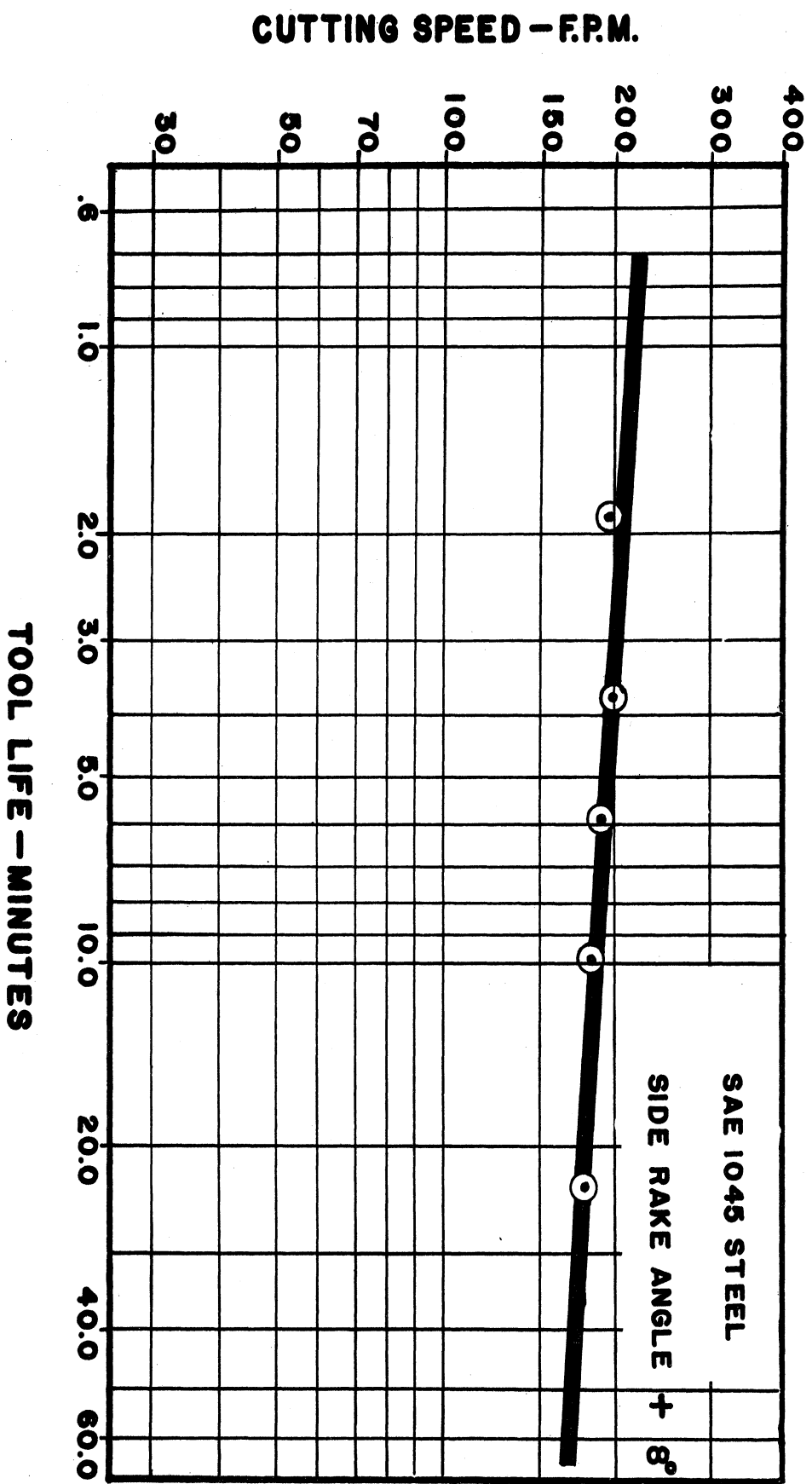


FIG. 34

# CUTTING SPEED — TOOL LIFE

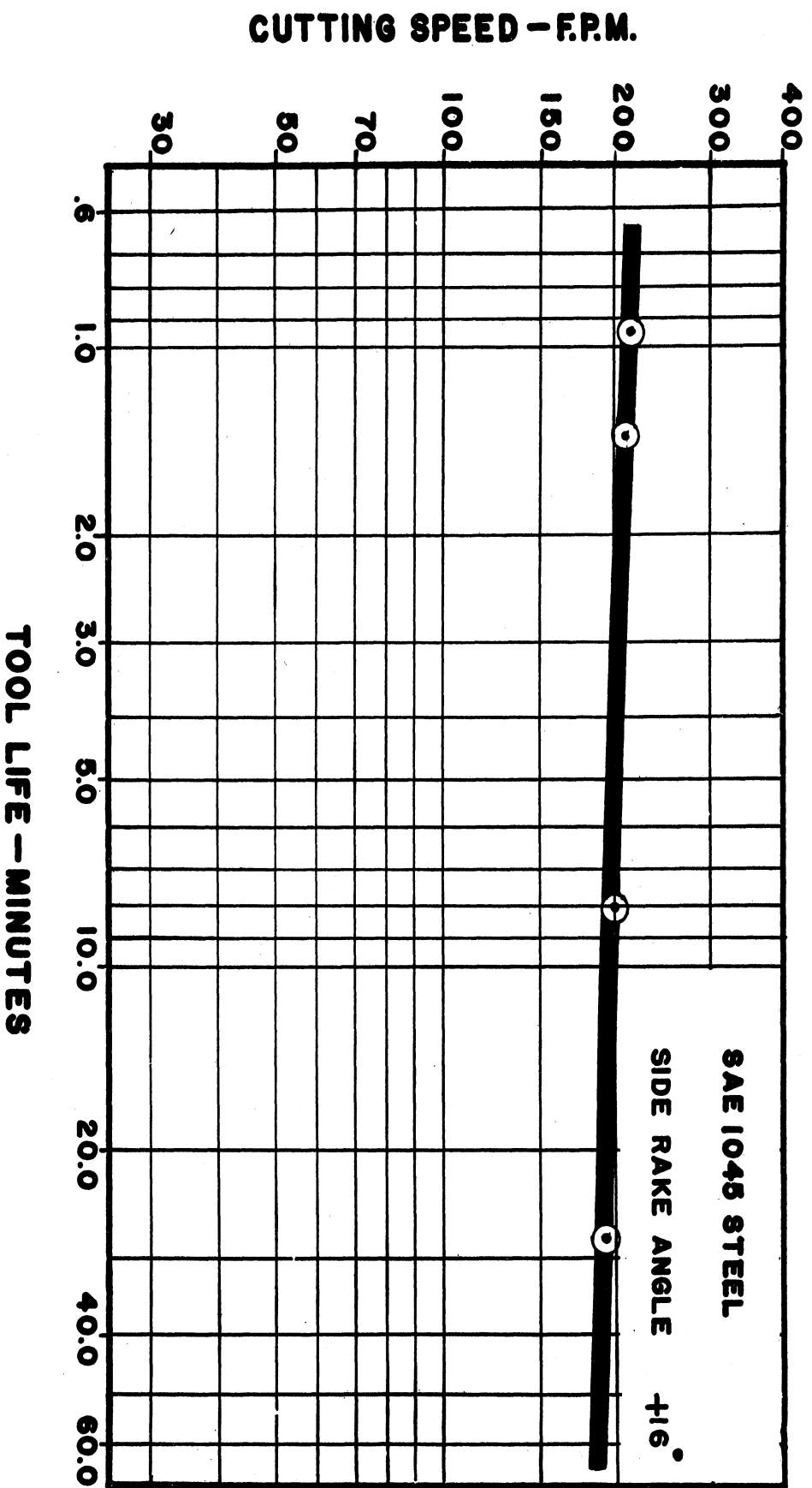


FIG. 35



# CUTTING SPEED — TOOL LIFE

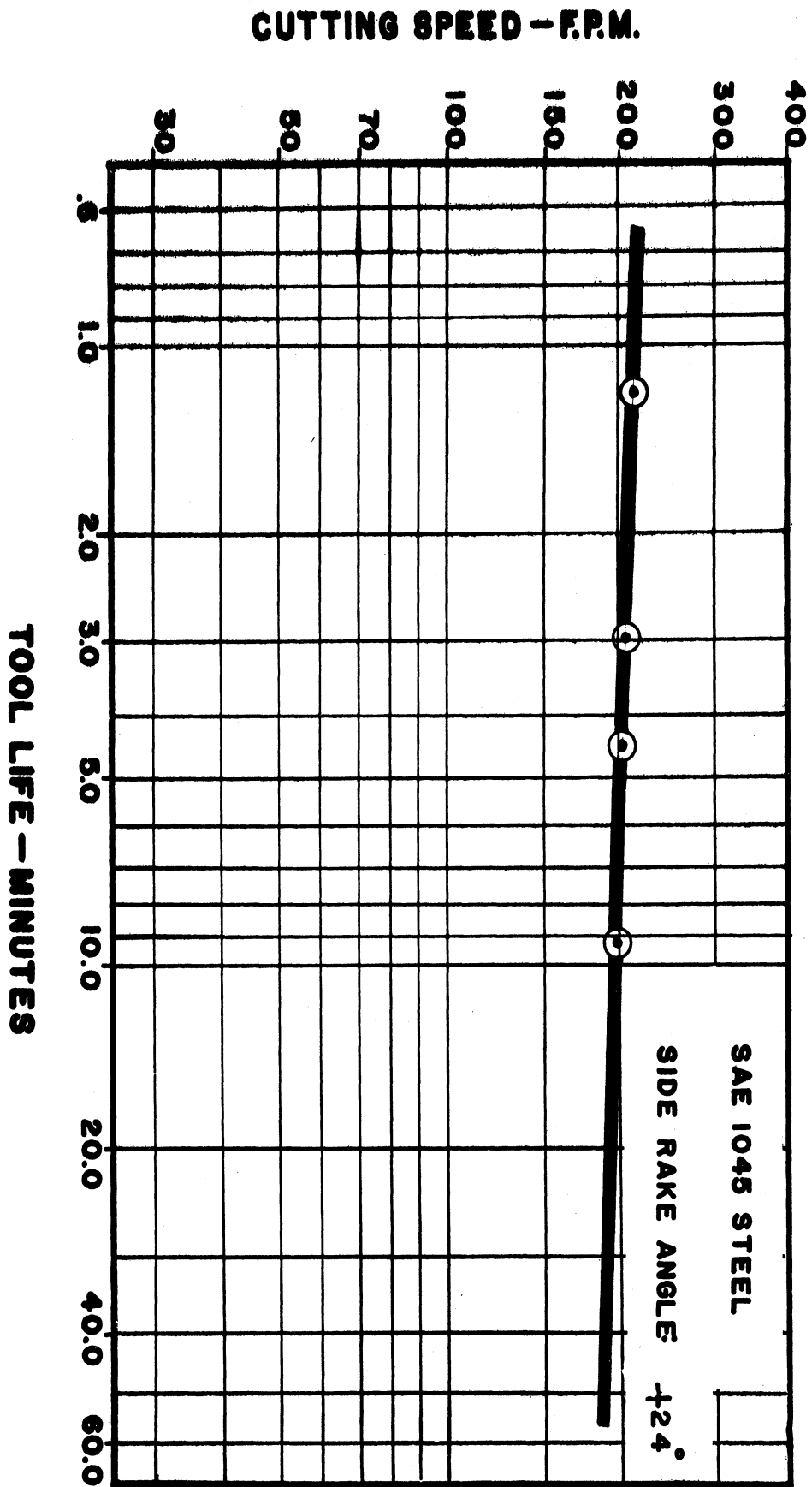


FIG. 36

# CUTTING SPEED — TOOL LIFE

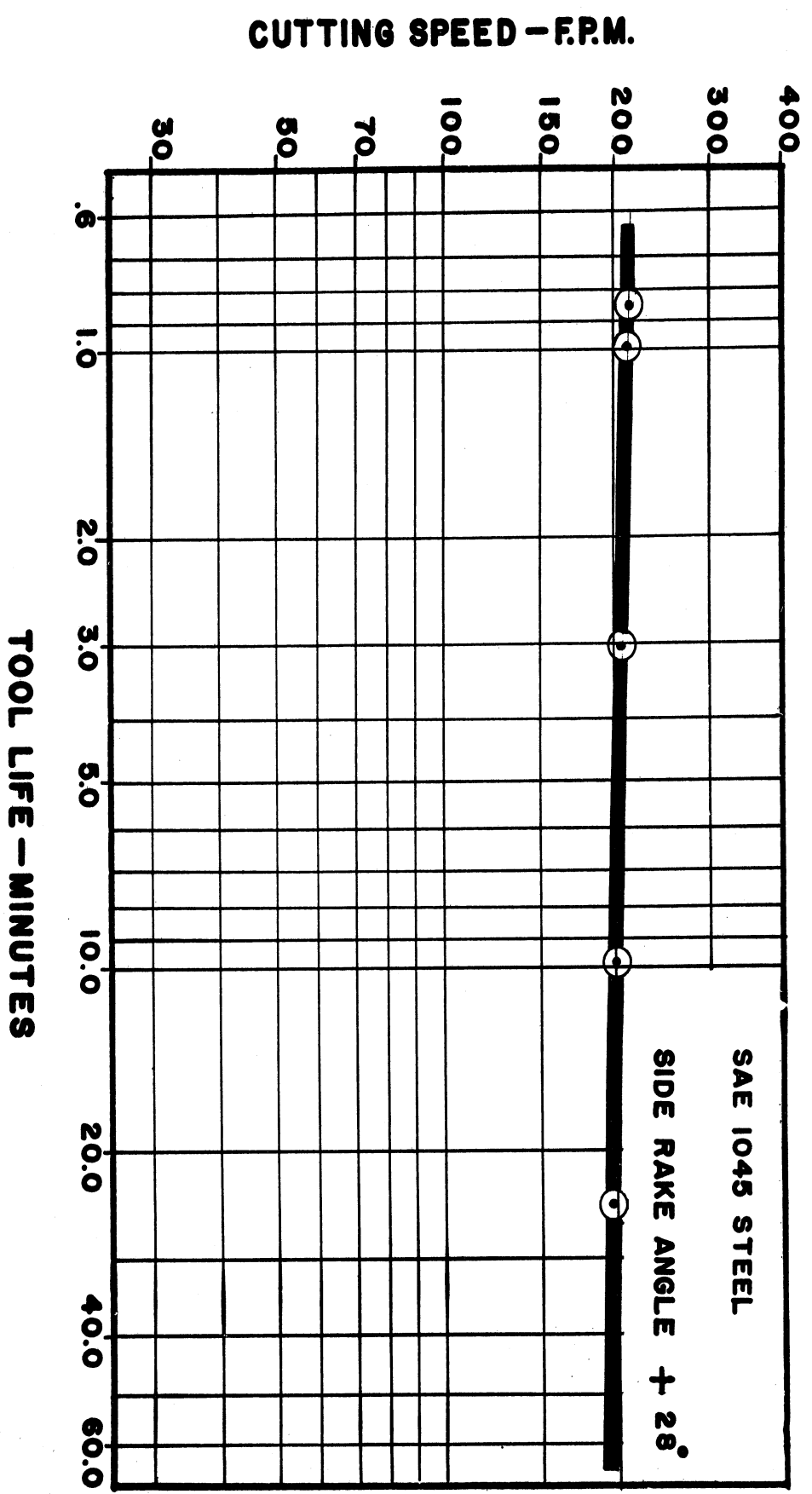


FIG. 37

# CUTTING SPEED — TOOL LIFE

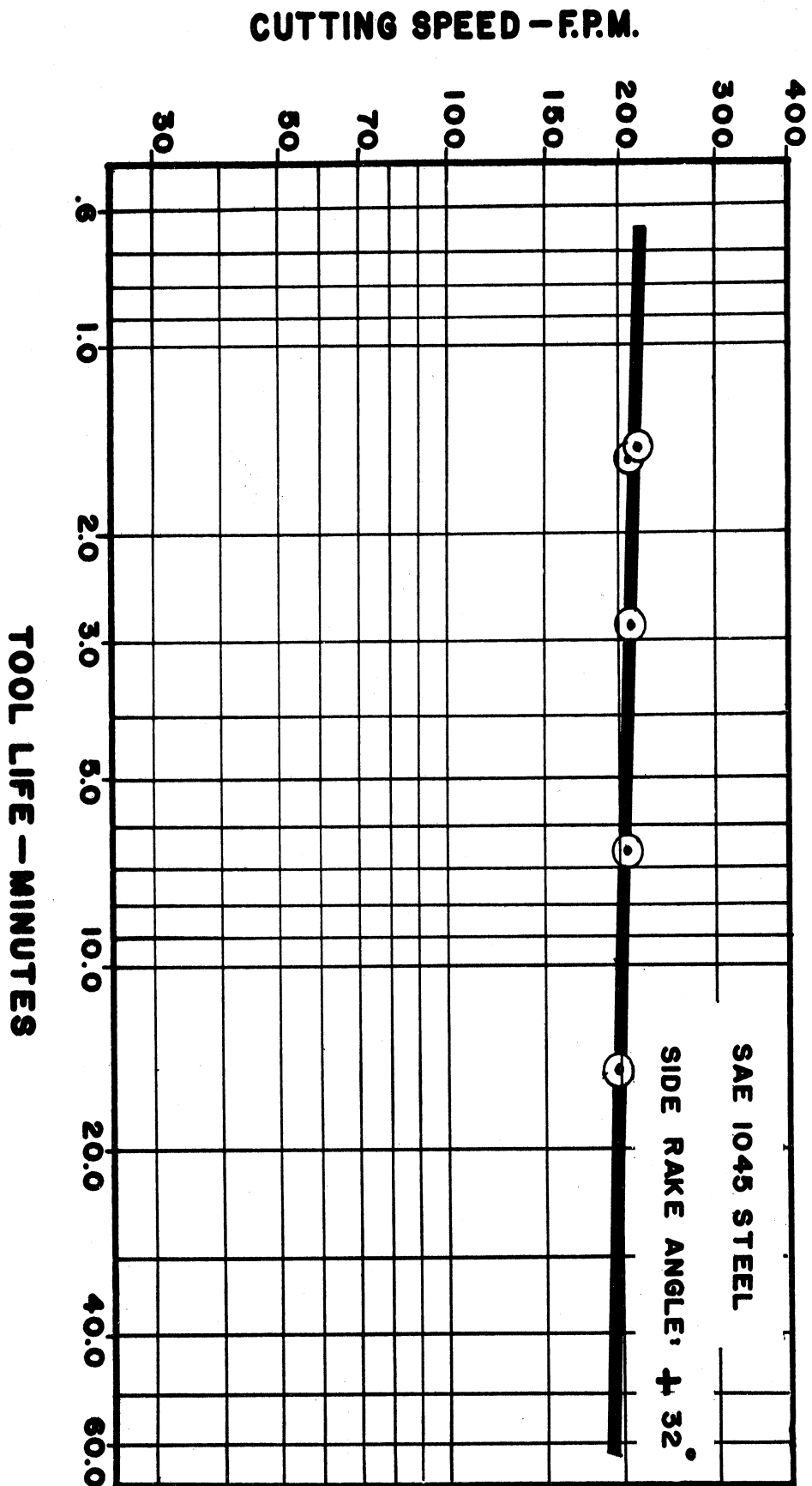


FIG. 38

# CUTTING SPEED — TOOL LIFE

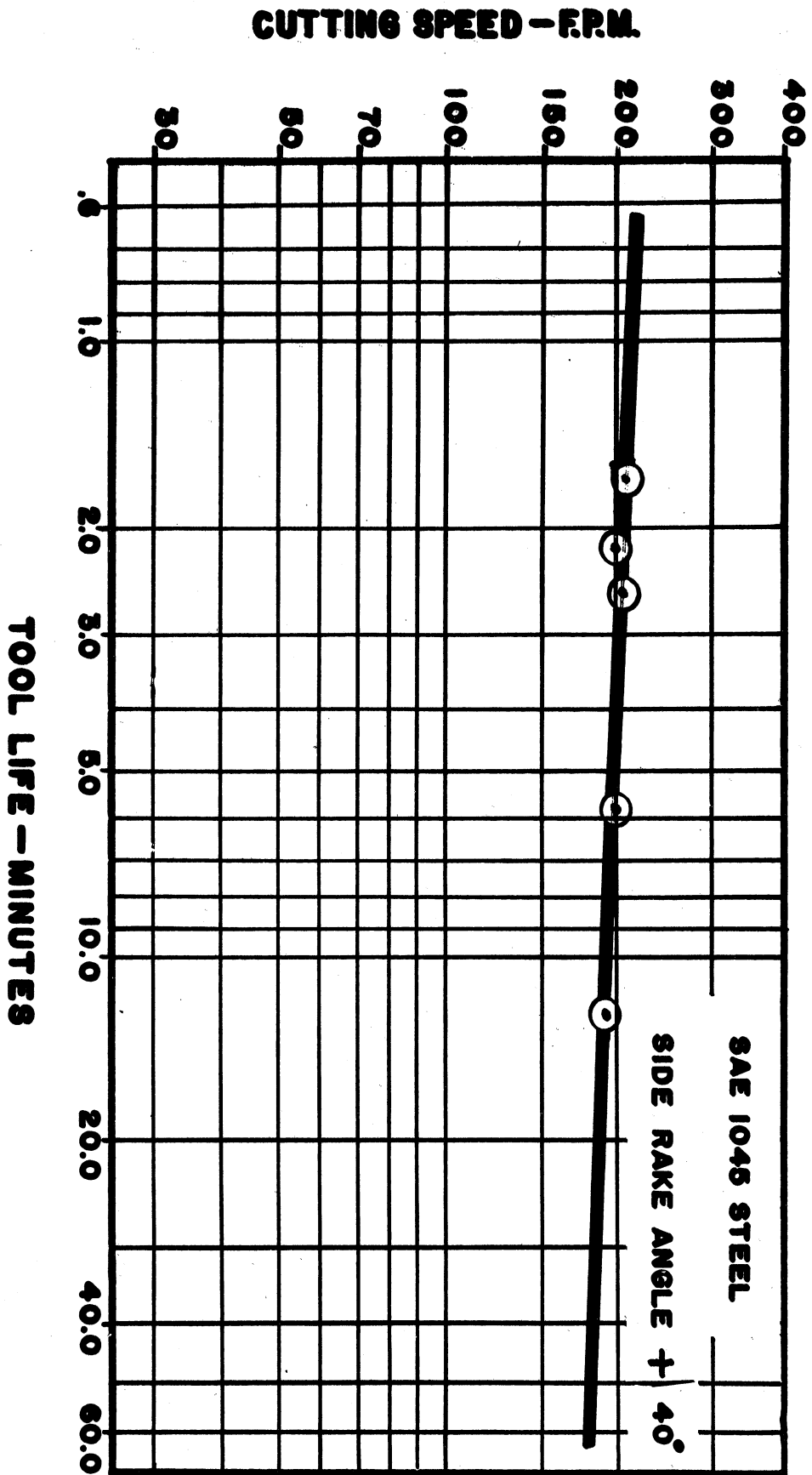


FIG. 39

# CUTTING SPEED — TOOL LIFE

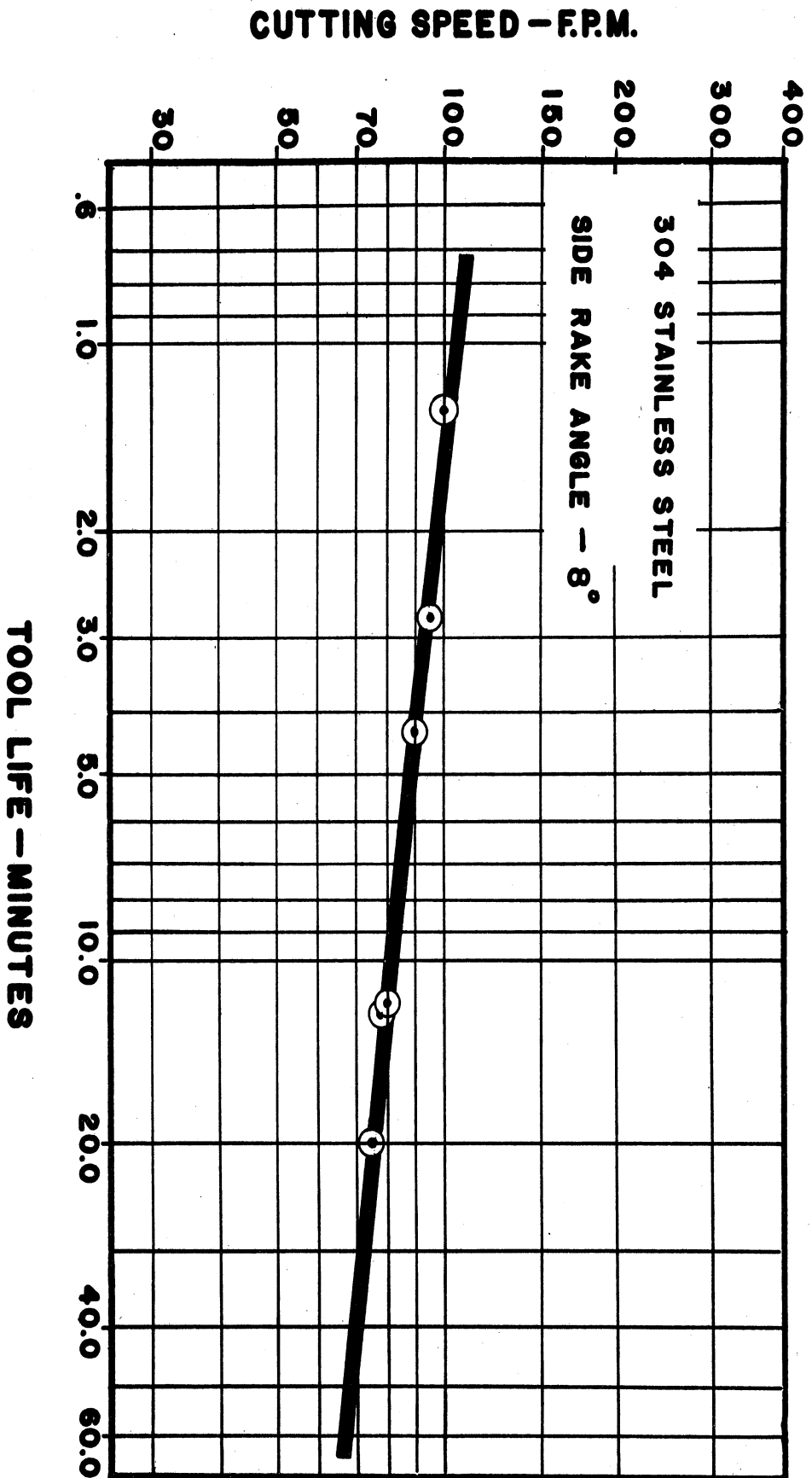


FIG. 40

# CUTTING SPEED — TOOL LIFE

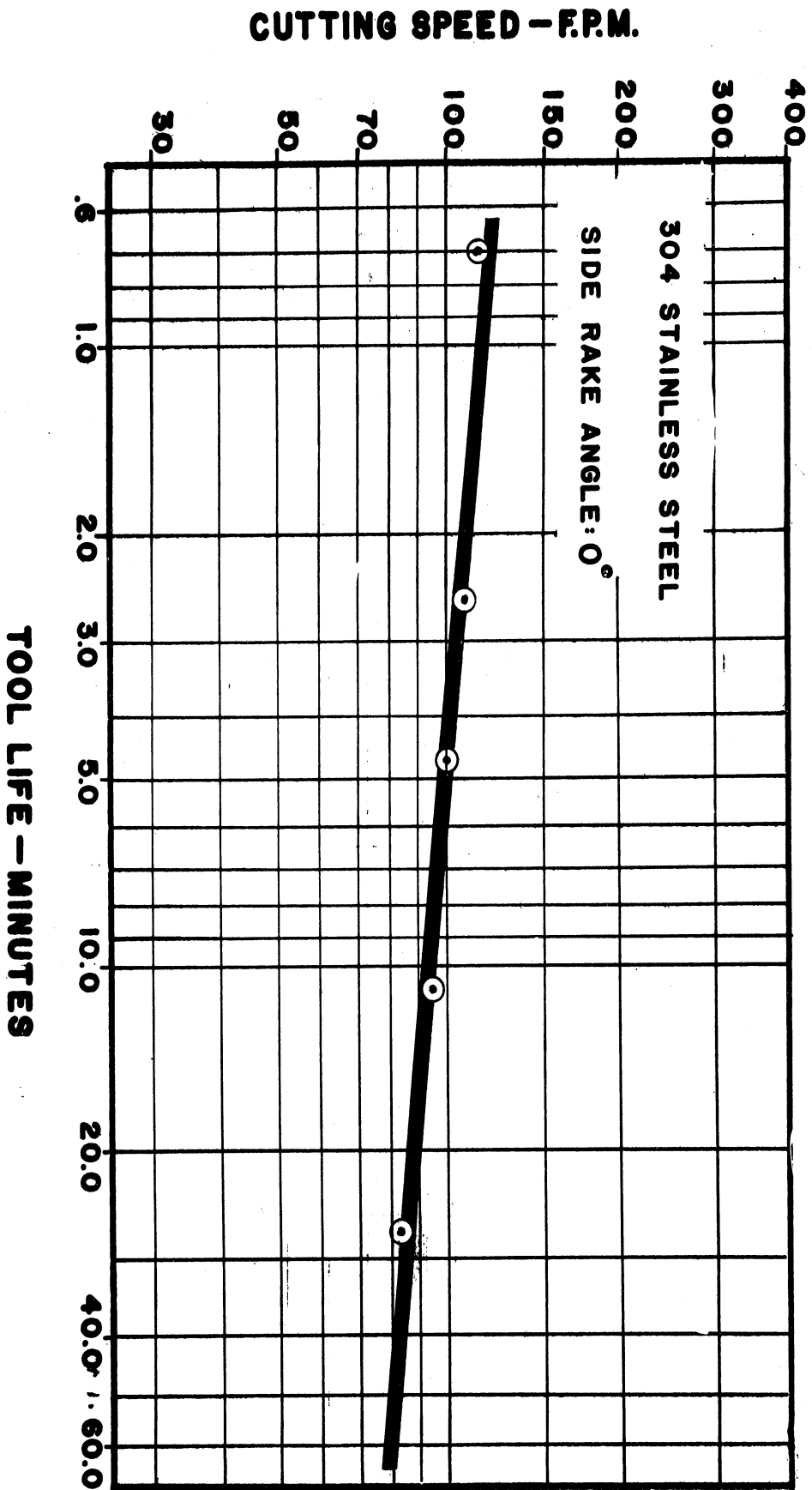


FIG. 41

# CUTTING SPEED — TOOL LIFE

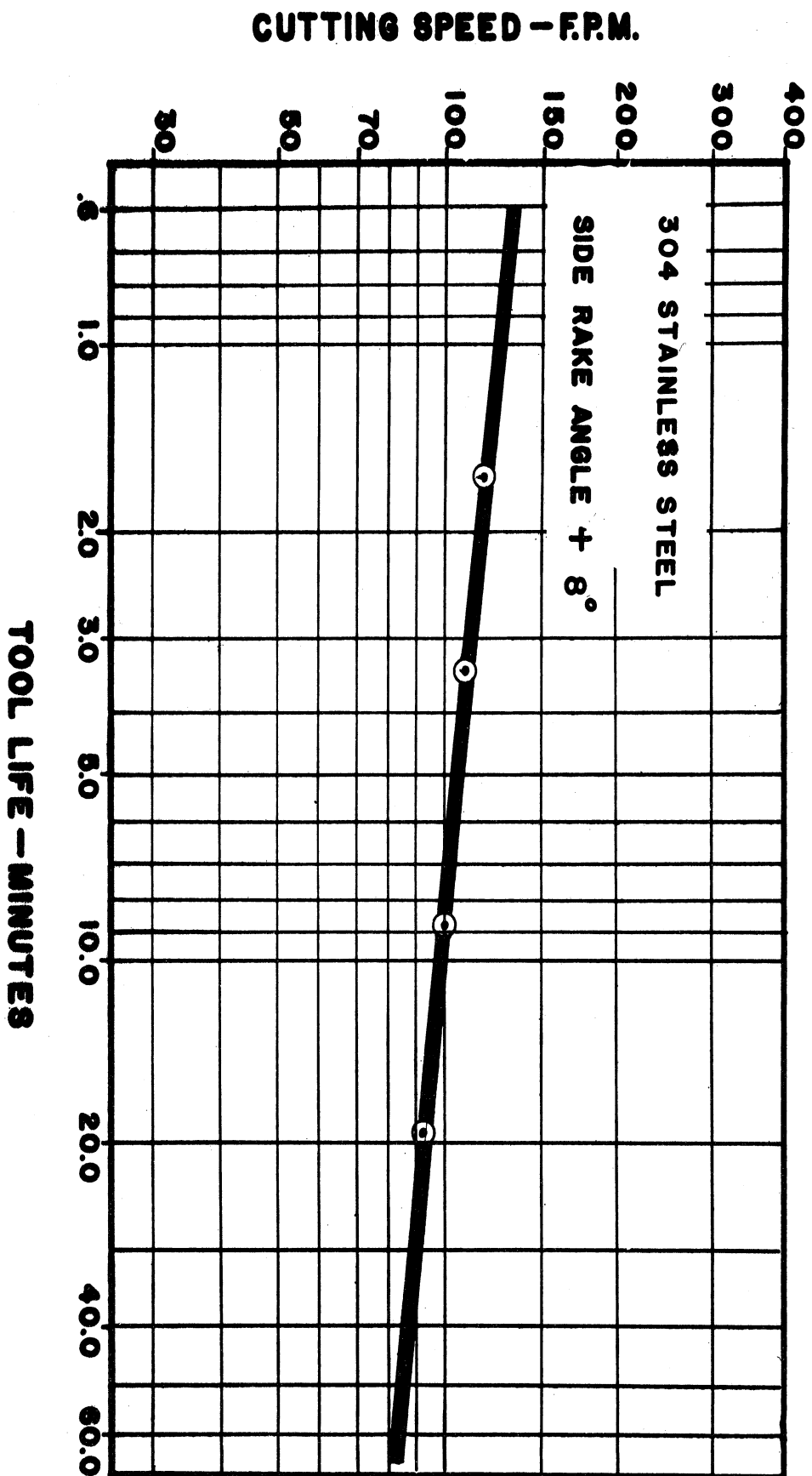


FIG. 42

# CUTTING SPEED — TOOL LIFE

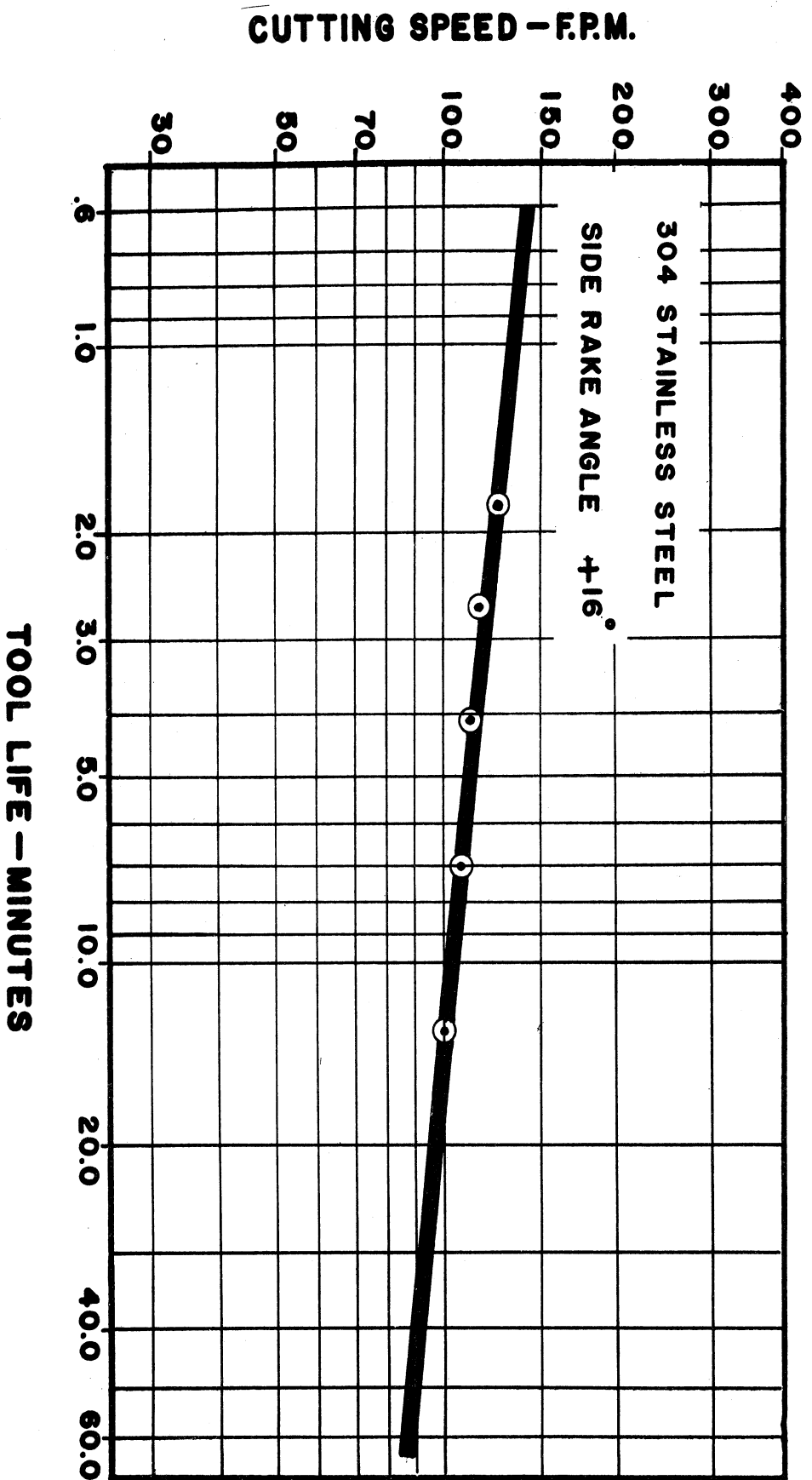


FIG. 43



# CUTTING SPEED — TOOL LIFE

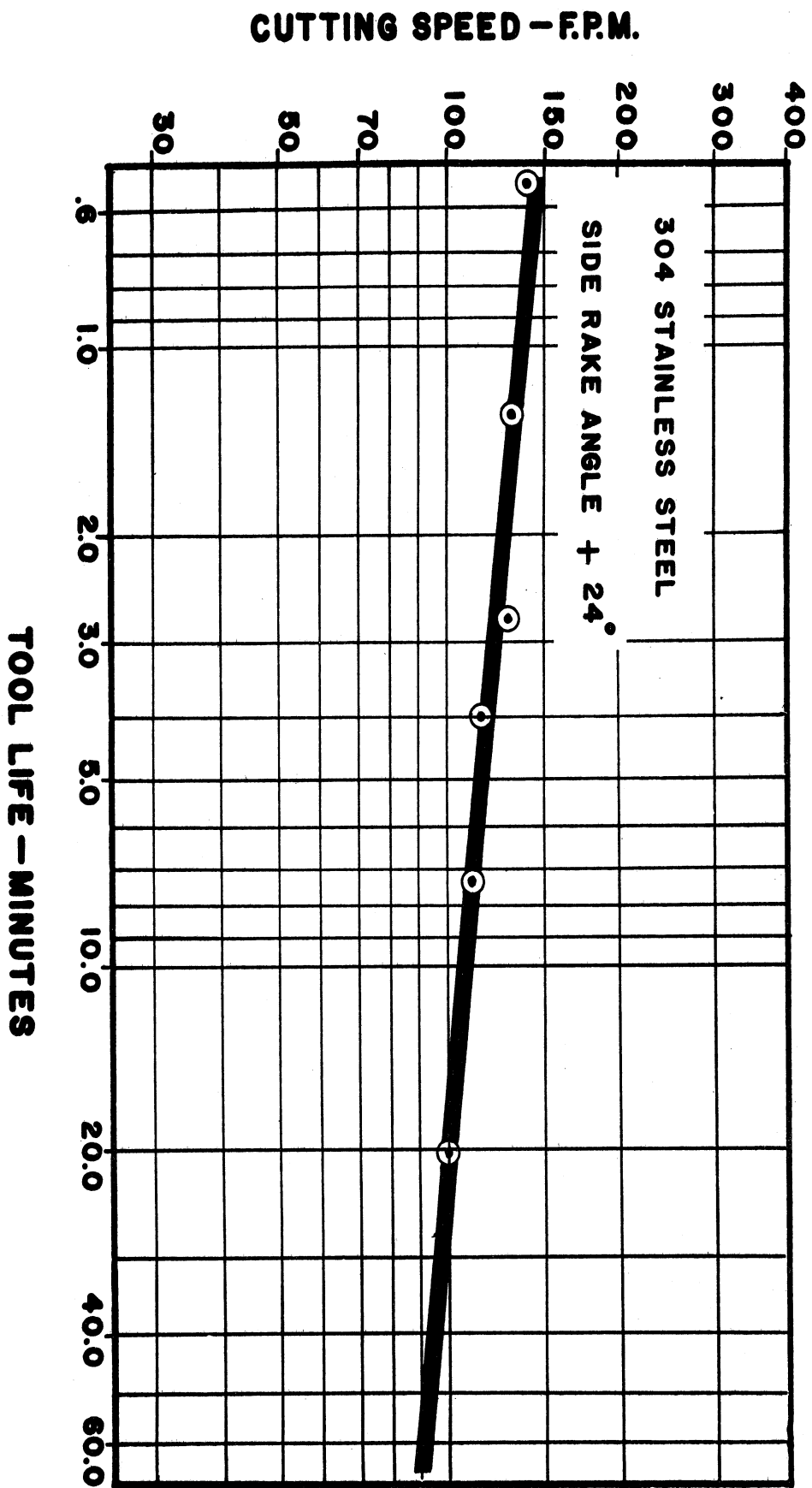


FIG. 44

# CUTTING SPEED — TOOL LIFE

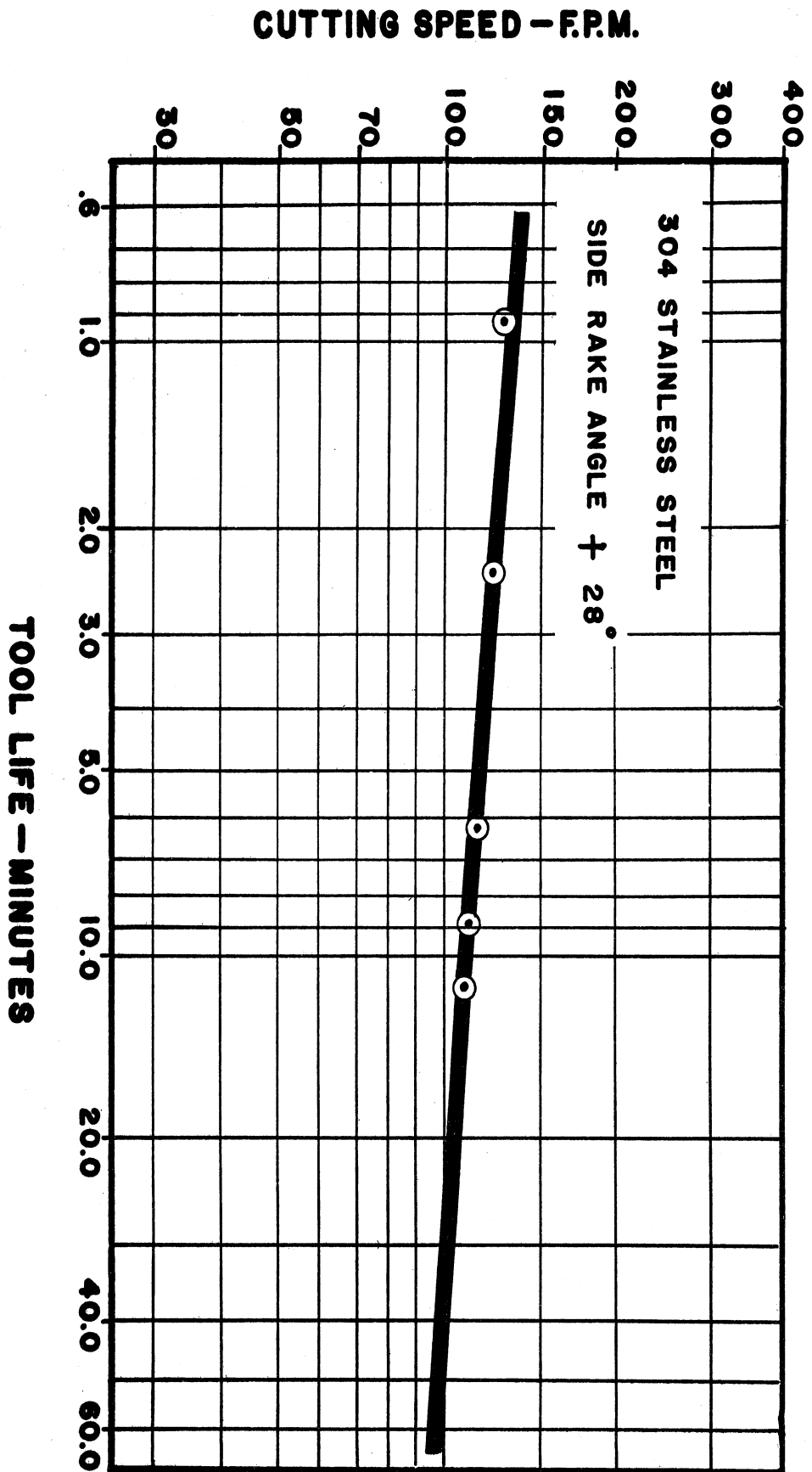


FIG. 45

# CUTTING SPEED — TOOL LIFE

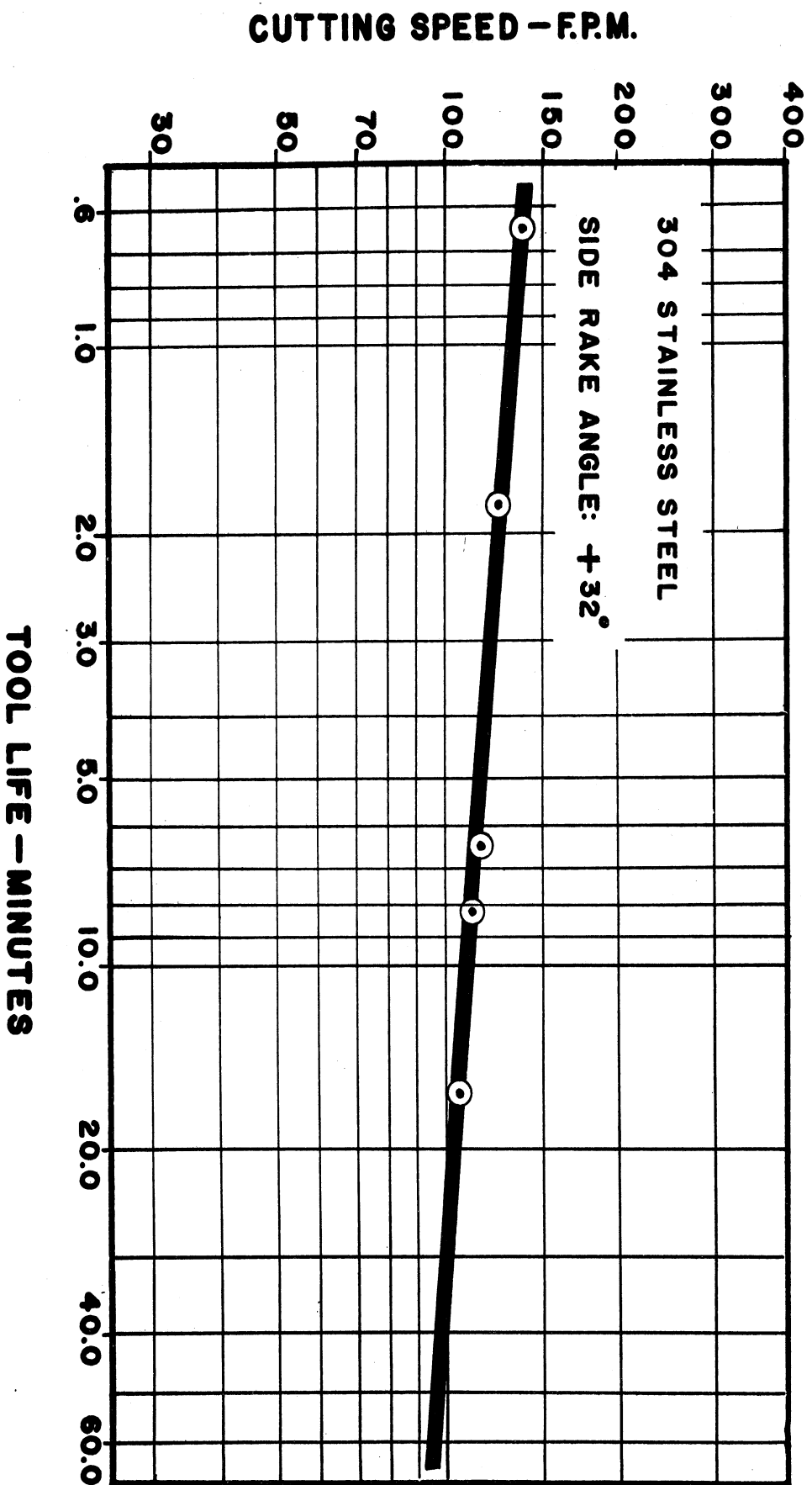


FIG. 46

# CUTTING SPEED — TOOL LIFE

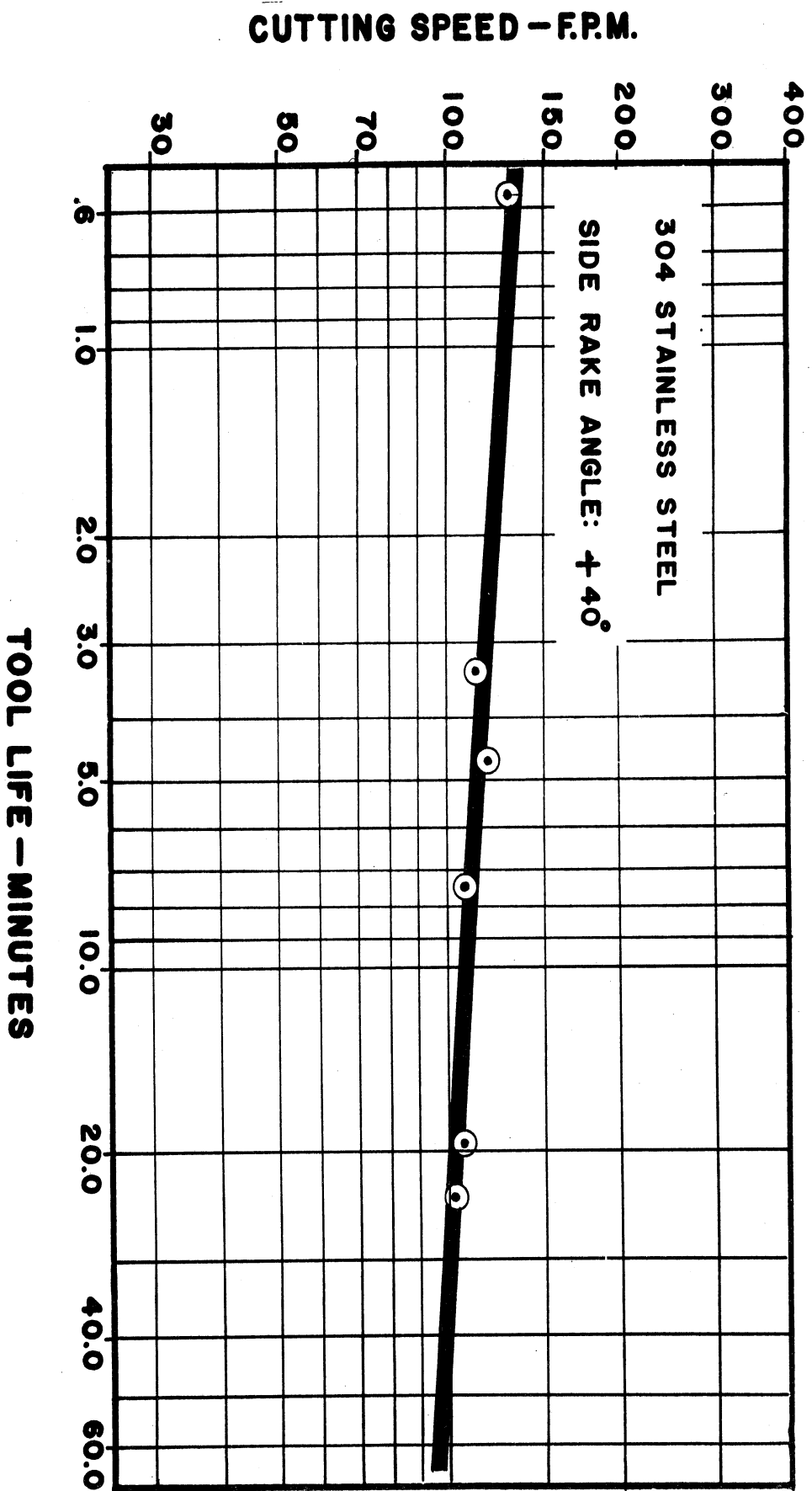


FIG. 47

# TOOL WEAR VS. TIME

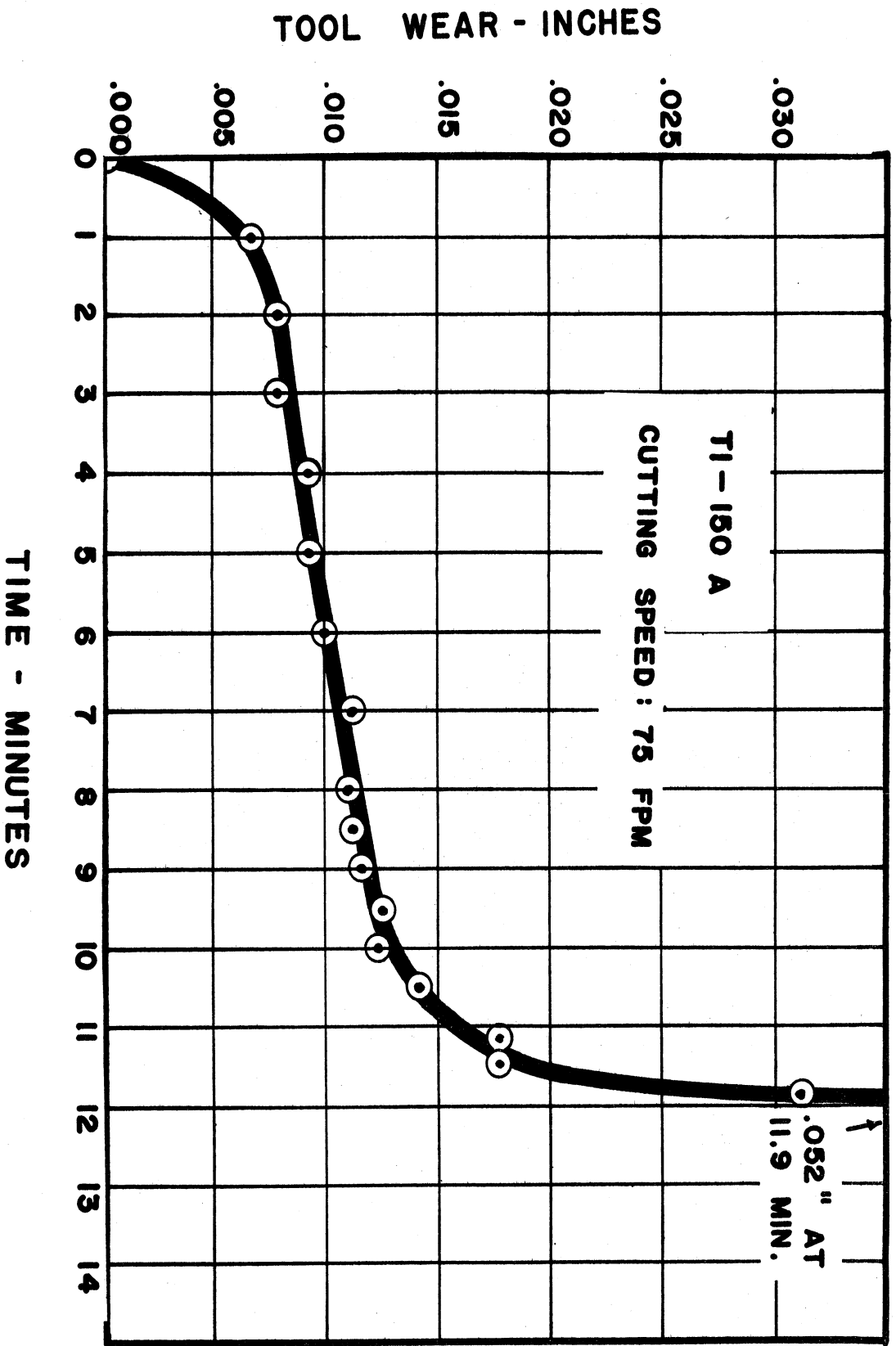


FIG. 48

# TOOL WEAR vs. TIME

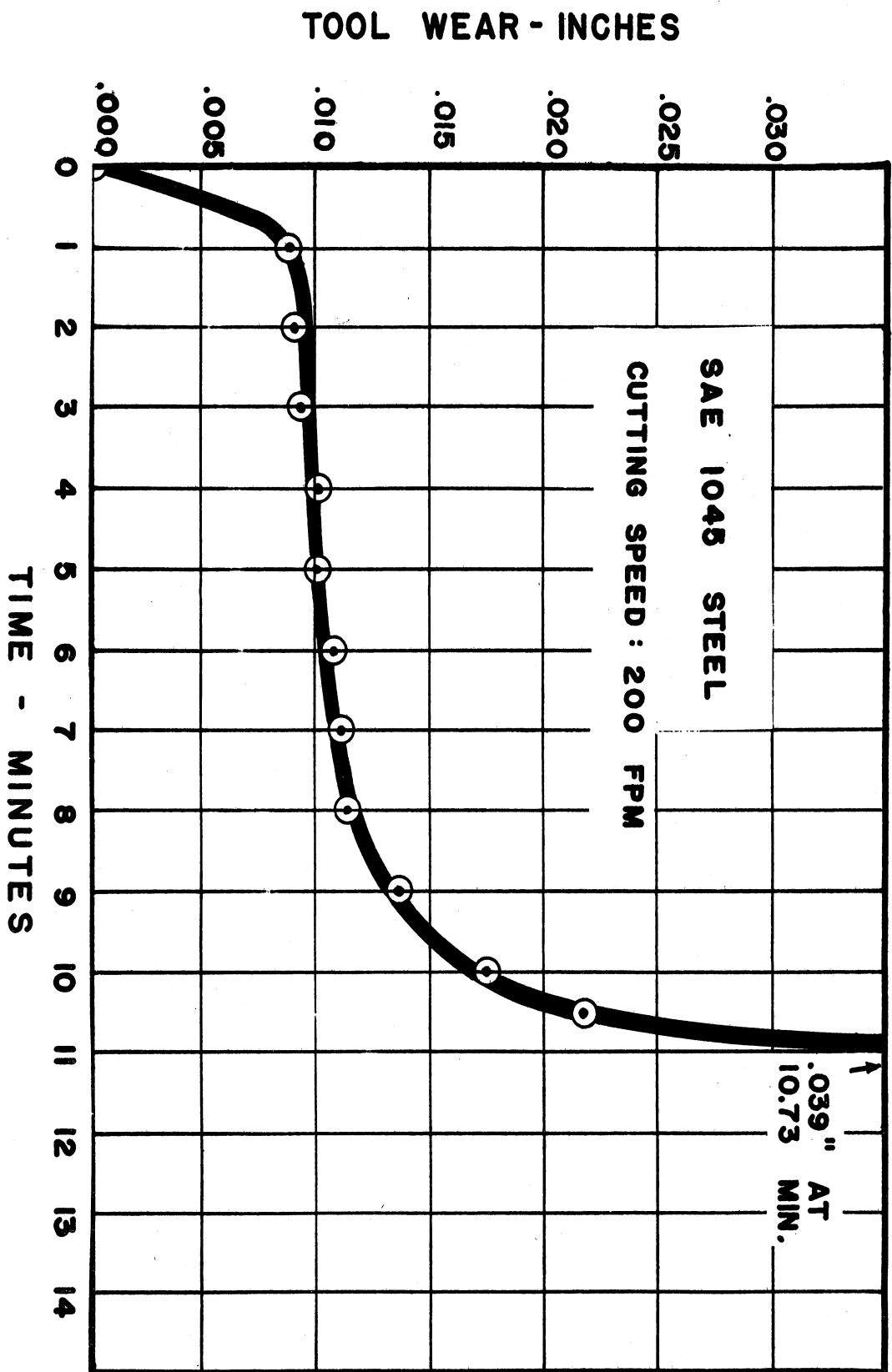
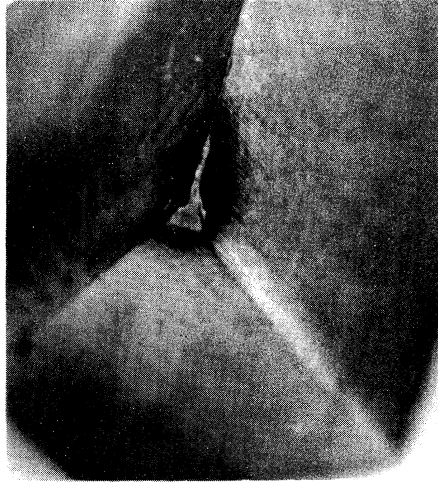
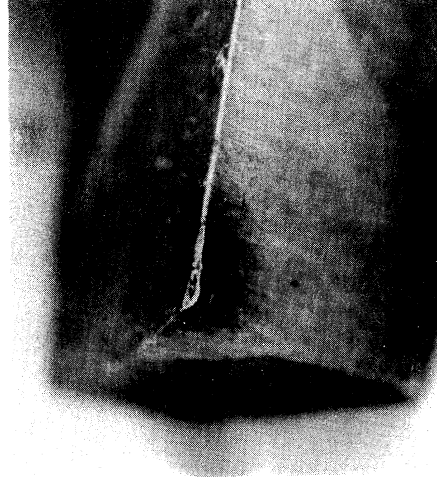


FIG. 49

**SAE  
1045  
STEEL**



**GRADE  
Ti 150 A  
TITANIUM**



**HALF LIFE**

**FAILED**

Flank wear at half life was .009 and .011 inches respectively for the steel and the titanium. Total tool life was approximately 11 minutes for each material. Tool signature was  $0^\circ$ ,  $32^\circ$ ,  $6^\circ$ ,  $6^\circ$ ,  $6^\circ$ ,  $15^\circ$ , and  $0.010$  inches, feed  $0.006$  ipr, depth =  $0.050$  inches, and cutting speed was 200 and 75 fpm respectively for the steel and the titanium