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February 1963

## MACHINING OF REFRACTORY MATERIALS

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CINCINNATI, OHIOContract: AF 33(600)-42349  
ASD Project: 7-532aPhase II Technical Engineering Report  
1 November 1962 - 31 January 1963

Tests to determine the feasibility of high speed milling (edge trimming) are in progress. Preliminary test results indicate that high speed milling offers a better than average potential for success in edge trimming 6Al-4V titanium sheet and 15-7 Mo sheet in the 500 to 2500 feet/minute cutting speed range. Drilling tests have been made using the Tornetic drilling unit and a constant speed drill press on D6AC steel in the 54-58 R<sub>C</sub> hardness range. Tapping test results on B-120VCA titanium at 400 BHN are presented comparing the Tornetic tapping data with conventional tapping. Machining test data is also presented on B-120 VCA titanium, TZM Molybdenum, Mo 0.5 Ti and D-31 Columbium alloy.

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Air Force Systems Command  
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MACHINING OF REFRACTORY MATERIALS

N. Zlatin

et al

Metcut Research Associates Inc.

An investigation to determine the feasibility of high speed milling (edge trimming) the thermal resistant alloys is in progress. Preliminary results obtained on 6Al-4V Titanium sheet and PH 15-7 Mo stainless sheet indicate that these alloys can be edge milled successfully at cutting speeds ranging from 500 to 2000 feet per minute.

A tool life of 202 feet of work travel was obtained when milling 6Al-4V Titanium sheet (35-36 R<sub>C</sub>) .125" thick, at a cutting speed of 500 feet/minute, a feed of .010 inches/tooth and a depth of cut of .050". A 1-1/4" diameter, 3 flute throw-away carbide end mill with Grade 883 (C-2) carbide inserts was used for these tests. The cutter had a 0° axial rake, 0° radial rake and a 5° peripheral clearance angle. Liquid CO<sub>2</sub> was used as the cooling medium. However, when this test was performed without liquid CO<sub>2</sub> (dry) a tool life of 172 feet of work travel was obtained.

With the same test conditions listed above, a tool life of 228 feet of work travel was obtained when milling a thinner 6Al-4V Titanium sheet (.063") with liquid CO<sub>2</sub>. Cutting speeds higher than 500 feet/minute - up to 2000 feet/minute - and feeds higher than .005 inches/tooth - up to .020 inches/tooth - reduced tool life significantly. Increasing the depth of cut from .050" to .100" also reduced tool life by about one half, however, when the depth of cut was increased from .100" to .150" tool life was reduced less than 10%.

When high speed edge trimming PH 15-7 Mo stainless steel sheet, .063" thick, annealed to 90 R<sub>B</sub>, a tool life of 150 feet of work travel was obtained. The cutting speed was 1500 feet/minute with a feed of .015 inches/tooth milling dry, without liquid CO<sub>2</sub>. With liquid CO<sub>2</sub>, the best tool life obtained was 97 feet of work travel at 1500 feet/minute and a .015 inches/tooth feed rate.

Comparative drilling tests performed on the Tornetic drilling unit and a constant speed and feed drilling machine on D6AC steel quenched and tempered 54-58 R<sub>C</sub> showed that approximately 25% fewer holes were obtained on the Tornetic unit. More important, however, was the fact that the feed rate had been reduced to one half of its original value by the time the last few holes were drilled.

When tapping B-120VCA titanium solution treated and aged to 400 BHN using the Tornetic tapping unit and a conventional tapping machine, almost twice as many holes were obtained on the conventional tapping machine.

MACHINING OF REFRACTORY MATERIALS

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METCUT RESEARCH ASSOCIATES INC.  
CINCINNATI, OHIO  
Contract: AF 33(600)-42349  
ASD Project: 7-532a

Phase II Technical Engineering Report  
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## FOREWARD

This Phase II Interim Technical Progress Report covers the work performed under Contract AF 33(600)-42349 from 1 November 1962 to 31 January 1963. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio was initiated under ASD Manufacturing Technology Laboratory Project 7-532a, "Machining of Refractory Materials". It is being administered under the direction of Mr. Robert T. Jameson of the Fabrications Branch (ASRCTF), Manufacturing Technology Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

Mr. Norman Zlatin, Director of Machinability Research at Metcut, is the engineer in charge of this program. Others who have cooperated in the investigation reported herein and preparation of the report were Mr. J. V. Gould, Project Engineer, and Dr. Michael Field, Research Director. This project has been given the Metcut Research Internal No. 470-3300.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR".

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional development required on this or other subjects will be appreciated.

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## PUBLICATION REVIEW

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## 1. INTRODUCTION

The purpose of this program is to investigate and evaluate the machining characteristics of the refractory materials, selected high temperature alloys, and high strength steels of importance to the aerospace industry.

The machining research on the various alloys is being carried out under Phase II of the subject contract, and this report presents the results obtained during the period of 1 November 1962 to 31 January 1963.

Tests to determine the feasibility of high speed milling (edge trimming) are in progress. Preliminary test results indicate that high speed milling offers a better than average potential for success in edge trimming 6Al-4V titanium sheet and 15-7 Mo sheet in the 500 to 2500 feet/minute cutting speed range. Drilling tests have been made using the Tornetic drilling unit and a constant speed drill press on D6AC steel in the 54-58 R<sub>c</sub> hardness range. Tapping test results on B-120VCA titanium at 400 BHN are presented comparing the Tornetic tapping data with conventional tapping. Machining test data is also presented on B-120VCA titanium, TZM Molybdenum, Mo 0.5 Ti and D-31 Columbium alloy.

## 2. MATERIALS USED IN MACHINING TESTS

The materials used in the machining tests were as follows:

|                                                            |                        |
|------------------------------------------------------------|------------------------|
| B-120VCA Titanium, Solution Treated                        | 285 BHN                |
| B-120VCA Titanium, Solution Treated and Aged               | 365 BHN and 400 BHN    |
| D6AC Steel, Quenched and Tempered                          | 54 - 58 R <sub>C</sub> |
| 6Al-4V Titanium, Solution Treated and Aged, Sheet Material | 35 - 36 R <sub>C</sub> |
| PH 15-7 Mo, Mill Annealed, Sheet Material                  | 90 R <sub>B</sub>      |

### 2.1 Chemical Composition

The nominal chemical compositions of the alloys used in the machining tests were as follows:

|                      |           |           |           |           |           |           |                      |           |
|----------------------|-----------|-----------|-----------|-----------|-----------|-----------|----------------------|-----------|
|                      | <u>V</u>  | <u>Cr</u> | <u>Al</u> | <u>C</u>  | <u>Fe</u> | <u>N</u>  | <u>O<sub>2</sub></u> |           |
| B-120VCA<br>Titanium | 13.5      | 11.0      | 3.5       | 0.035     | 0.22      | 0.02      | 0.007                |           |
|                      | <u>C</u>  | <u>Mn</u> | <u>Si</u> | <u>Ni</u> | <u>Cr</u> | <u>Mo</u> | <u>V</u>             | <u>Fe</u> |
| D6AC Steel           | 0.45      | 0.80      | 0.25      | 0.55      | 1.15      | 1.0       | .05                  | Bal.      |
|                      | <u>Al</u> | <u>V</u>  | <u>Ti</u> |           |           |           |                      |           |
| 6Al-4V               | 6         | 4         | 90        |           |           |           |                      |           |
|                      | <u>C</u>  | <u>Mn</u> | <u>Si</u> | <u>Ni</u> | <u>Cr</u> | <u>Mo</u> | <u>Al</u>            | <u>Fe</u> |
| PH 15-7 Mo           | .09       | 1.00      | 1.0       | 7.0       | 15.0      | 2.5       | 1.0                  | Bal.      |

### 2.2 Heat Treatment

The heat treatment given these alloys was as follows:

|                                                | <u>Hardness</u>   |
|------------------------------------------------|-------------------|
| <u>B-120VCA Titanium</u>                       |                   |
| Solution at 1450°F for one-half hour, air cool | 285 BHN           |
| Age at 900°F for 60 hours, air cool            | 400 BHN           |
| <u>D6AC Steel</u>                              |                   |
| Heat to 1650°F for one hour, oil quench        |                   |
| Temper 500°F for 2 hours, air cool             | 54 R <sub>C</sub> |
| Temper 400°F for 2 hours, air cool             | 56 R <sub>C</sub> |
| Temper 300°F for 2 hours, air cool             | 58 R <sub>C</sub> |

No heat treatment was performed on the 6Al-4V Titanium sheet material or the PH 15-7 Mo sheet material.

### 3. MACHINING TEST CONDITIONS

#### 3.1 Machine Tools Used for Testing

Photographs of the lathe, milling machines, drilling machines and surface grinders used in the machinability tests were shown in ASD Interim Report 7-532a(III), dated August, 1961.

The turning tests were made on a 16" x 30" American Pacemaker lathe. This lathe is equipped with a 30 H. P. infinitely variable speed drive to provide exact cutting speed control as the bar diameter changes.

Milling tests were performed on a Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine. The machine is equipped with a cast iron flywheel to maintain a more constant speed when the interrupted cuts in face milling are encountered.

End milling tests were performed on a Cincinnati Vertical No. 2 Dial Type Milling Machine. A rotary seal is attached to the top of a hollow draw bar for applying spray mist or cutting fluid through a hole along the axis of the cutter. The machine also contains the standard integral cutting fluid system.

A Fosdick Heavy Duty 25" Box Column Upright Drill Press and a Cincinnati 16" Box Column Drill Press were used for the drilling, reaming and tapping tests. Both machines are equipped with separate infinitely variable speed drives to obtain feeds of .0001 to .025 inches per revolution. The Cincinnati drilling machine is also equipped with an infinitely variable spindle speed drive to provide exact drilling speed control.

The grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder. Grinding wheel speeds ranging from 1000 to 7500 surface feet per minute can be obtained on this machine by means of an infinitely variable speed spindle drive.

#### 3.2 Turning Conditions

Turning tests were made using high speed steel, cast alloy and carbide tools.

##### Machine

16" x 30" American Pacemaker lathe equipped with a 30 H. P. variable speed drive.

### 3.2 Turning Conditions (continued)

#### Test Bars

Turning test bars were 4" in diameter by 18" long. A surface skin cut was taken on each bar before machining tests were made to remove any surface effects.

#### Cutting Tools

Turning tests were made using throwaway type and brazed tip carbide tools and 5/8" square high speed steel tool bits.

#### Tool Materials - Carbide

A variety of Carbide grades were used. The data charts give specific applications.

#### Tool Geometry - Carbide

|                                |                 |
|--------------------------------|-----------------|
| Side Rake (SR)                 | 20° to -15°     |
| Back Rake (BR)                 | 0° to -15°      |
| Side Cutting Edge Angle (SCEA) | 0° to 45°       |
| End Cutting Edge Angle (ECEA)  | 5° to 15°       |
| Side Relief                    | 5° to 10°       |
| End Relief                     | 5° to 10°       |
| Nose Radius (NR)               | 1/64" and 1/32" |

#### Machining Conditions - Carbide

Feed: .005 in./rev. to .015 in./rev.

Depth of Cut: .100"

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil, water soluble emulsions and dry.

Tool Life End Point: .015" uniform wearland or .030" localized wearland.

#### Tool Material - High Speed Steel Tools

M-2, T-1, T-15, Braecut, Rex 49 and Hypercut high speed steel tool bits

#### Tool Geometry - High Speed Steel

Type: 5/8" square tool bits

Tool Geometry:

|                         |           |
|-------------------------|-----------|
| Side Rake               | 0° to 30° |
| Back Rake               | 0°        |
| Side Cutting Edge Angle | 0° to 15° |
| End Cutting Edge Angle  | 5°        |
| Side Relief             | 5°        |
| End Relief              | 5°        |
| Nose Radius (NR)        | 1/64"     |

### 3.2 Turning Conditions (continued)

#### Machining Conditions - High Speed Steel Tools

Feed: .005 in./rev. to .015 in./rev.

Depth of Cut: .100"

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil,  
water soluble emulsions and chemical solutions.

Tool Life End Point: .030" to .060" wearland.

### 3.3 Face Milling Conditions

Face milling tests were made using single and multiple tooth carbide and high speed steel cutters.

#### Machine

A Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine was used in the face milling tests.

#### Test Bars

The test bars were nominally 2" thick by 4" wide by 10" long. A clean-up machining cut was made on all sides to remove any surface effects from prior treatment.

#### Cutters

A 4" diameter experimental cutter using clamped-in 5/8" square tool bits was used as a single tooth cutter for the tool material, tool geometry, cutting speed and feed evaluation.

#### Tool Material - Carbide

A variety of carbide grades was used in the face milling tests. The data charts give specific applications.

#### Tool Geometry - Carbide

|                               |             |
|-------------------------------|-------------|
| Axial Rake (AR)               | 10° to -10° |
| Radial Rake (RR)              | 10° to -5°  |
| Corner Angle (CA)             | 45°         |
| End Cutting Edge Angle (ECEA) | 5°          |
| Peripheral Clearance          | 6° to 10°   |

#### Machining Conditions - Carbide

Feed per Tooth: .003" to .010"

Depth of Cut: .030" to .060"

Width of Cut: 2"

Cutting Fluid: Soluble oil (1:20), highly chlorinated oil,  
highly sulphurized oil and dry.

Tool Life End Point: .015" wearland on peripheral flank of cutter  
or .030" localized wear, whichever occurred first.

### 3.3 Face Milling Conditions (continued)

#### Tool Material - High Speed Steel

M-2, T-1, T-15, Braecut, Rex 49, and Hypercut high speed steel

#### Tool Geometry - High Speed Steel

|                               |           |
|-------------------------------|-----------|
| Axial Rake (AR)               | 0° to 20° |
| Radial Rake (RR)              | 0° to 30° |
| Corner Angle (CA)             | 45°       |
| End Cutting Edge Angle (ECEA) | 5°        |
| Peripheral Clearance          | 10°       |

#### Machining Conditions - High Speed Steel

Feed per Tooth: .005" to .010"

Depth of Cut: .030" to .060"

Width of Cut: 1-1/2" to 2"

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil  
and water soluble emulsions.

Tool Life End Point: .016" uniform wear or .030" localized  
wear, whichever occurred first.

### 3.4 End Milling Conditions

End milling tests were made using high speed steel cutters for producing slotting cuts and peripheral cuts. Tool life is expressed in inches of work travel to obtain a specific wearland on the tool.

#### Machine

A Cincinnati No. 2 Vertical Dial Type Milling Machine was used for the end milling tests.

#### Test Bars

The test bars were nominally 2" thick by 4" wide by 10" long. All sides were clean-up machined prior to testing to remove any surface effects from prior treatment.

#### Cutters - High Speed Steel

The end mills used in the tests were 3/4" diameter, 4 tooth, right hand spiral, right hand cut, high speed steel end mills.

#### Tool Materials - High Speed Steel

Type M-2, Type M-3 and Type T-15

### 3.4 End Milling Conditions (continued)

#### Tool Geometry - High Speed Steel

Number of Teeth:

Helix Angle

Radial Rake (RR)

Corner Angle (CA)

Peripheral Clearance

4<sup>°</sup>  
30<sup>°</sup>  
10<sup>°</sup>  
45<sup>°</sup> x .060"  
6<sup>°</sup> to 10<sup>°</sup>

#### Machining Conditions

Feed per Tooth: .001" to .004"

Depth of Cut: .125" to .500"

Width of Cut: 1/2" and 3/4"

Cutting Fluid: Highly chlorinated oil, highly sulphurized oil and water soluble emulsions

Tool Life End Point: .015" uniform wearland or .030" localized wear on peripheral cutting edge, whichever occurred first.

### 3.5 Drilling Conditions

Drilling tests were made using high speed steel drills.

#### Machine

Drill life testing was done on a Cincinnati 16" Box Column Drilling Machine. This machine was equipped with an infinitely variable spindle speed and feed drive to provide exact cutting speed control and to obtain feeds of .0001 to .025 inches per revolution.

#### Drill Material - High Speed Steel

M-1, M-2, M-3, T-15 and M-33 high speed steel drills were used in the tests.

#### Test Samples

The drilling test samples were 1/2" thick plates cut from round and rectangular bar stock.

#### Drill Geometry - High Speed Steel

Drill Diameter: .250"

Drill Length: 2-1/2"

Point Angle: 90<sup>°</sup>, 118<sup>°</sup>, 90<sup>°</sup>/118<sup>°</sup>, 135<sup>°</sup>, 90<sup>°</sup>/135<sup>°</sup>

Helix Angle: 29<sup>°</sup>

Clearance: 7<sup>°</sup>

Point Grind: Plain and split

### 3.5 Drilling Conditions (continued)

#### Drilling Conditions - High Speed Steel

Feed: .002 to .005 inches/revolution

Depth of Hole: .500" through hole

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil and water soluble emulsions.

### 3.6 Reaming Conditions

Reaming tests were made using high speed steel chucking reamers.

#### Machine

The reaming tests were made on a Cincinnati 16" Box Column Drilling Machine.

#### Test Samples

The reaming tests were made on 1/2" thick slugs on which drilling studies had previously been made.

#### Reamer Material

M-2 type high speed steel.

#### Reamer Geometry

Type: Straight 6 Flute Chucking Reamers and 6 Flute, 10° R. H. Spiral Chucking Reamers

Diameter: .272"

Axial Rake (AR): 0° and 10°

Radial Rake (RR): 0°

Helix Angle: 0° and 10°

Corner Angle: 45°

Peripheral Clearance: 10°

#### Reaming Conditions

Feed: .005 to .015 inches/revolution

Depth of Hole: .500" through hole

Stock Removed: .010" on radius

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil and water soluble emulsions.

Tool Life End Point: .012" wear on reamer corner.

### 3.7 Tapping Conditions

Tapping tests were made with 5/16-24 NF high speed steel taps.

#### Machine

A Fosdick 25" Box Column Drilling Machine was used for the tapping tests.

#### Test Samples

The 1/2" thick slugs previously drilled and reamed were used for the tapping tests.

#### Tap Material

Type M-10 high speed steel taps were used in the tests.

#### Tap Geometry

Tap: 4 Flute Plug, 2 Flute Chipdriver Plug  
Percent Thread: 60% and 75%

#### Machining Conditions

Depth of Hole: .500" through hole  
Cutting Fluid: Highly sulphurized oil and highly chlorinated oil  
Tool Life End Point: Galling and seizure of tap or tap breakage

### 3.8 Grinding Conditions

Grinding tests were made using various grinding wheels and a range of grinding conditions to effect the best Grinding Ratio.

#### Machine

The grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder equipped with a variable speed spindle drive to obtain wheel speeds from 1000 to 7500 feet per minute.

#### Test Bars

The test bars had a nominal size of 1" thick x 1-1/2" wide x 6" long. All surfaces were clean-up machined prior to testing to remove any surface effects.

### 3.8 Grinding Conditions (continued)

#### Grinding Wheels

The following grinding wheels were used for the tests:

##### Aluminum Oxide Wheels

32A46H8VBE

32A46J8VBE

32A46K8VBE

##### Silicon Carbide Wheels

GC60J6VP

GC46K6VP

GC46L6VP

GC80N6VP

#### Grinding Conditions

Wheel Speed: 2000 to 6000 feet per minute

Down Feed: .0005 to .005 inches per pass

Cross Feed: .025 to .100 inches per pass

Table Speed: 20 to 60 feet per minute

Grinding Fluid: Highly chlorinated oil, highly sulphurized oil,  
water soluble emulsion and chemical solution.

#### Test Procedure

The procedure used in the surface grinding tests to study the effectiveness of a set of grinding conditions was one of measuring the amount of wheel wear for a given amount of stock removed. Wheel wear was measured using a vernier caliper and an accurate indicator and depth measurements were made to determine the stock removed. The volume of stock removed and volume of wheel removed was thus calculated.

The Grinding Ratio (G) which indicates the effectiveness of a set of grinding conditions is defined as:

$$G = \frac{\text{Volume of Stock Removed}}{\text{Volume of Wheel Removed}}$$

All test samples were examined for surface cracking, chatter marks and any other detrimental surface effects produced by the test grinding.

## 4. HIGH SPEED MILLING TEST CONDITIONS

### 4.1 Machine Tool Setup

A photograph of the 36" x 6' Gray planer and the high speed milling head adapted to this machine for these tests is shown in Figure 1, page 27. This machine is equipped with a motor generator set which provides variable voltage to the drive motor through adjustable rheostats. The speed of the table is determined by the drive motor speed and the planer gear ratio. Normally, table speeds ranging from 37.5 to 300 feet/minute are available. However, this machine was modified to provide infinitely variable table speeds ranging from 40 inches/minute to 400 inches/minute.

The high speed milling head was designed and built using a Varidrive motor to provide spindle speeds ranging from 150 rpm to 9000 rpm.

A holding fixture was bolted to the machine table and hold-down screws spaced at approximately 6 inch intervals held the sheet metal workpiece securely to the table.

Figure 2, page 28, shows a close-up view of the high speed milling cutter head and the carbide throw-away type end mill holder used for these tests. Two nozzles with .027" diameter orifices were used to direct liquid CO<sub>2</sub> on the tool and workpiece. Only one nozzle is shown in the photograph, the other nozzle is behind the cutter. The sheet metal workpiece projected out approximately 1/2" from the edge of the table at the start of a test. After a series of test cuts were made, the workpiece was moved out another 1/2".

Figure 3, page 29, shows the high speed edge trimming operation with liquid CO<sub>2</sub> coolant spraying on the workpiece and cutter. The work material was 6Al-4V Titanium sheet (35-36 R<sub>C</sub>), .063" thick. The cutter was revolving at 6000 rpm (2000 feet/minute) and the table was traveling at 270 inches/minute.

### 4.2 High Speed Milling Test Conditions

#### Cutters

The high speed milling tests were made using a three tooth throw-away carbide end mill cutter with the following geometry:

Cutter Diameter: 1-1/4"  
Number of Teeth: 3  
Throw-away Carbide Shape: Positive rake triangular inserts  
Axial Rake (AR): 0°  
Radial Rake (RR): 0°  
Peripheral Clearance: 5°

#### 4.2 High Speed Milling Test Conditions (continued)

##### Tool Material - Carbide

Positive rake throw-away type carbide inserts in a wide variety of grades were used. See the individual data charts for specific applications.

##### Work Material

To date, two work materials have been machined in this program. These are 6Al-4V Titanium sheet (35-36 R<sub>C</sub>) and PH 15-7 Mo stainless sheet (90 R<sub>B</sub>). Testing consisted of straight climb cuts on .063" and .125" thick material.

##### Machining Conditions

Cutting Speed: 500 feet/minute to 2500 feet/minute

Feed per Tooth: .005' to .030"

Depth of Cut: .050" to .150"

Width of Cut: .063" to .125"

Cooling Medium: Liquid CO<sub>2</sub>, Dry, and Soluble Oil Spray Mist

Tool Life End Point: .030" or .060" Wearland on Peripheral Flank of Cutter, or Excessive Burr on Work Material

## 5. TEST RESULTS

### 5.1 High Speed Milling (Edge Trimming) Test Results

#### 5.1.1 High Speed Milling 6Al-4V Titanium Sheet (35-36 R<sub>C</sub>)

Figures 4 through 12, pages 30 through 38, present the data obtained when high speed milling (edge trimming) 6Al-4V Titanium sheet at 35-36 R<sub>C</sub>. Figure 4, page 30, shows the effect of cutting speed at constant feeds using a 1-1/4" diameter 3 tooth end mill with Grade 883 (C-2) carbide inserts. Maximum tool life, 228 feet, was obtained at a cutting speed of 500 feet/minute with a feed of .010 inches/tooth. Tool life decreased rapidly when the cutting speed was increased up to 2000 feet/minute. At this cutting speed a tool life of 32 feet was obtained.

Figure 5, page 31, presents the same data plotted as a function of feed rate with constant cutting speeds. This chart shows that feeds of the order of .005-.010 inches/tooth provided the best tool life over the range of cutting speeds used.

The effect of cutting speed and sheet thickness is shown in Figure 6, page 32. Again, the best tool life was obtained at a cutting speed of 500 feet/minute when edge trimming sheet material .063" thick and .125" thick. When the cutting speed was increased, tool life was reduced significantly for both sheet thicknesses. Another interesting test point is shown on this chart. This test point was made without liquid CO<sub>2</sub> when milling the .125" thickness material at 500 feet/minute. A tool life of 172 feet of work travel was obtained without liquid CO<sub>2</sub> compared with a tool life of 202 feet of work travel when using liquid CO<sub>2</sub> as the cooling medium.

Figure 7, page 33, shows the effect of sheet thickness on tool life when the feed was increased from .005 inches/tooth to .020 inches/tooth. This data was obtained using a cutting speed of 1000 feet/minute with liquid CO<sub>2</sub>. A tool life of 120 feet of work travel was obtained with the .063" thick material at a feed of .005 inches/tooth. Tool life decreased to 60 feet of work travel when milling the .125" thick sheet material with this feed. At a feed of .020 inches/tooth, tool life was almost the same, 30 feet, for both sheet thicknesses. The effect of depth of cut when varying the feed per tooth is shown in Figure 8, page 34. When milling at a cutting speed of 1000 feet/minute with a feed of .005 inches/tooth, a tool life of 120 feet of work travel was obtained at a depth of cut of .050" on the .063" thickness material. When the depth of cut was increased to .100", tool life decreased to 69 feet of work travel. However, another .050" increase in depth of

#### 5.1.1 High Speed Milling 6Al-4V Titanium Sheet (35-36 R<sub>C</sub>), (continued)

cut, i. e., .150", reduced tool life to 63 feet of work travel. When the feed was increased to .020 inches/tooth - tool life was reduced to values ranging from 10 to 25 feet of work travel for the three depths of cut taken in this series of tests.

Figure 9, page 35, shows the effect of depth of cut when using liquid CO<sub>2</sub> and also when milling this Titanium alloy dry. For these tests the cutting speed and feed were held constant at 1000 feet/minute and .005 inches/tooth respectively. When a depth of cut of .050" was taken, a tool life of 120 feet of work travel was obtained with liquid CO<sub>2</sub> and 102 feet of work travel dry or without liquid CO<sub>2</sub>. This resulted in approximately a 20% increase in tool life when using liquid CO<sub>2</sub>. However, when the depth of cut was increased to .100" and .150", a tool life of about 65 feet of work travel was obtained using liquid CO<sub>2</sub> and 35 feet of work travel without liquid CO<sub>2</sub>. The beneficial effects of liquid CO<sub>2</sub> when taking the higher depths of cut are obvious.

Figure 10, page 36, presents in bar chart form the effects of a cooling medium and depth of cut on tool life when high speed milling the 6Al-4V Titanium alloy. This chart shows that at a depth of cut of .050" little difference in tool life was obtained when using liquid CO<sub>2</sub>, soluble oil spray mist and milling dry. However, at depths of cut of .100" and .150" tool life was highest when liquid CO<sub>2</sub> was used as the cooling medium.

The effect of carbide grade, Figure 11, page 37, shows that the best carbide for high speed milling this alloy was Grade 883 (C-2). This carbide provided a tool life of almost 40 feet of work travel at a cutting speed of 1500 feet/minute with a feed of .020 inches/tooth. The next best two carbide grades were Grade K-2S (C-6) and Grade K-6 (C-2). A tool life of just over 30 feet of work travel was obtained with these grades, while the poorest grade tested was Grade K-8 (C-3). This carbide provided 15 feet of work travel.

Figure 12, page 38, shows the effect of rate of wear on the carbide tool plotted against feet of work traveled at two cutting speeds, namely 500 feet/minute and 1000 feet/minute. This chart shows that for a length of cut of 100 feet of work travel, a wearland of about .010" was observed on the tool when milling at 500 feet/minute. However, when the cutting speed was doubled to 1000 feet/minute the wearland increased threefold to .030".

### 5.1.2 High Speed Milling PH 15-7 Mo Stainless Sheet

The data obtained when high speed milling PH 15-7 Mo stainless sheet, annealed at 90 R<sub>B</sub> - .063" thick - is presented in Figures 13 through 20, pages 39 through 46. The effect of cutting speed at constant feeds and feed rate at constant cutting speeds is presented in Figures 13 and 14, pages 39 and 40. These charts show that maximum tool life was obtained in the 1000 to 2000 feet/minute cutting speed range and the .010 to .020 inch/tooth feed range. The best tool life, 97 feet of work travel, was obtained when using a cutting speed of 1500 feet/minute with feeds of .015 to .020 inches/tooth. This data was obtained when using liquid CO<sub>2</sub> as the cooling medium.

The data presented in Figures 15 and 16, pages 41 and 42, show the effects of cutting speed and feed when high speed milling PH 15-7 Mo stainless sheet dry. It should be noted that tool life is increased approximately 50% over milling with liquid CO<sub>2</sub> as the cooling medium. Figure 15, page 41, shows that the optimum cutting speed was found to be 1500 feet/minute. At this cutting speed a tool life of 150 feet of work travel was obtained. Figure 16, page 42, shows that when a cutting speed of 1500 feet/minute was used, approximately the same tool life - 150 feet of work travel - was obtained with feeds of .010, .015 and .020 inches/tooth. At feeds lower than .010 inches/tooth and feeds higher than .020 inches/tooth, tool life decreased significantly. Feeds appeared to be somewhat more critical at the other cutting speeds used.

Figures 17 and 18, pages 43 and 44 show the effects of cutting speed and depth of cut on tool life when high speed edge trimming PH 15-7 Mo. When taking a .050" depth of cut with liquid CO<sub>2</sub>, best tool life of 97 feet of work travel was obtained at 1500 feet/minute. When the depth of cut was increased to .100" tool life decreased to 77 feet of work travel, and at a depth of cut of .150" a tool life of 45 feet of work travel was obtained. At cutting speeds above and below 1500 feet/minute, tool life decreased significantly. Figure 18, page 44 presents the same type of data when milling dry. Significantly higher tool life values were obtained using the three depths of cut of .050", .100" and .150".

The effect of type of cooling medium is presented in Figure 19, page 45. This chart shows that no increase in tool life was obtained when using liquid CO<sub>2</sub> or a soluble oil spray mist over cutting dry. The data show that when taking a .050" depth of cut, a tool life of 150 feet of work travel was obtained cutting dry, while a tool life of 97 feet of work travel was obtained when using liquid CO<sub>2</sub> or a soluble oil spray mist.

### 5.1.2 High Speed Milling PH 15-7 Mo Stainless Sheet (continued)

The effect of different carbide grades, Figure 20, page 46, shows that Grade K-2S (C-6) was far superior to the other grades tested. At a cutting speed of 2000 feet/minute and a feed of .010 inches/tooth, Grade K-2S provided a tool life of 67 feet of work travel. The second best carbide, Grade K-6 (C-2) provided a tool life of 36 feet of work travel while less than 25 feet of work travel was obtained with Grades 883 (C-2) and K-8 (C-3).

## 5.2 Comparative Drilling and Tapping Tests Using Tornetic and Constant Speed and Feed Drill Press

### 5.2.1 Drilling D6AC Steel, Quenched and Tempered 54-58 R<sub>C</sub>

Figure 21, page 47, shows the data obtained when drilling D6AC steel quenched and tempered at 54, 56 and 58 R<sub>C</sub> using the Tornetic drilling unit and a constant speed and feed drilling machine. All of the drilling tests on D6AC steel were made at 100 feet/minute with an initial feed of .001 inches/rev. using Grade 883 (C-2) carbide tipped, #3 (.213") diameter drills. A drill life of 76 holes was obtained at the 54 R<sub>C</sub> hardness level with the constant speed and feed machine, while 60 holes were obtained on the Tornetic drilling unit. By the time the 60th hole was drilled, the feed rate had decreased to one half of its initial value because of the dulling of the drill point and cutting lips.

A drill life of 66 holes was obtained on the constant speed and feed drill press when drilling this alloy at 56 R<sub>C</sub>. With the Tornetic drilling unit 55 holes were obtained with corresponding decrease in feed rate as drilling progressed. When drilling this alloy at 58 R<sub>C</sub> on the constant speed and feed drilling machine, a drill life of 40 holes was obtained, while the Tornetic drilling unit provided 32 holes.

### 5.2.2 Drilling AISI 410 Stainless Steel, Quenched and Tempered 45 R<sub>C</sub>

In drilling AISI 410 stainless steel quenched and tempered to 45 R<sub>C</sub>, no significant difference in drill life was observed when using the constant speed and feed drilling machine and the Tornetic drilling unit. The data presented in Figure 22, page 48, shows that very low drill life was obtained on both drilling machines when drilling this alloy with Type T-15 HSS drills, at 75 and 100 feet/minute with a feed of .002 inches/rev. When the cutting speed was reduced to 50 feet/minute a drill life of 195 holes was obtained on the constant speed and feed drilling machine, and 205 holes on the Tornetic drilling unit. The feed rate decreased about 10% during the drilling of these holes on the Tornetic unit.

### 5.2.3 Drilling 6Al-4V Titanium, Solution Treated and Aged 360 BHN

Comparative data obtained when drilling 6Al-4V Titanium solution treated and aged 360 BHN with the Tornetic drilling unit and a constant speed and feed drilling machine, is presented in Figure 23, page 49. At a cutting speed of 75 feet/minute with a feed of .002 inches/rev., both drilling machines provided less than 20 holes. However, at a cutting speed of 65 feet/minute over twice as many holes were drilled on the constant speed and feed unit as were obtained on the Tornetic drilling unit. When the cutting speed was reduced to 50 feet/minute, 100 holes were drilled on both units before the test was discontinued. The drill used with the constant speed and feed drilling machine had a wearland of .006", while the drill used in the Tornetic drilling unit had a wearland of .010". In addition, the feed rate on the Tornetic unit had decreased 30% by the time the last hole was drilled.

### 5.2.4 Tapping B-120VCA Titanium, Solution Treated and Aged 400 BHN

Figure 24, page 50 shows the data obtained when tapping B-120VCA Titanium at 400 BHN with a conventional tapping unit and the Tornetic tapping unit. At a cutting speed of 17 feet/minute less than 10 holes were tapped with the Tornetic tapping unit before the tap stalled in the workpiece. At this cutting speed, using the optimum motor-spindle belt ratio, a maximum torque value of 120 in.-lbs. was available at the spindle. When the cutting speed was reduced to 10 feet/minute, by decreasing the motor-spindle ratio, tap life increased to 50 holes before the tap stalled in the workpiece. Cycling the tap did not increase tap life. A maximum torque value of 250 in.-lbs. was available when making this test. The cutting speed was reduced further to 6 feet/minute with a maximum torque of 300 in.-lbs. Tap life was increased to 72 holes before the tap broke in the workpiece. At a cutting speed of 9 feet/minute the conventional tapping machine provided a tap life of 100 holes before the test was discontinued.

## 5.3 Machining Tests on B-120VCA Titanium

### 5.3.1 Face Milling Tests

Climb cutting was employed in all of the face milling tests on the B-120VCA titanium alloy. A comparison of the super high speed steel, cast alloy and high speed steel tools is presented in Figure 25, page 51. Both the Braecut and Hypercut tools were superior to the others. The types M-2 and T-1 high speed steels had very short tool life. A similar comparison of the various grades of tools in face milling the same alloy but solution treated and aged to 400 BHN is shown in Figure 26, page 52.

#### 5.3.1 Face Milling Tests (continued)

The relationships of cutting speed and tool life with a Braecut HSS tool in face milling the alloy at the two hardness levels are shown in Figures 27 and 28, pages 53 and 54. A reasonable cutting speed for the solution treated alloy was 30 to 40 feet/minute and 25 feet/minute for the solution treated and aged alloy. A tool life curve is shown in Figure 29, page 55 for the solution treated alloy with carbide tools. It is interesting to note that the permissible cutting speed is over 300% faster than with the super high speed steel tools.

As shown in Figure 30, page 56, the feed was critical. Increasing the feed from .005 to .008 inches/tooth resulted in decreasing the tool life from 125 to 45 inches of work travel.

The carbide Grade 883 (C-2) was far superior to the (C-1), (C-6), and (C-7) grades in face milling the B-120VCA Titanium alloy at both strength levels, 285 and 400 BHN, as illustrated in Figure 31, page 57.

#### 5.3.2 End Milling Tests

The effect of cutting speed on tool life for end mill slotting B-120VCA Titanium in two different heat treated conditions is presented in Figure 32, page 58. The cutting speed for a given tool life on the solution treated alloy (285 BHN) was about 10% higher than with the solution treated and aged alloy (400 BHN).

As shown in Figure 33, page 59, the feed was very critical on the alloy in both heat treated conditions. Doubling the feed from .002 to .004 inches/tooth resulted in decreasing the tool life from a reasonable value to a very short tool life. As shown in Figure 34, page 60, while the type of cutting fluid selected did not affect tool life to any great extent, heavy duty soluble oil at 1:20 was slightly better than the other fluids tested.

Cutter life was also sensitive to feed in peripheral end milling, see Figure 35, page 61. Tool life decreased rapidly as the feed was increased or decreased from a feed of .002 inches/tooth on the B-120VCA alloy at 400 BHN. The relationship between tool life and cutting speed for the alloy at 400 BHN is shown in Figure 36, page 62.

## 5.4 Molybdenum Alloys

### 5.4.1 Turning Tests

The relationship between tool life and cutting speed for turning the TZM Molybdenum alloy is shown in Figure 37, page 63, for two different depths of cut. A tool life of 25 minutes was obtained at a cutting speed of 450 feet/minute, a feed of .009 inches/rev. and a depth of cut of .030". When the depth of cut was doubled to .060" the tool life dropped to 5 minutes. Also when the TZM Molybdenum alloy was cut dry, the tool life decreased to as much as one third of the value obtained with a soluble oil. The harder grade of carbide K-8 (C-3) appeared to be no better than the K-6 (C-2) grade, and the 44A (C-2) grade was somewhat poorer.

As indicated in Figure 38, page 64, longer tool life was obtained with the lighter feeds. At a feed of .005 inches/rev., the tool life was 41 minutes or 38 cubic inches as compared to 10 minutes or 22 cubic inches at a feed of .012 inches/rev.

The chart in Figure 39, page 65, shows superiority of soluble oil (1:20) over a highly chlorinated or sulphurized oil. The improvement in tool life with the higher side rake angle is presented in Figure 40, page 66. The tool life was increased almost 4 times by increasing the rake angle from  $7^{\circ}$  to  $20^{\circ}$ .

### 5.4.2 Face Milling Tests

A comparison of various high speed steel and cast alloy tools is presented in Figure 41, page 67, for face milling the TZM Molybdenum alloy. The tool life with the super high speed steels, T-15 and Braecut, was about 50% greater than with the types T-1 and M-2 high speed steels. While the cast alloy tools showed some advantage over the T-1 and M-2 tools in one instance, these tools were poorer than the super high speed steels.

Although the feed is not critical as it affects tool life with high speed steel tools in face milling, there is a definite advantage in using a feed of .010 inches/tooth as shown in Figure 42, page 68. Also as indicated in Figure 43, page 69, tool life decreased appreciably as the depth of cut was increased. The depth of cut appears to have appreciable influence on tool life, see Figure 43, page 69. At a cutting speed of 152 feet/minute, the tool life decreased from 42 inches of work travel at a depth of cut of .030" to 25 inches when the depth was increased to .060". However, if the cutting speed is reduced 15%, the depth of cut can be increased from .030" to .060" without sacrificing tool life.

#### 5.4.2 Face Milling Tests (continued)

From the results shown in Figure 44, page 70, tool geometry with high speed steel tools is a very important factor influencing tool life. Negative rake angles should not be used in milling TZM molybdenum. High positive radial rake angles should be used.

The tool life curves in Figure 45, page 71, show that a practical cutting speed for face milling the extruded TZM molybdenum alloy is 300 to 350 feet/minute with a C-2 grade carbide tool. With carbide tools, the depth of cut does not influence tool life very much. Increasing depth of cut from .030" to .060" resulted in a reduction in tool life of less than 10%. It should be noted that the tool life was appreciably poorer on the recrystallized, hot rolled and stress relieved alloy at the lower cutting speeds.

As indicated in Figure 46, page 72, soluble oil (1:20) was better than the highly chlorinated oil and considerably better when face milling dry with carbide tools.

Negative rake angles are not to be used with carbide cutters for face milling the TZM molybdenum alloy, see Figure 47, page 73. The optimum tool geometry is  $0^{\circ}$  axial rake and  $0^{\circ}$  radial rake. Higher positive rake angles also result in decreasing tool life. The feed was more critical with carbide tools. Note in Figure 48, page 74, that tool life decreased about 60% when the feed was increased from .005 to .008 inches/tooth.

#### 5.4.3 End Milling

The TZM molybdenum alloy at 248 BHN can be slot milled at relatively high cutting speeds with high speed steel cutters, as shown by the tool life curves in Figure 49, page 75. A tool life of 70 inches work travel was obtained with an M-3 HSS cutter at a cutting speed of 160 feet/minute. The cutting speed can be increased to 190 feet/minute with a T-15 HSS cutter for the same tool life.

As shown in Figure 50, page 76, the type of cutting fluid used in end milling the TZM molybdenum alloy is not critical. The differences in the three fluids shown are not significant.

Heavier feeds should be employed in end milling. By increasing the feed from .002 to .005 inches/tooth, tool life in terms of inches of work travel was doubled, see Figure 51, page 77.

#### 5.4.3 End Milling (continued)

The depth of cut should not exceed about .250", for as presented in Figure 52, page 78, if a depth of cut of .500" is taken, the cutter will break down rapidly and tool life will be about 50% of that obtained at a depth of .250".

The cutting speed for peripheral milling was about 50% greater than that used in slot milling. The tool life curves in Figure 53, page 79, show that for a tool life of 80 inches of work travel the cutting speed for end milling was 150 feet/minute as compared to 250 feet/minute for peripheral milling.

#### 5.4.4 Drilling

Cutting speed tool life curves are presented in Figure 54, page 80, for two types of points and point angles. The 135° split point was appreciably better than the 118° plain point. For a drill life of 100 holes, the drilling speed was 125 feet/minute with drills having a 135° split point and approximately 105 feet/minute with drills having a 118° plain point. The tool life curve in Figure 55, page 81, shows that when the feed is increased from .005 to .009 inches/rev. the drill life decreases from 98 to 34 holes.

In drilling TZM molybdenum, the highly chlorinated oil showed an advantage over both the highly sulphurized oil and the soluble oil at a drill speed of 125 feet/minute, see Figure 56, page 82.

The bar chart in Figure 57, page 83, illustrates the importance of drill geometry. The split point was the best in most cases and the 135° point angle was superior to all of the other point angles. Of all of the grades of high speed steel drills tested, the premium grades proved the best, as demonstrated in Figure 58, page 84.

The drill life curves obtained on several TZM molybdenum alloys which were processed differently are shown in Figure 59, page 85. The drill life on the extruded and recrystallized (220 BHN) alloy was appreciably better than that obtained on the extruded (229 BHN) only, or the extruded, recrystallized, hot rolled and stress relieved (248 BHN).

#### 5.4.5 Reaming

The tool life curves in Figure 60, page 86, indicate that the optimum feed for reaming is .015 inches/rev. over a range of cutting speeds. At lower and higher feeds the reamer life was poorer. The reaming speed should be 50 to 60 feet/minute. As shown in Figure 61, page 87, a highly chlorinated oil proved superior to the other two types of cutting fluids.

#### 5.4.6 Tapping

The effect of cutting speed and tap style on tapping TZM molybdenum is demonstrated in Figure 62, page 88. From the chart it appears that the optimum cutting speed was 70 feet/minute. Tap life decreased at very low and also at higher cutting speeds. Four flute plug taps should be used, although at the proper cutting speed the two flute chip driver plug tap performed almost as well. Active cutting oils must be used in order to get a reasonable tap life. A comparison of active cutting oils with soluble oil is presented in Figure 63, page 89.

#### 5.4.7 Grinding

The relative merits of several grades of grinding wheels for grinding the TZM molybdenum alloys are shown in Figure 64, page 90. At a wheel speed of 5000 feet/minute and using a soluble oil the harder grade 32A46N5VBE wheel produced the highest "G" ratio. However, chatter occurred under these conditions.

Further test results on the best three grades are presented in Figure 65, page 91. The "G" ratio was improved considerably by using a 5% solution of potassium nitrite and reducing the wheel speed. Under the conditions listed in Figure 65, page 91, a "G" ratio of 25 was obtained with the 32A46N5VBE wheel. The 5% solution of potassium nitrite also proved to be superior to active oils as shown in Figure 66, page 92. The table speed should be in the range of 20 to 50 feet/minute; the "G" ratio decreased at higher table speeds, see Figure 67, page 93.

As indicated in Figures 68 and 69, pages 94 and 95, the down feed should not exceed .002 inches/pass and the cross feed should be in the range of .050 to .100 inches/pass.

#### 5.4.8 Recommendations for Machining TZM Molybdenum Alloy

The recommendations for machining the TZM molybdenum alloy are given in Table I, pages 123 and 124.

### 5.5 Columbium Alloy

#### 5.5.1 Turning

Appreciable differences were found in the various carbide grades used in turning the D-31 columbium alloy. As shown in Figure 70, page 96, the C-6 grade was the poorest and the C-2 grade the best. A comparison of the C-2 grade of carbide with high speed steel and cast alloy tools is presented in Figure 71, page 97. The cutting speed with carbide is 50% faster than with the cast alloy and more than 300% faster than with high speed steel tools.

#### 5.5.1 Turning (continued)

Tool life decreased rapidly as the feed was increased above .005 inches/rev. The tool life curve versus feed in Figure 72, page 98, indicates that the tool life at a feed of .009 inches/rev. was only one-third the tool life obtained at a feed of .005 inches/rev.

Tool geometry is also a very important factor in turning the D-31 Columbium alloy. Note in Figure 73, page 99, how the tool life increased as the side rake angle increased. Changing the side rake from  $20^{\circ}$  to  $30^{\circ}$  more than doubled the tool life.

#### 5.5.2 Face Milling

The relationship between tool life and cutting speed is shown in Figure 74, page 100 for a feed of .010 inches/tooth with an M-2 high speed steel tool. In addition, test points are presented for lighter and heavier feeds. At the feed of .010 inches/tooth, the cutting speed should be 100 feet/minute. Test data in the chart also indicates that by reducing the feed 50%, tool life was doubled. Also as shown in Figure 75, page 101, tool life was improved considerably by using the premium grades of high speed steel tools.

A further increase in tool life was obtained through the use of a highly chlorinated oil, see Figure 76, page 102. As shown in Figure 77, page 103, tool geometry is another important factor in milling the D-31 columbium alloy with high speed steel tools. An axial rake of  $0^{\circ}$  and a radial rake of  $30^{\circ}$  proved best.

A comparison of the tool life curves in Figures 74 and 78, pages 100 and 104, shows that the cutting speed with carbide was 40% higher than with an M-2 high speed steel cutter. The feed was .010 inches/tooth in both cases.

#### 5.5.3 End Milling

The proper selection of cutting fluid in end milling the D-31 columbium alloy is very important. Note in Figure 79, page 105, the great differences obtained in tool life with the three cutting fluids tested. The highly chlorinated oil was 500% better than the soluble oil and 50% better than the highly sulphurized oil.

The tool life curves in Figure 80, page 106, demonstrate the advantage of the T-15 high speed steel cutter over the M-2 cutter. The cutting speed for the equivalent tool life was 35% higher with the T-15 than with the M-2 cutter.

#### 5.5.3 End Milling (continued)

As shown in Figure 81, page 107, the feed is also very critical. Tool life at a feed of .002 inches/tooth was over 50% greater than at a feed of .001 inches/tooth; while at a feed of .003 inches/tooth the tool life was nil.

#### 5.5.4 Drilling

The effect of cutting speed and feed in drilling the D-31 columbium alloy is demonstrated in Figure 82, page 108. A feed of .002 inches/rev. permitted a 50% increase in cutting speed over that permitted with a feed of .005 inches/rev., however the production rate on the 85 holes drilled at 75 feet/minute and the heavier feed was greater than that for the 85 holes drilled at 120 feet/minute and the lighter feed. A tool life curve for a range of cutting speeds is shown in Figure 83, page 109, for a 1/8" diameter drill at a feed of .005 inches/rev.

In the smaller drills, the feed is even more important. Note in Figure 84, page 110, the wide range of drill life as the feed was increased with a 1/16" diameter drill. Also note how the drill life improved when the cutting speed was increased from 25 to 50 feet/minute. Chip removal was better at the higher drill speed. A feed of .0005 inches/rev. at a cutting speed of 50 feet/minute should be used on drills 1/16" diameter.

Another important factor in drilling small diameter holes is the length of the drill. In the chart in Figure 85, page 111, the overall length of the drill was 1-5/8", however by reducing the drill length from 1-5/8" to 1-1/4", the drill life increased from 15 holes to 61 holes.

#### 5.5.5 Reaming

The relationship between cutting speed and reamer life is illustrated in Figure 86, page 112. Using a 10° right hand spiral reamer and a highly sulphurized oil, 100 holes .213" diameter can be reamed at a cutting speed of 125 feet/minute. The reamer life was appreciably less with either the highly chlorinated or the soluble oil, and with a straight flute reamer. As indicated by Figure 87, page 113, the feed rate is extremely important. A 40% reduction in reamer life resulted when the feed was reduced from .005 inches/rev. to .002 inches/rev. An even greater reduction occurred when the feed was increased to .009 inches/rev.

#### 5.5.6 Tapping

A relatively low cutting speed must be used in tapping the D-31 columbium alloy. Note in Figure 88, page 114 that at a cutting speed of 12 feet/minute 50 holes were tapped, while only 17 holes were tapped at 16 feet/minute. The selection of cutting fluid is also critical. The chart in Figure 89, page 115, demonstrates the vast superiority of the highly chlorinated oil over various other types.

#### 5.5.7 Grinding

The bar charts in Figures 90 and 91, pages 116 and 117, indicate that the best wheel of the group tested was the grade 32A46K8VBE for surface grinding both the unalloyed columbium and the D-31 columbium alloy. Various grinding fluids are also compared in Figure 92, page 118, on both metals. Note that potassium nitrite ( $\text{KNO}_2$ ) was the best of the group on the D-31 columbium alloy. This fluid had not as yet been tested in grinding the unalloyed columbium.

The relationship between wheel speed and "G" ratio is presented in Figure 93, page 119. Note how rapidly the "G" ratio decreased on the D-31 columbium alloy when the wheel speed was increased beyond 4000 feet/minute. The "G" ratio for the unalloyed columbium may be greater when the tests are conducted using potassium nitrite as the grinding fluid.

The effect of table speed on "G" ratio is shown in Figure 94, page 120, for two types of wheels. As shown in the chart, a change in table speed over a range of 20 to 60 feet/minute did not affect appreciably the grinding ratio. However, as illustrated in Figures 95 and 96, pages 121 and 122, increasing either or both the down feed or the cross feed can adversely effect the "G" ratio.

#### 5.5.8 Recommendations for Machining D-31 Columbium Alloy

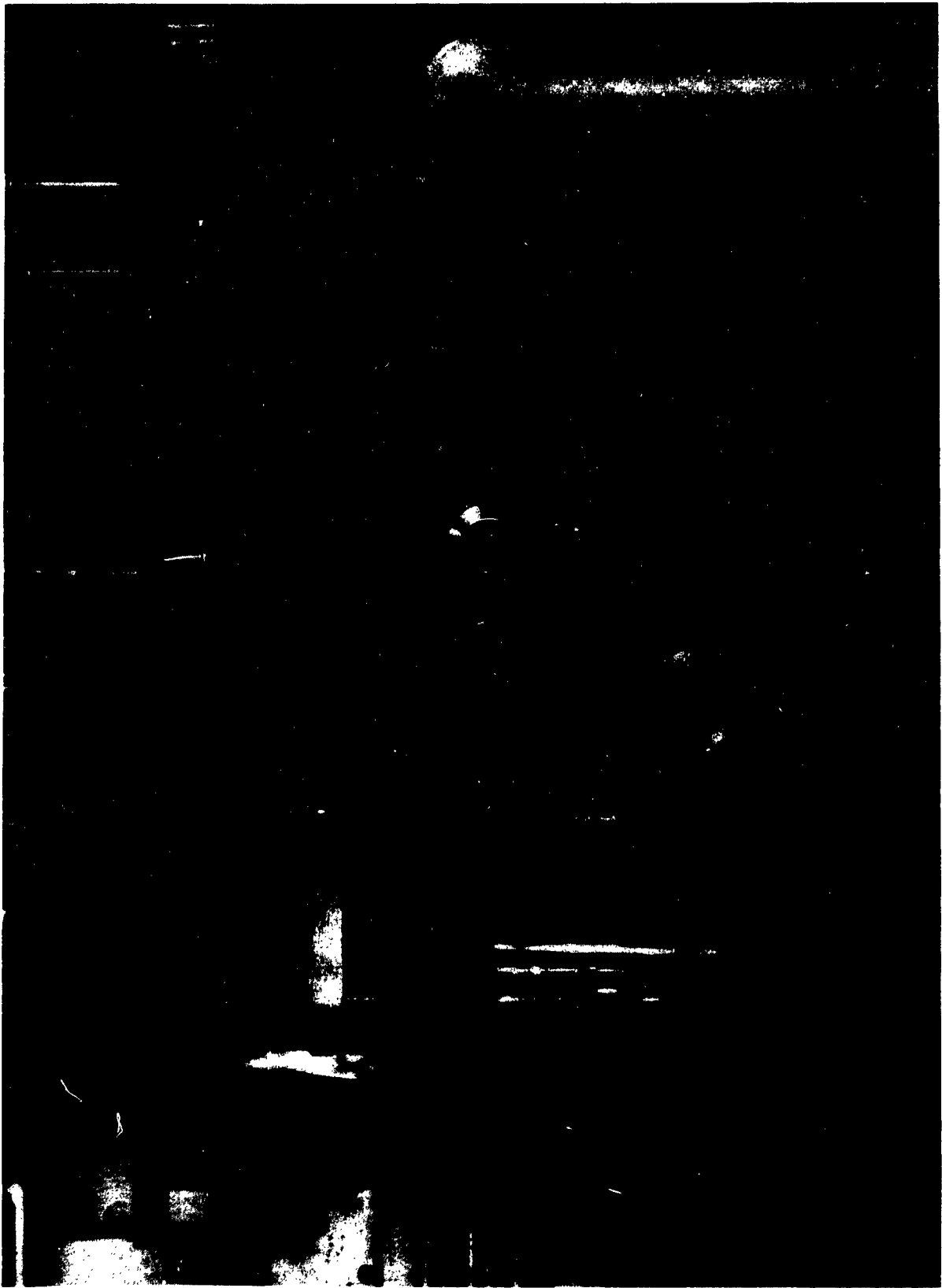
The recommendations for machining D-31 columbium alloy are given in Table II, pages 125 and 126.

#### 6. PROGRAM FOR NEXT QUARTER

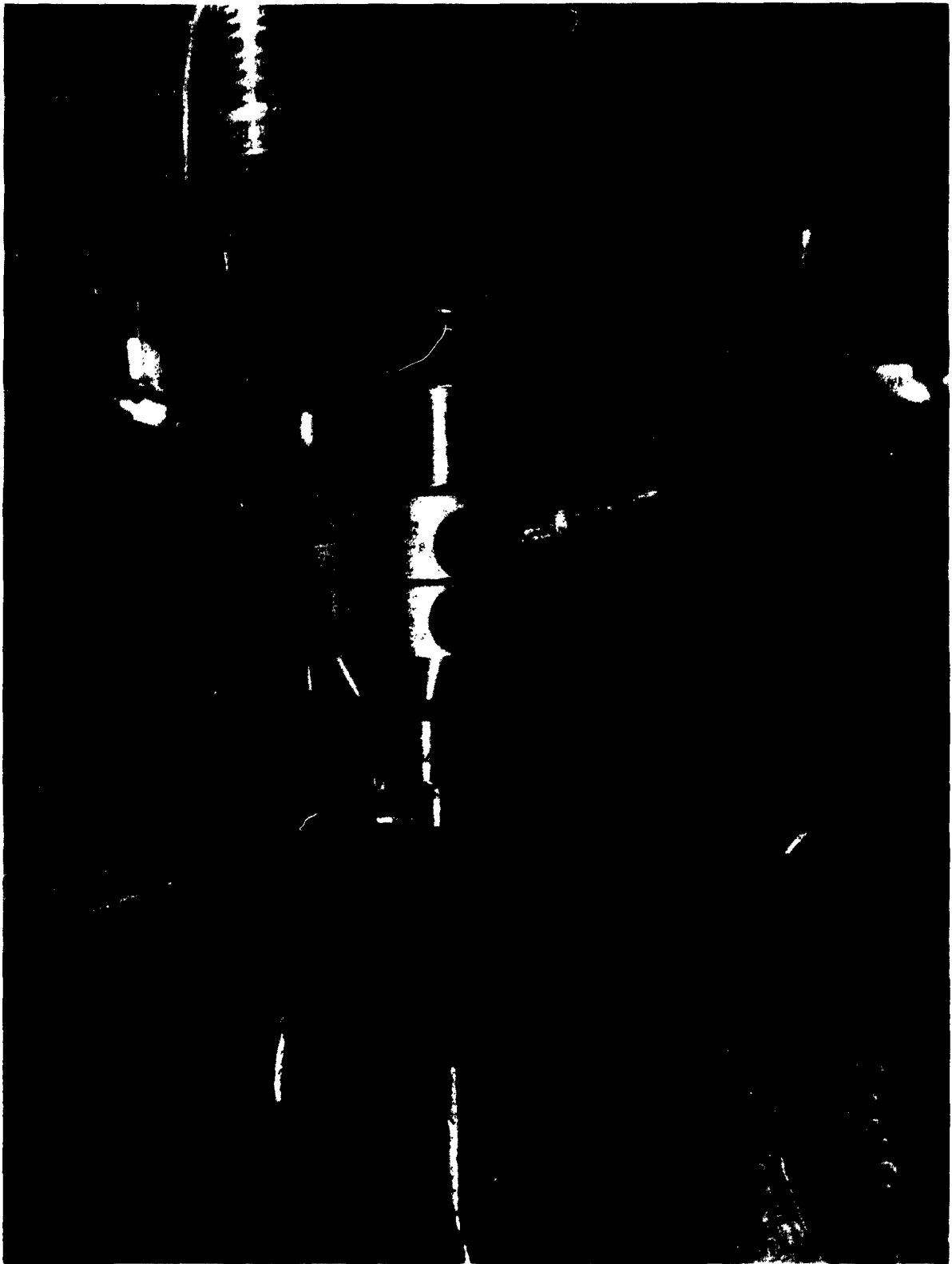
In the next quarter the machining program will be completed. Additional data necessary to fully complete the machinability evaluation of the various alloys tested in this program will be generated.

The high speed milling program will be completed. Additional materials to be tested are HS-25, Rene' 41 and B-120VCA Titanium sheet.

Drilling and tapping tests on the Tornetic units will be completed.



An overall view of 36" x 6' Gray planer and high speed milling head adapted to this machine. The planer provides infinitely variable table speeds ranging from 40 inches/minute to 400 inches/minute. Spindle speeds ranging from 150 rpm to 9000 rpm are available on the milling head.



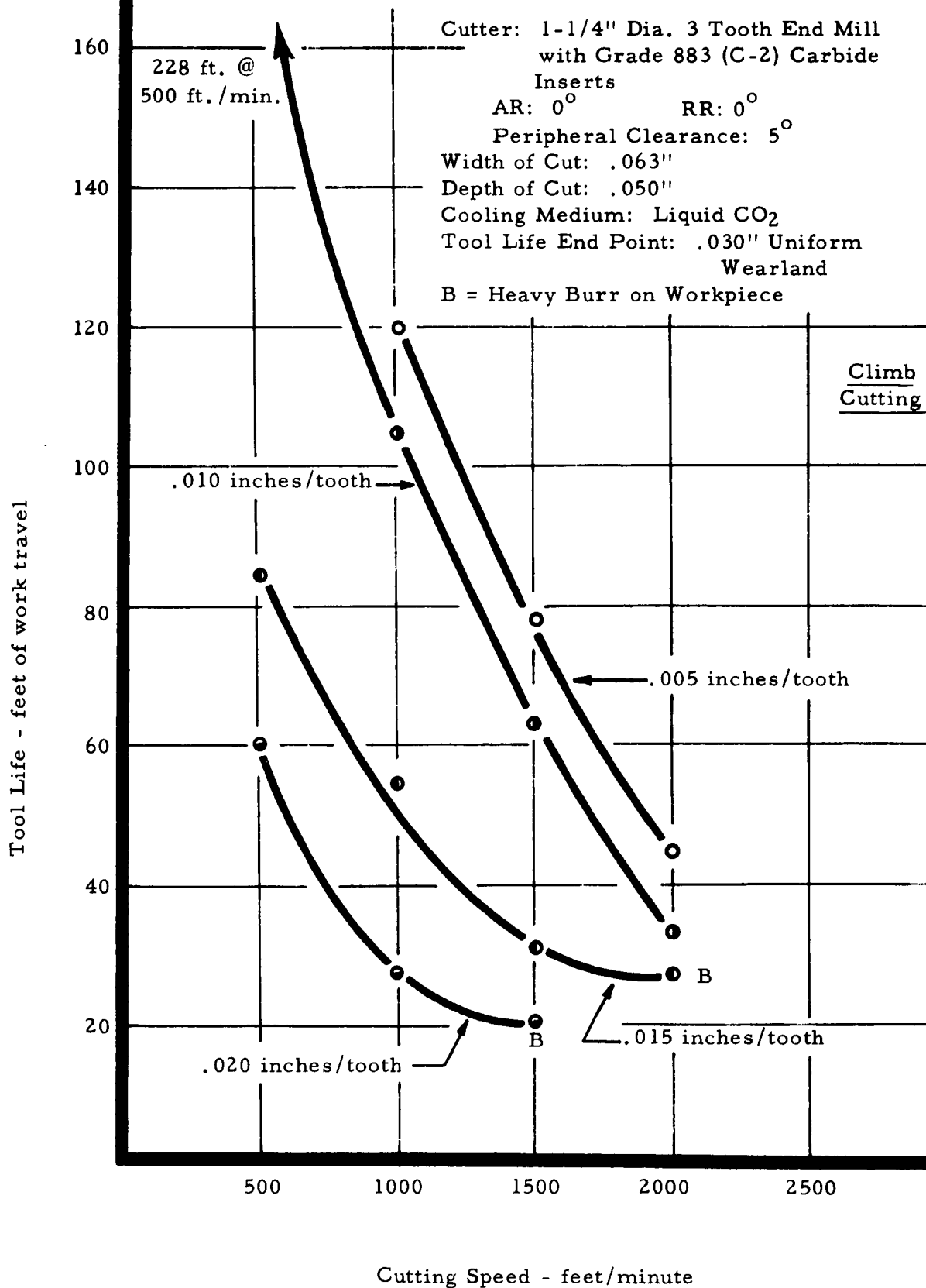
Close-up view of high speed milling cutter head and carbide throw-away type end mill. One of the two nozzles used to direct liquid CO<sub>2</sub> on the cutter and workpiece is shown.

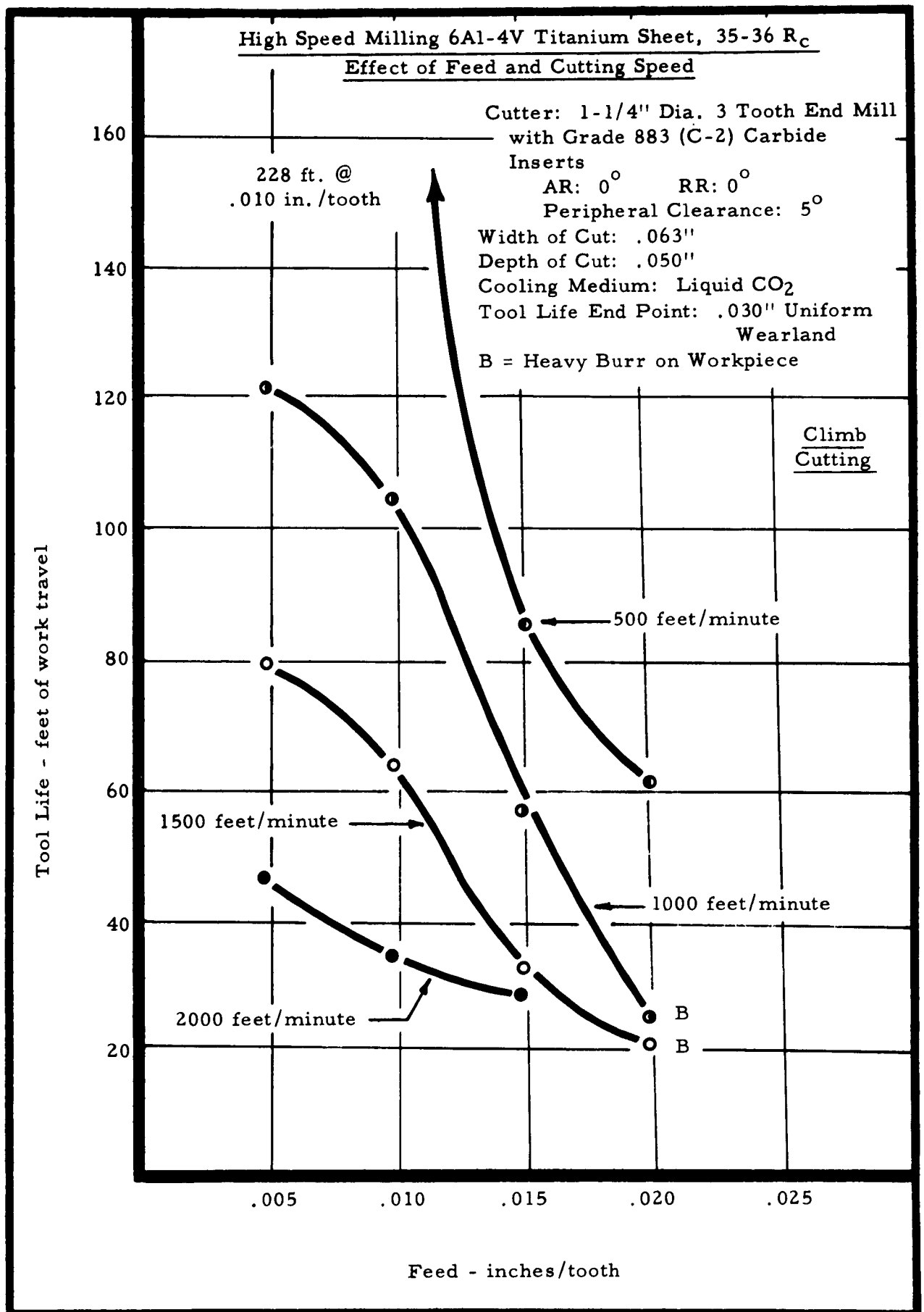


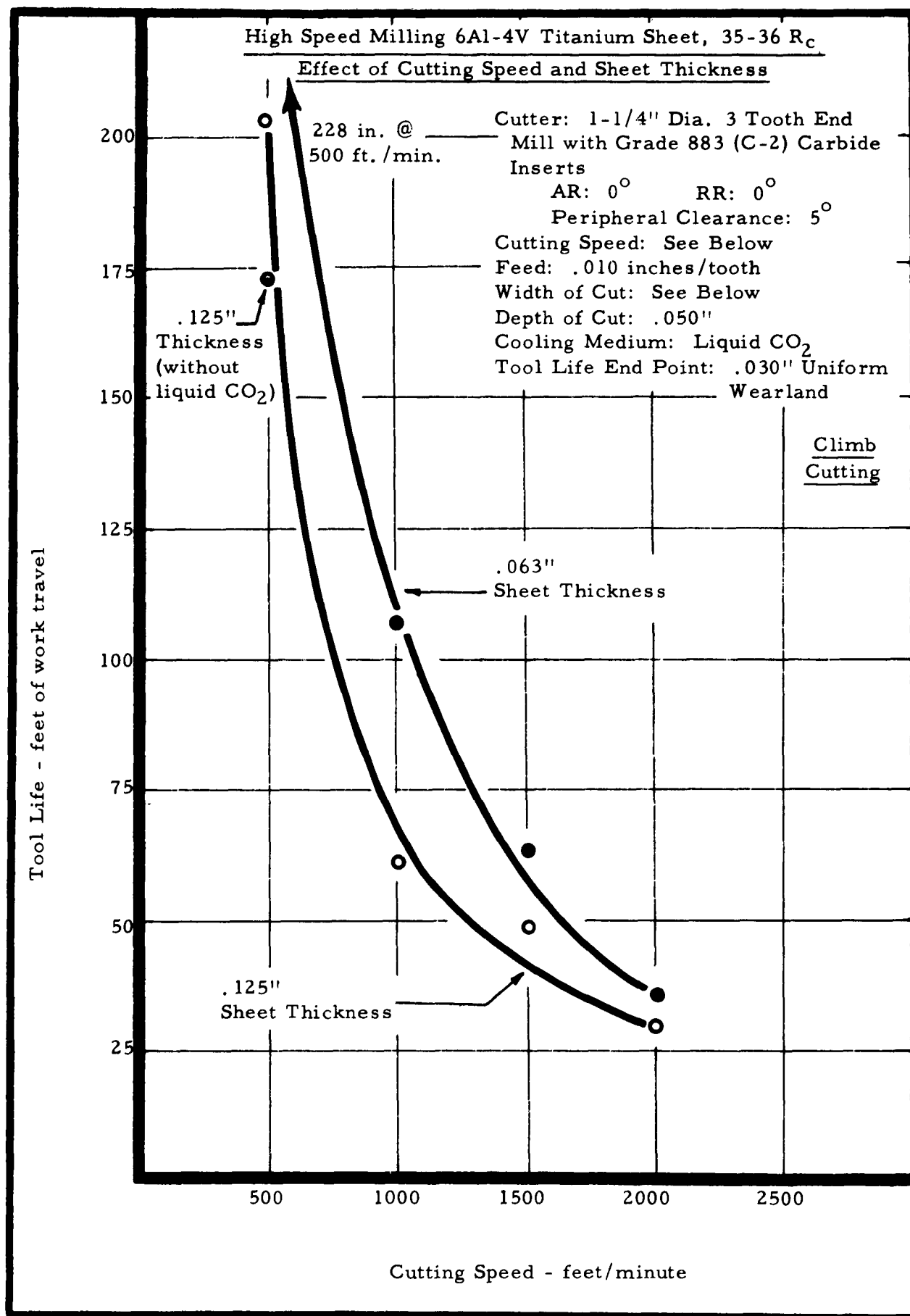
Close-up of high speed edge trimming operation with liquid CO<sub>2</sub> spraying on workpiece and cutter. The cutter was revolving at 6000 rpm (2000 feet/minute) and the table was traveling at 270 inches/minute.

# High Speed Milling 6Al-4V Titanium Sheet, 35-36 R<sub>c</sub>

## Effect of Cutting Speed and Feed







High Speed Milling 6Al-4V Titanium Sheet, 35-36 R<sub>c</sub>  
Effect of Feed and Sheet Thickness

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
 Grade 883 (C-2) Carbide Inserts

AR: 0° RR: 0°

Peripheral Clearance: 5°

Cutting Speed: 1000 feet/minute, 3000 rpm

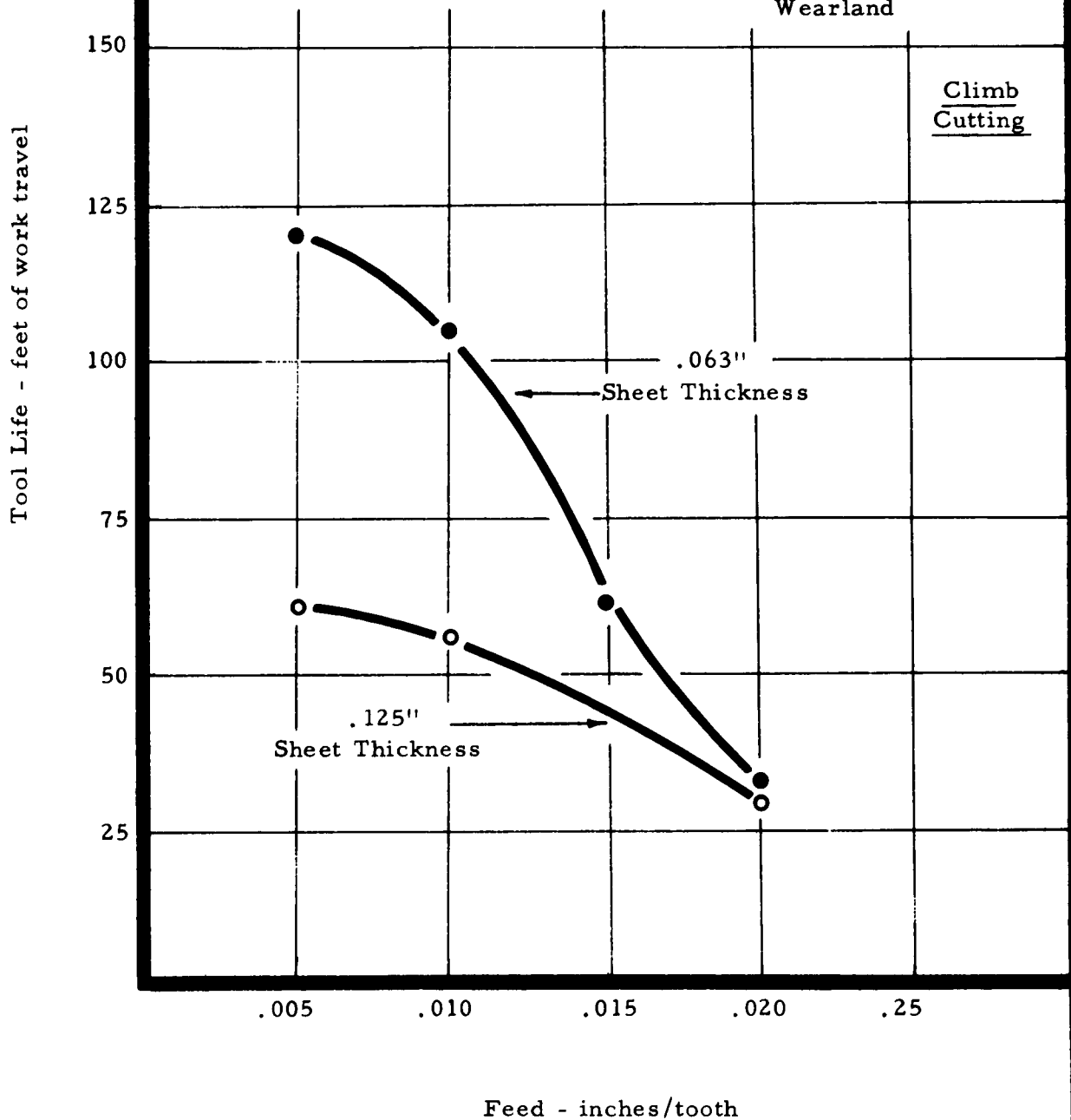
Feed: See Below

Depth of Cut: .050"

Width of Cut: See Below

Cooling Medium: Liquid CO<sub>2</sub>

Tool Life End Point: .030" Uniform  
 Wearland



# High Speed Milling 6Al-4V Titanium Sheet, 35-36 R<sub>c</sub>

## Effect of Feed and Depth of Cut

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
Grade 883 (C-2) carbide inserts

AR: 0° RR: 0°

Peripheral Clearance: 5°

Cutting Speed: 1000 feet/minute, 3000 rpm

Feed: See Below

Width of Cut: .063"

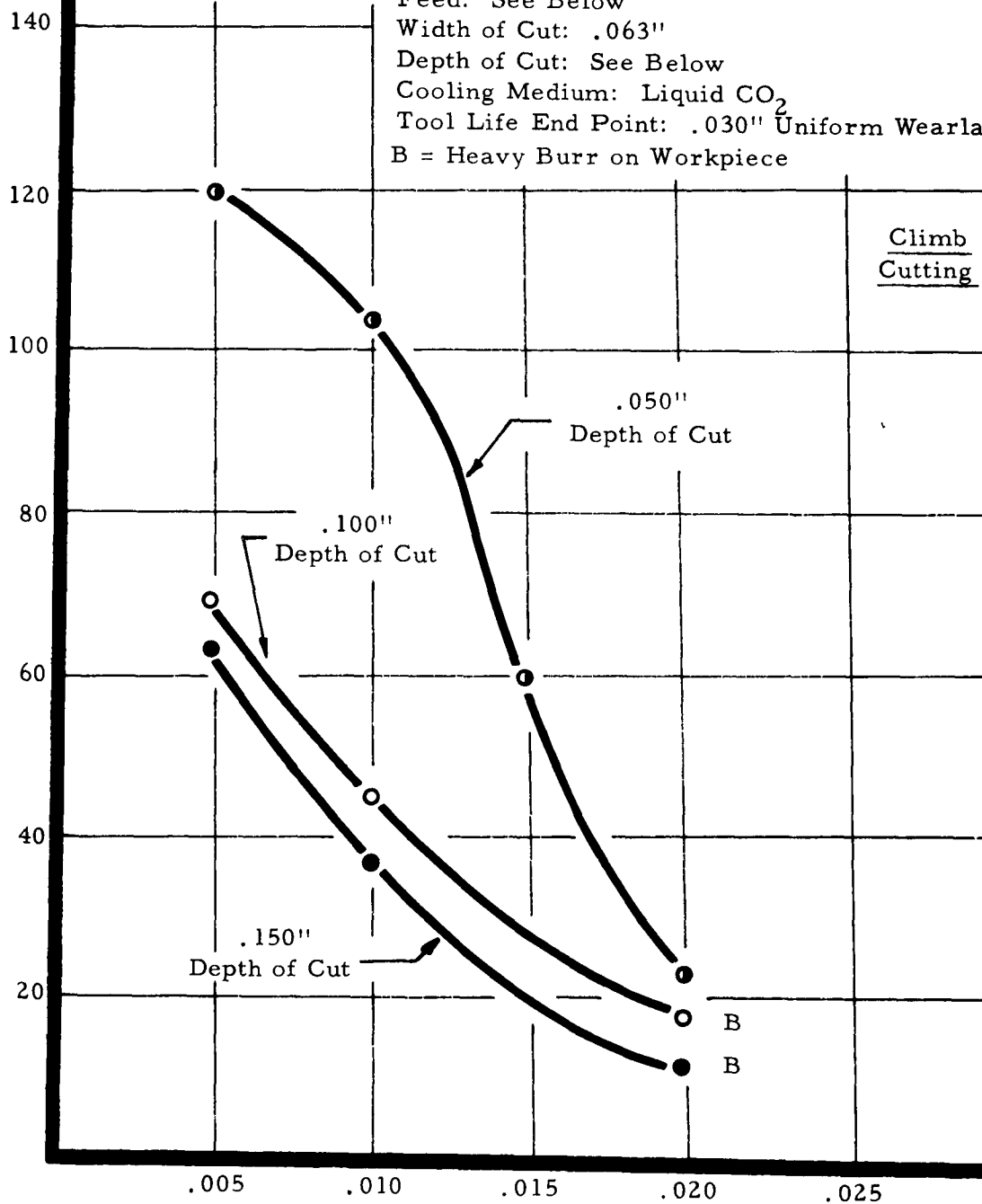
Depth of Cut: See Below

Cooling Medium: Liquid CO<sub>2</sub>

Tool Life End Point: .030" Uniform Wearland

B = Heavy Burr on Workpiece

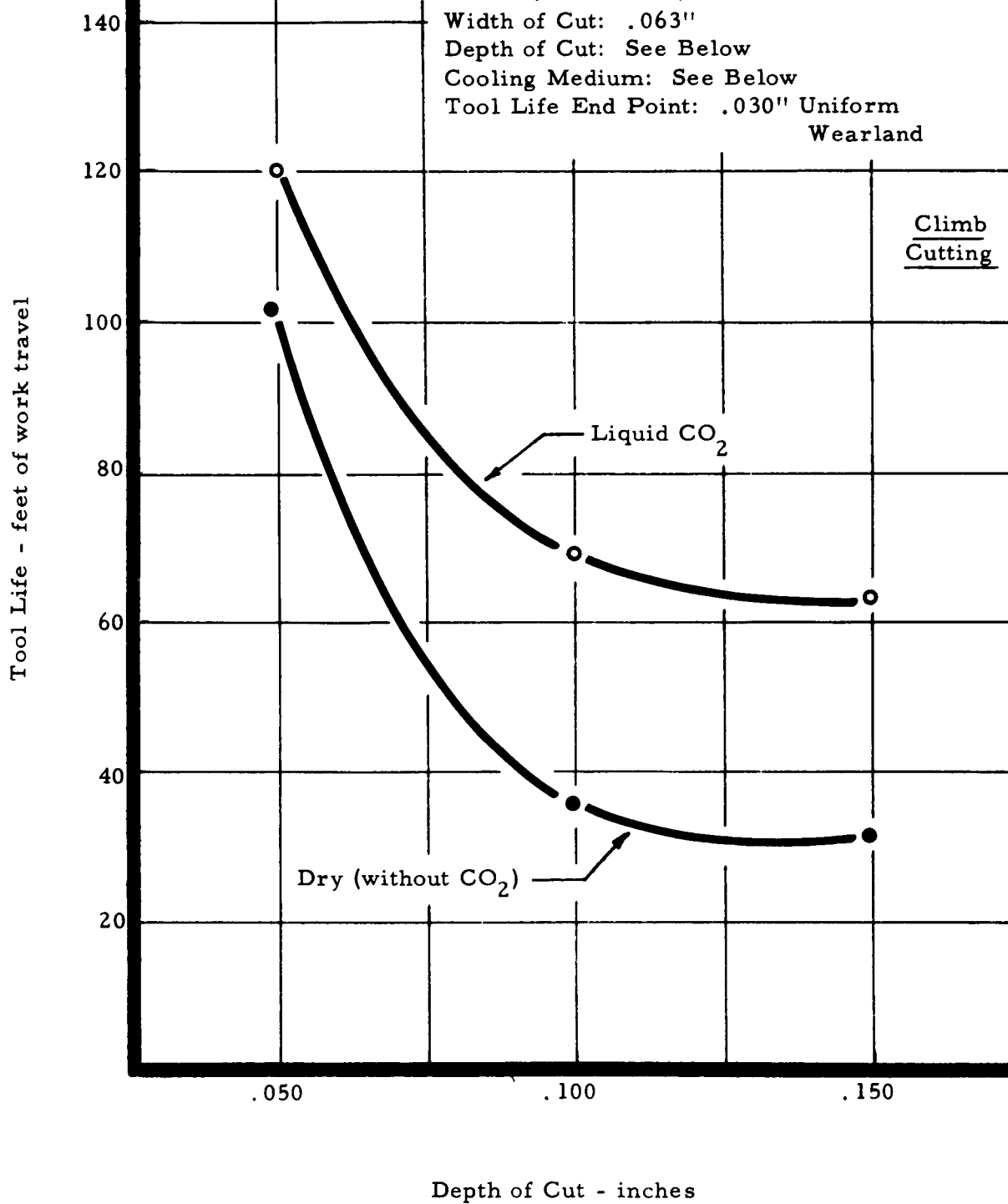
Tool Life - feet of work travel



Feed - inches/tooth

High Speed Milling 6Al-4V Titanium Sheet, 35-36 Rc  
Effect of Depth of Cut and Cooling Medium

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
Grade 883 (C-2) Carbide Insert  
AR: 0° RR: 0°  
Peripheral Clearance: 5°  
Cutting Speed: 1000 feet/minute, 3000 rpm  
Feed: .005 inches/tooth  
Width of Cut: .063"  
Depth of Cut: See Below  
Cooling Medium: See Below  
Tool Life End Point: .030" Uniform  
Wearland



# High Speed Milling 6Al-4V Titanium Sheet, 35-36 R<sub>C</sub>

## Effect of Cooling Medium and Depth of Cut

Cutter: 1-1/4" Dia. 3 Tooth End Mill with

Grade 883 (C-2) Carbide Insert

AR: 0° RR: 0°

Peripheral Clearance: 5°

Cutting Speed: 1000 feet/minute, 3000 rpm

Feed: .005 inches/tooth

Width of Cut: .063"

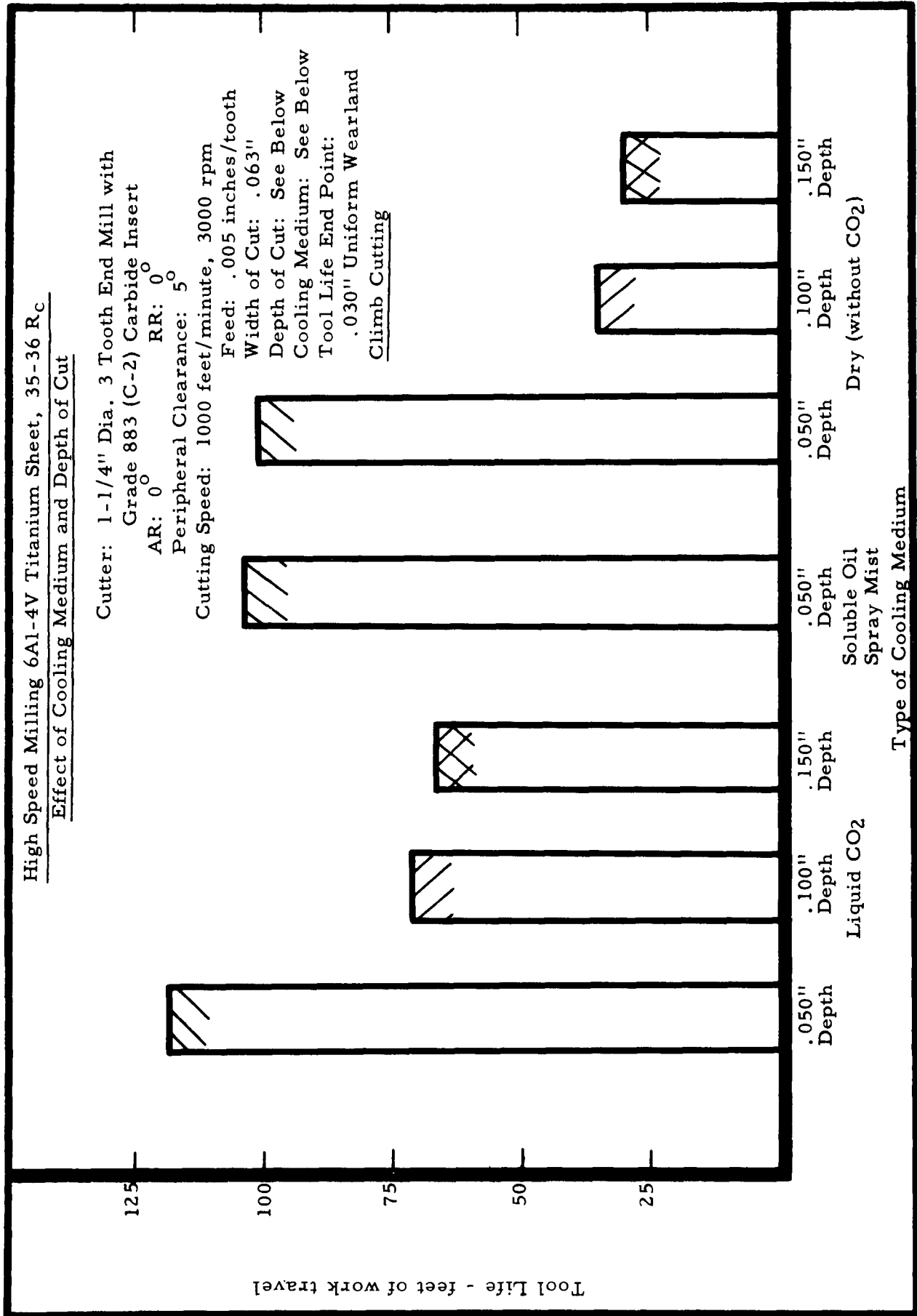
Depth of Cut: See Below

Cooling Medium: See Below

Tool Life End Point:

.030" Uniform Wearland

Climb Cutting



High Speed Milling 6Al-4V Titanium Sheet, 35-36 R<sub>c</sub>

Effect of Carbide Grade

Cutter: 1-1/4" Dia. 3 Tooth End Mill  
with Carbide Inserts (See Grade Below)

AR: 0° RR: 0°

Peripheral Clearance: 5°

Cutting Speed: 1500 feet/minute, 4500 rpm

Feed: .020 inches/tooth

Width of Cut: .063"

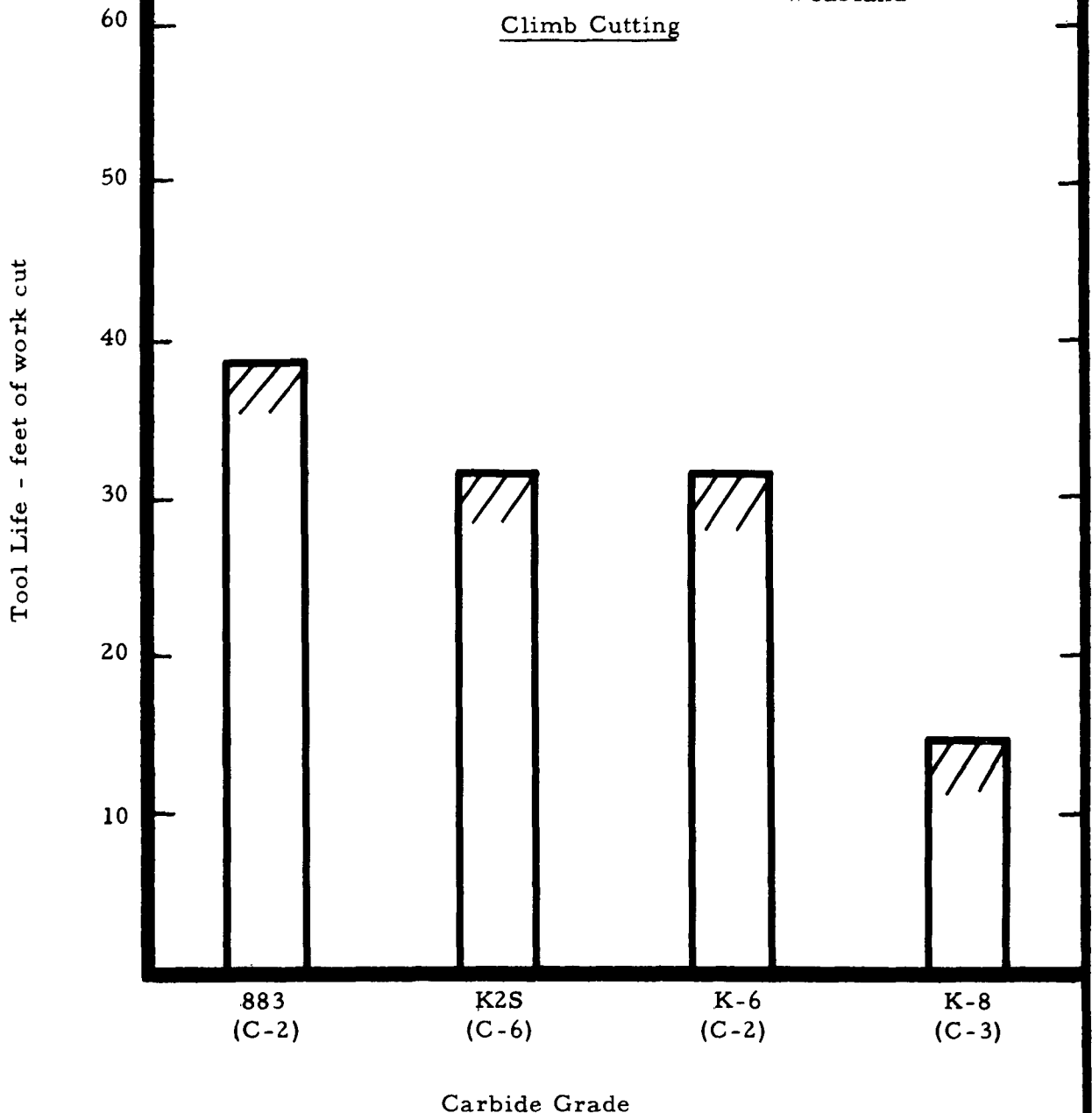
Depth of Cut: .050"

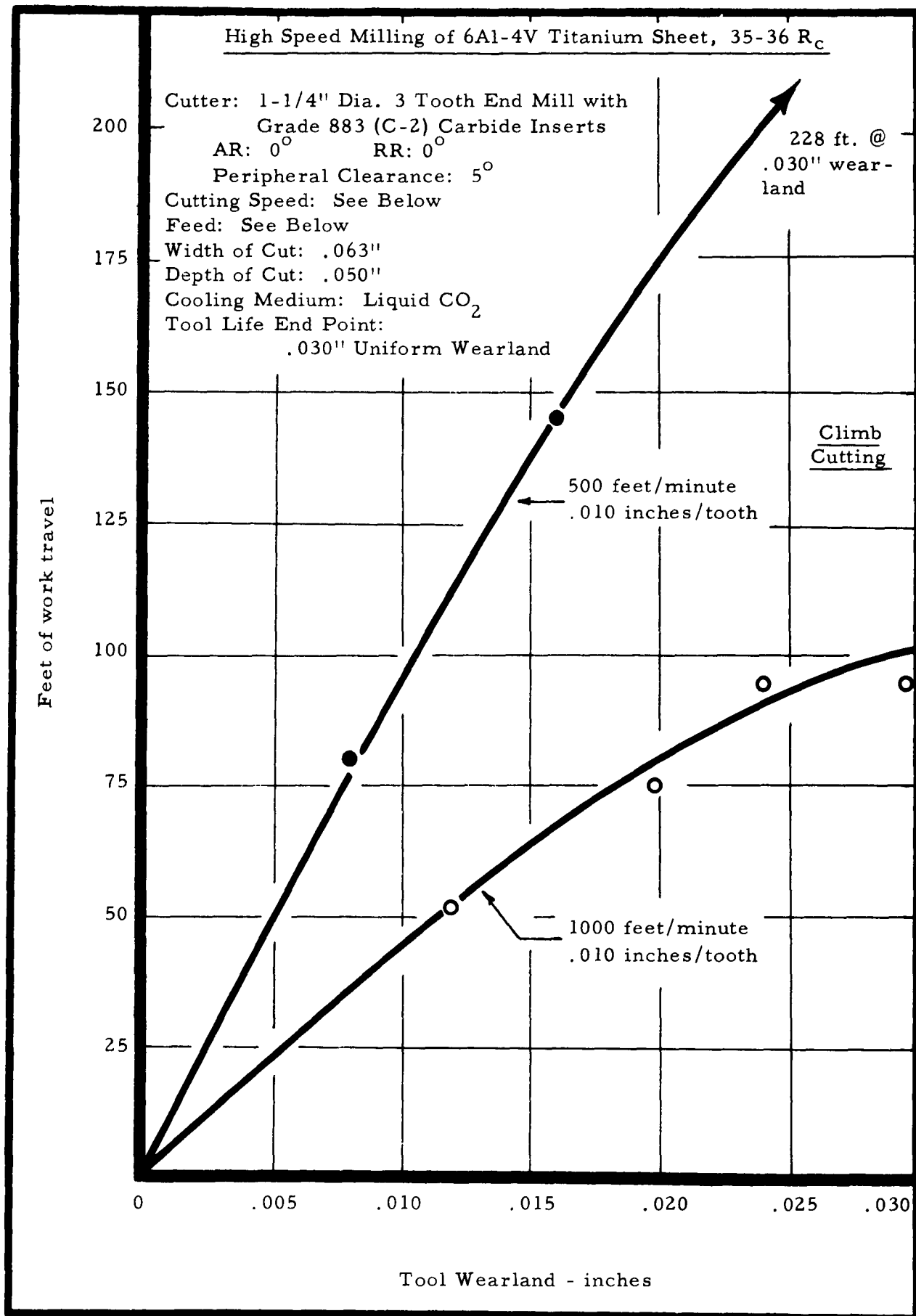
Cooling Medium: Liquid CO<sub>2</sub>

Tool Life End Point: .030" Uniform

Wearland

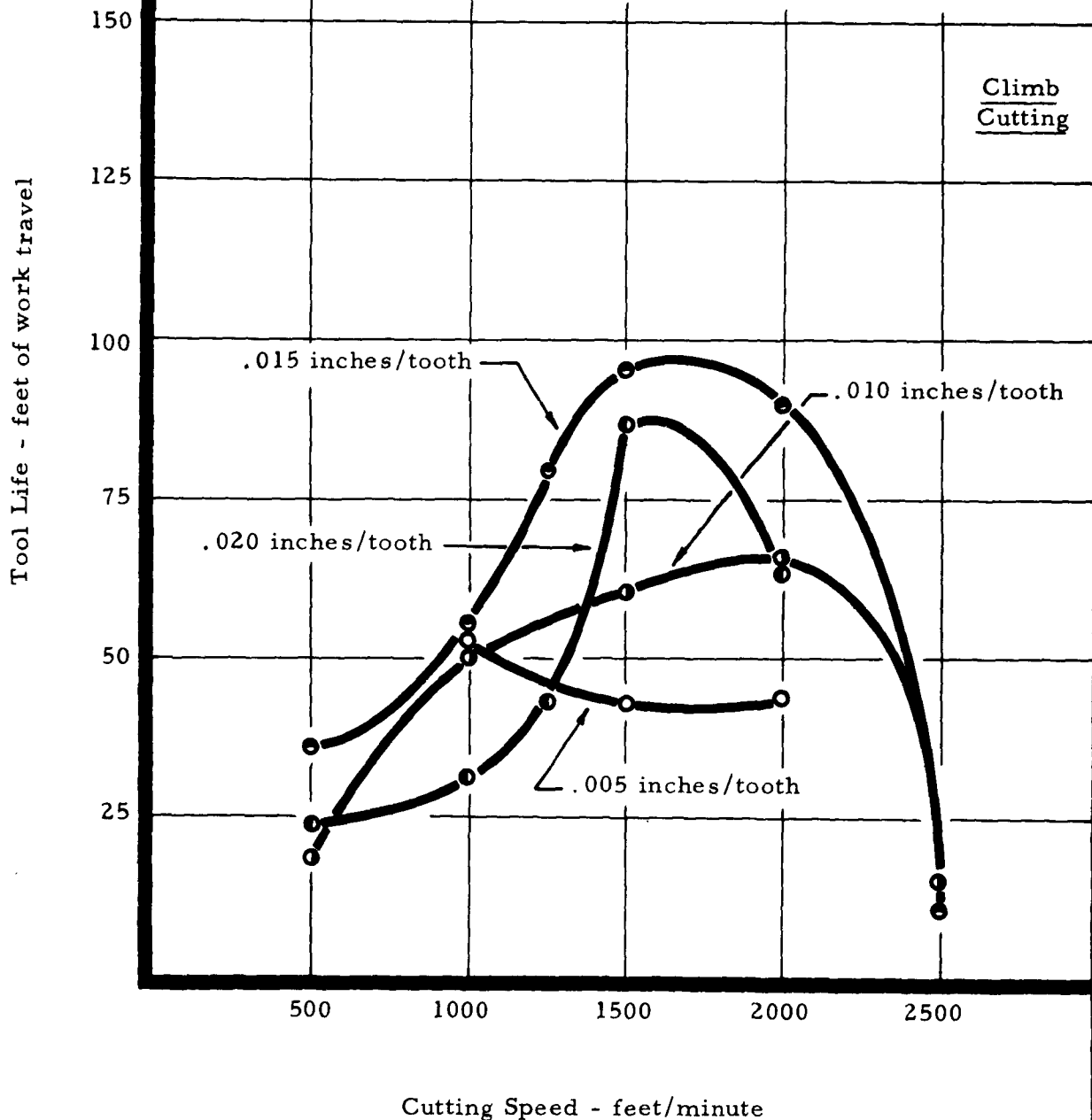
Climb Cutting





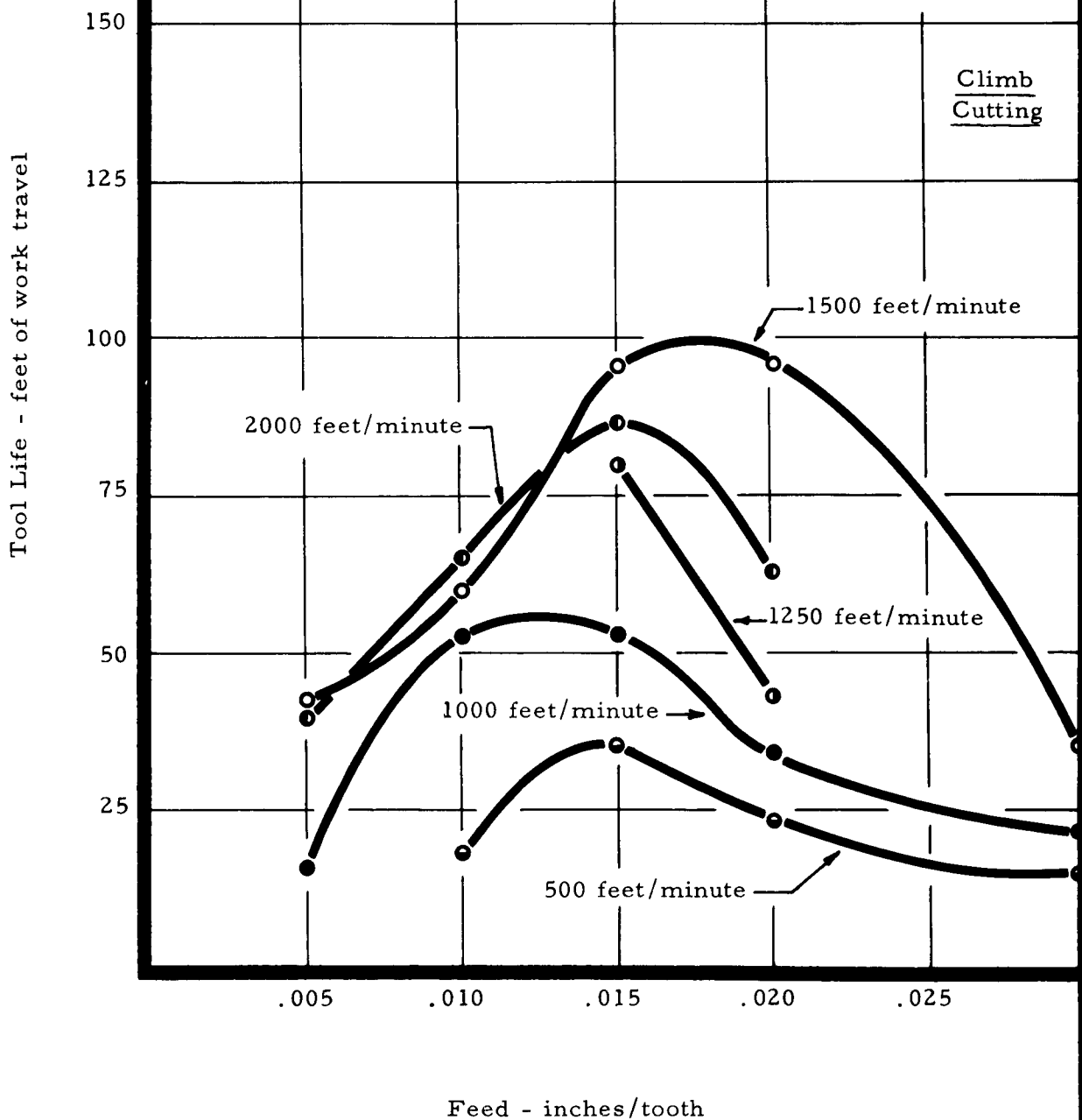
High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB  
Effect of Cutting Speed with Constant Feeds Using Liquid CO<sub>2</sub>

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
 Grade K-2S (C-6) Carbide Inserts  
 AR: 0°      RR: 0°  
 Peripheral Clearance: 5°  
 Cutting Speed: See Below  
 Feed: See Below  
 Width of Cut: .063"  
 Depth of Cut: .050"  
 Cooling Medium: Liquid CO<sub>2</sub>  
 Tool Life End Point: .060" Uniform  
 Wearland



High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB  
 Effect of Feed with Constant Cutting Speeds using Liquid CO<sub>2</sub>

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
 Grade K-2S (C-6) Carbide Inserts  
 AR: 0° RR: 0°  
 Peripheral Clearance: 5°  
 Cutting Speed: See Below  
 Feed: See Below  
 Width of Cut: .063"  
 Depth of Cut: .050"  
 Cooling Medium: Liquid CO<sub>2</sub>  
 Tool Life End Point: .060" Uniform  
 Wearland

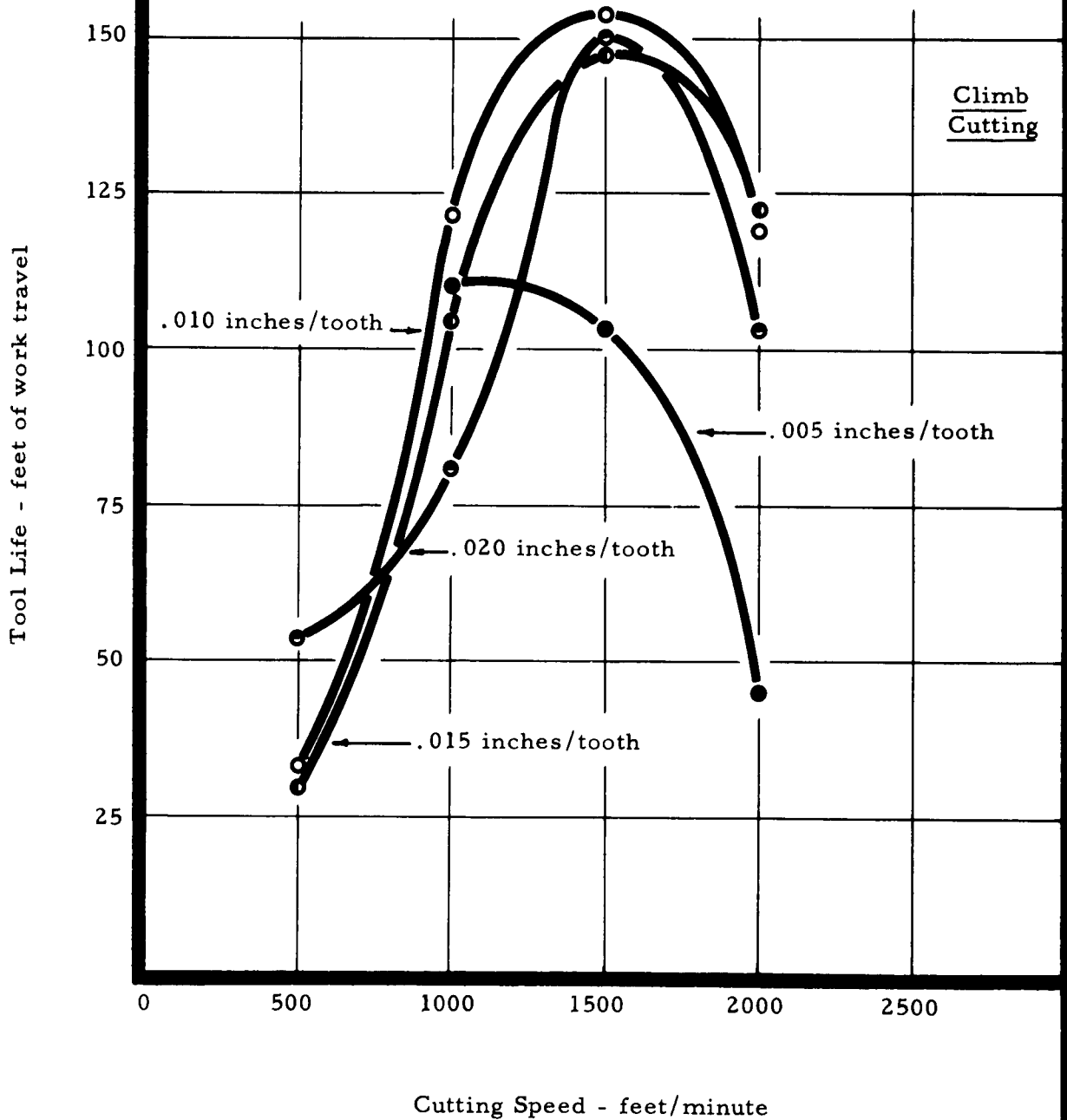


# High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB

## Effect of Cutting Speed with Constant Feeds Dry (Without Liquid CO<sub>2</sub>)

Cutter: 1-1/4" Dia. 3 Tooth  
End Mill with Grade K-2S  
(C-6) Carbide Inserts  
AR: 0° RR: 0°  
Peripheral Clearance: 5°  
Cutting Speed: See Below

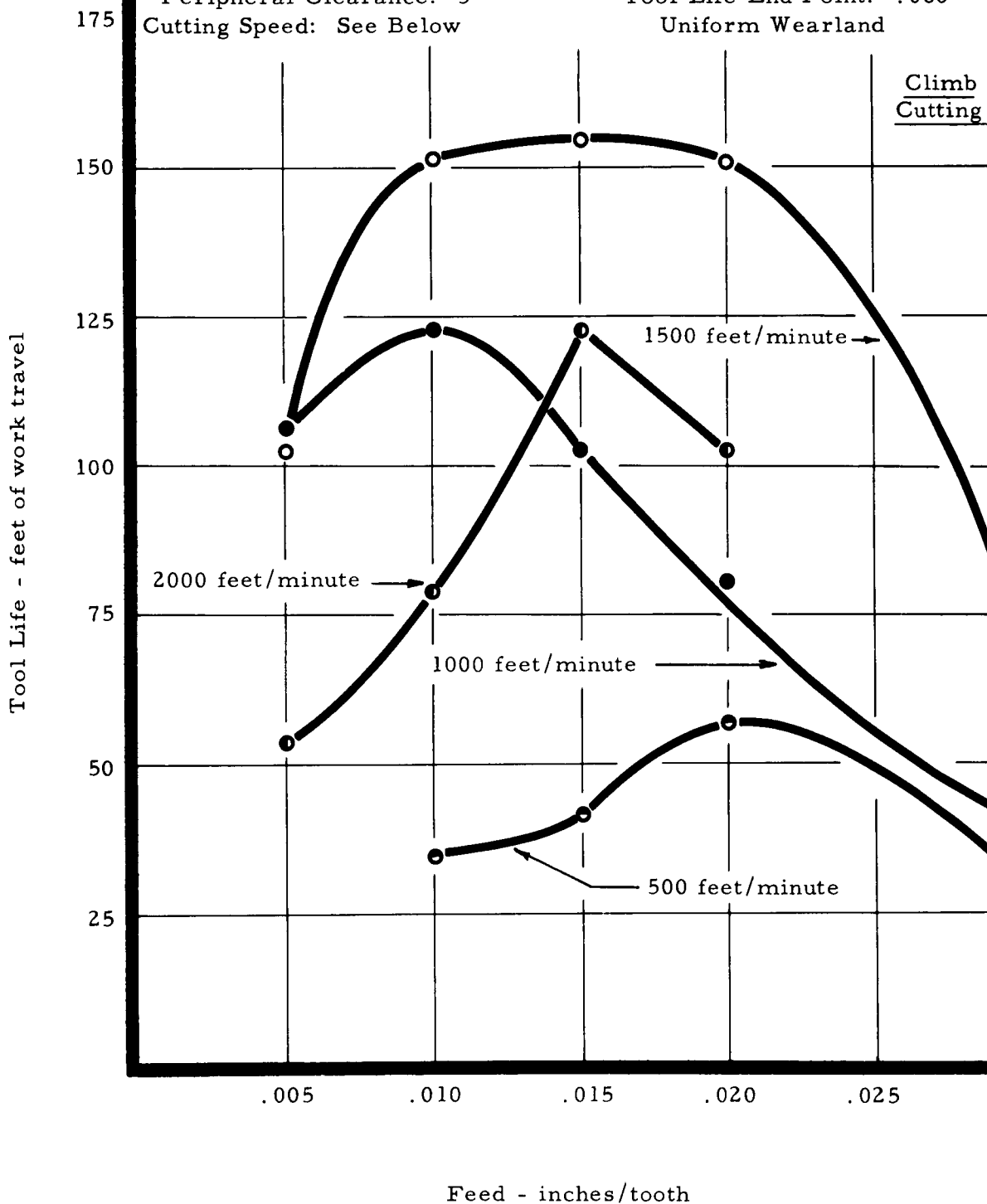
Feed: See Below  
Width of Cut: .063"  
Depth of Cut: .050"  
Cooling Medium: Dry  
Tool Life End Point: .060"  
Uniform Wearland



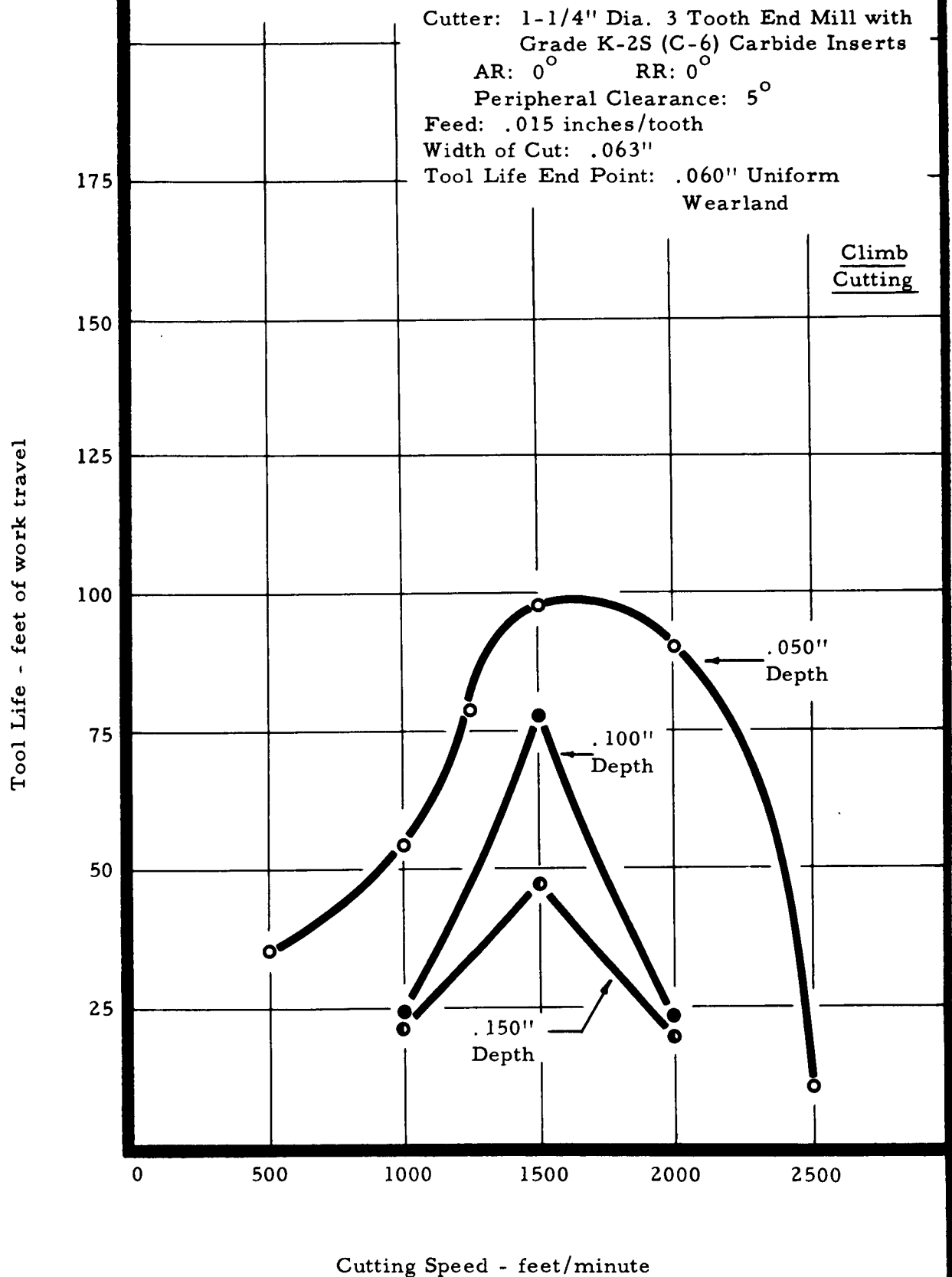
High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB  
Effect of Feed with Constant Cutting Speeds  
Dry (Without Liquid CO<sub>2</sub>)

Cutter: 1-1/4" Dia. 3 Tooth  
 End Mill with Grade K-2S  
 (C-6) Carbide Inserts  
 AR: 0°      RR: 0°  
 Peripheral Clearance: 5°  
 Cutting Speed: See Below

Feed: See Below  
 Width of Cut: .063"  
 Depth of Cut: .050"  
 Cooling Medium: Dry  
 Tool Life End Point: .060"  
 Uniform Wearland



High Speed Milling PH 15-7 Mo Sheet, Annealed 90 R<sub>B</sub>  
 Effect of Cutting Speed and Depth of Cut Using Liquid CO<sub>2</sub>



# High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB

## Effect of Cutting Speed and Depth of Cut

Dry (Without Liquid CO<sub>2</sub>)

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
Grade K-2S (C-6) Carbide Inserts

AR: 0° RR: 0°

Peripheral Clearance: 5°

Feed: .015 inches/tooth

Width of Cut: .063"

Tool Life End Point: .060" Uniform  
Wearland

Tool Life - feet of work travel

175

150

125

100

75

50

25

.050"  
Depth

.100"  
Depth

.150"  
Depth

Climb  
Cutting

500

1000

1500

2000

2500

Cutting Speed - feet/minute

# High Speed Milling PH 15-7 Mo Sheet, Annealed 90 RB.

## Effect of Cooling Medium and Depth of Cut

Cutter: 1-1/4" Dia. 3 Tooth End Mill with  
 Grade K 2S (C-6) Carbide Inserts  
 AR: 0° RR: 0°  
 Peripheral Clearance: 5°  
 Cutting Speed: 1500 feet/minute, 4500 rpm  
 Feed: .015 inches/tooth  
 Width of Cut: .063"  
 Depth of Cut: See Below  
 Tool Life End Point: .060" Uniform Wearland  
Climb Cutting

Tool Life - feet of work travel

200

150

100

50

.050"  
Depth

.100"  
Depth

.150"  
Depth

.050"  
Depth  
Soluble Oil  
Spray Mist

.050"  
Depth

.100"  
Depth

.150"  
Depth

Dry (without CO<sub>2</sub>)

Liquid CO<sub>2</sub>

Type of Cooling Medium

High Speed Milling PH 17-7 Mo Sheet, Annealed 90 RB

Effect of Carbide Grade

Cutter: 1-1/4" Dia. 3 Tooth End Mill  
with Carbide Inserts (See Grade  
Below)

AR: 0° RR: 0°

Peripheral Clearance: 5°

Cutting Speed: 2000 feet/minute, 6000 rpm

Feed: .010 inches/tooth

Depth of Cut: .050"

Width of Cut: .063"

Cooling Medium: Liquid CO<sub>2</sub>

Tool Life End Point: .060" Uniform  
Wearland

Climb Cutting

Tool Life - feet of work travel

70

60

50

40

30

20

10

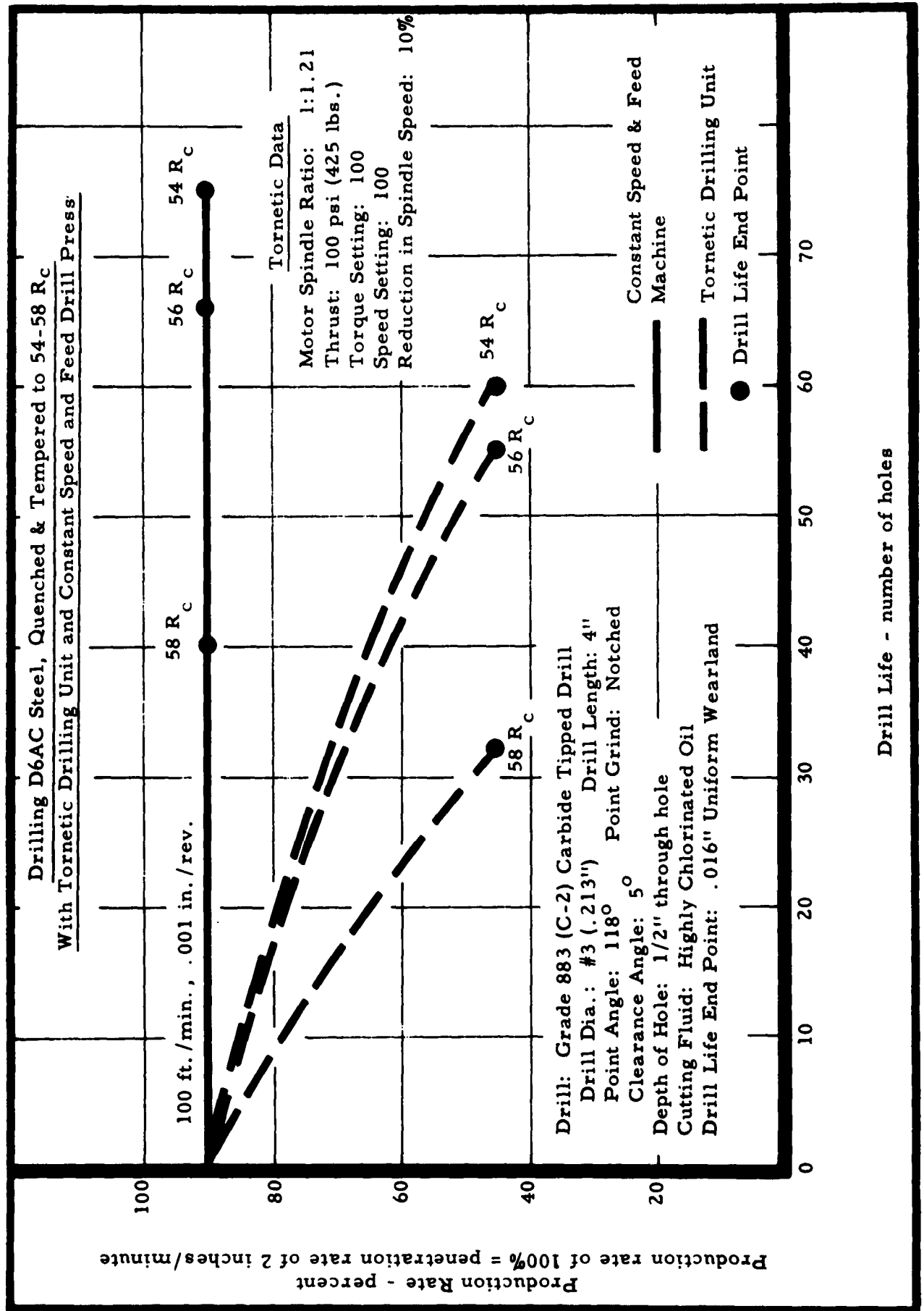
K-2S  
(C-6)

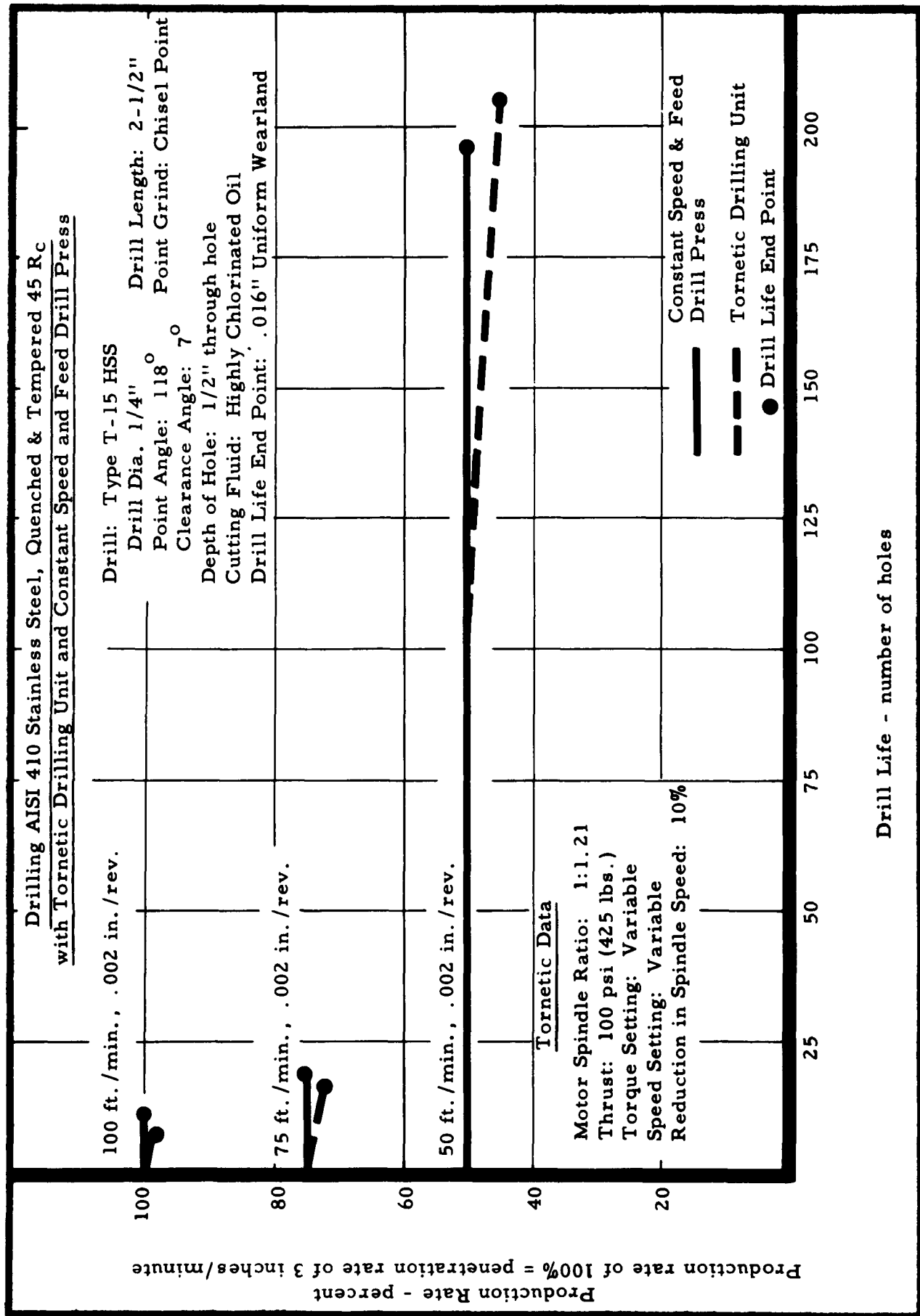
K-6  
(C-2)

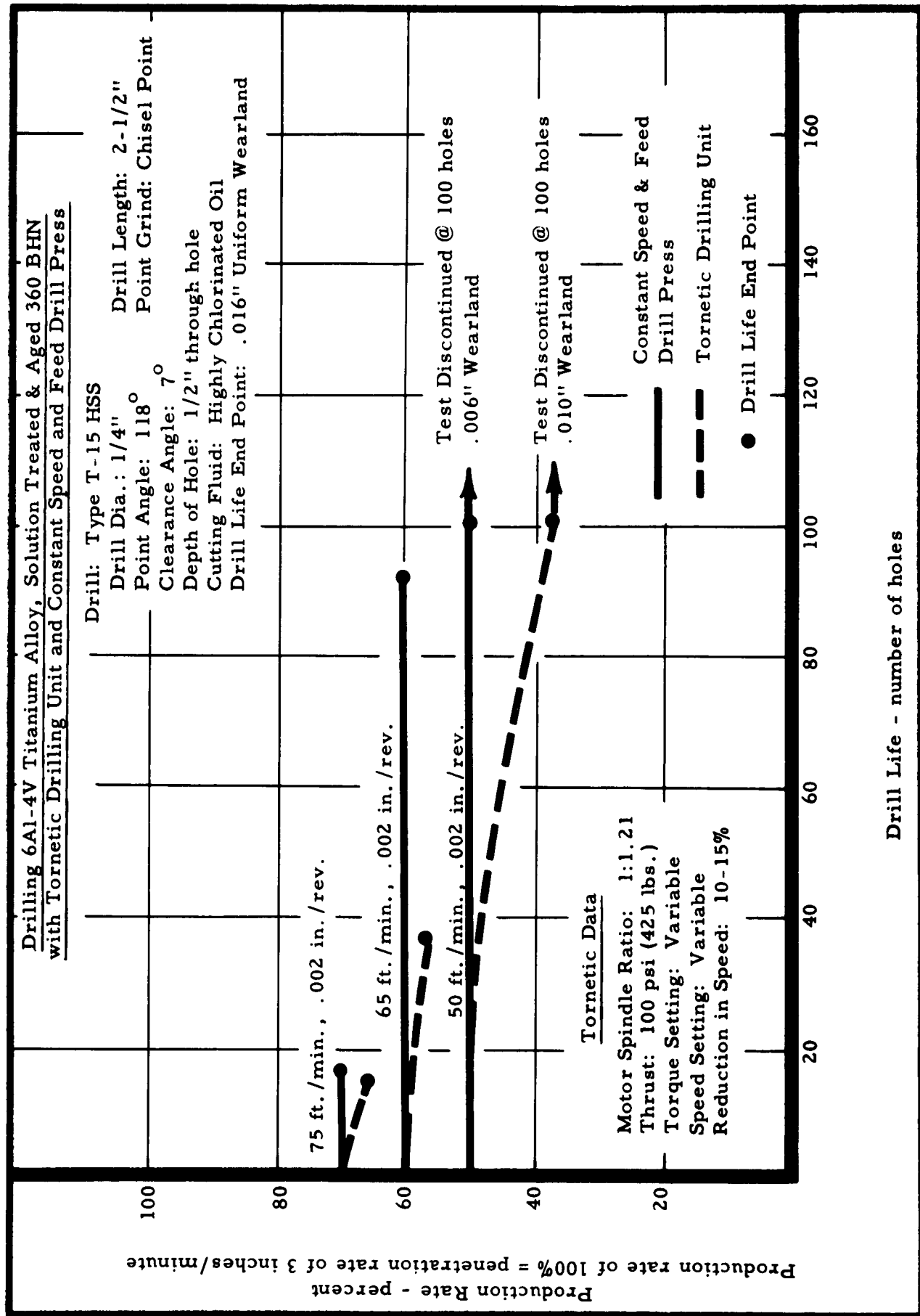
883  
(C-2)

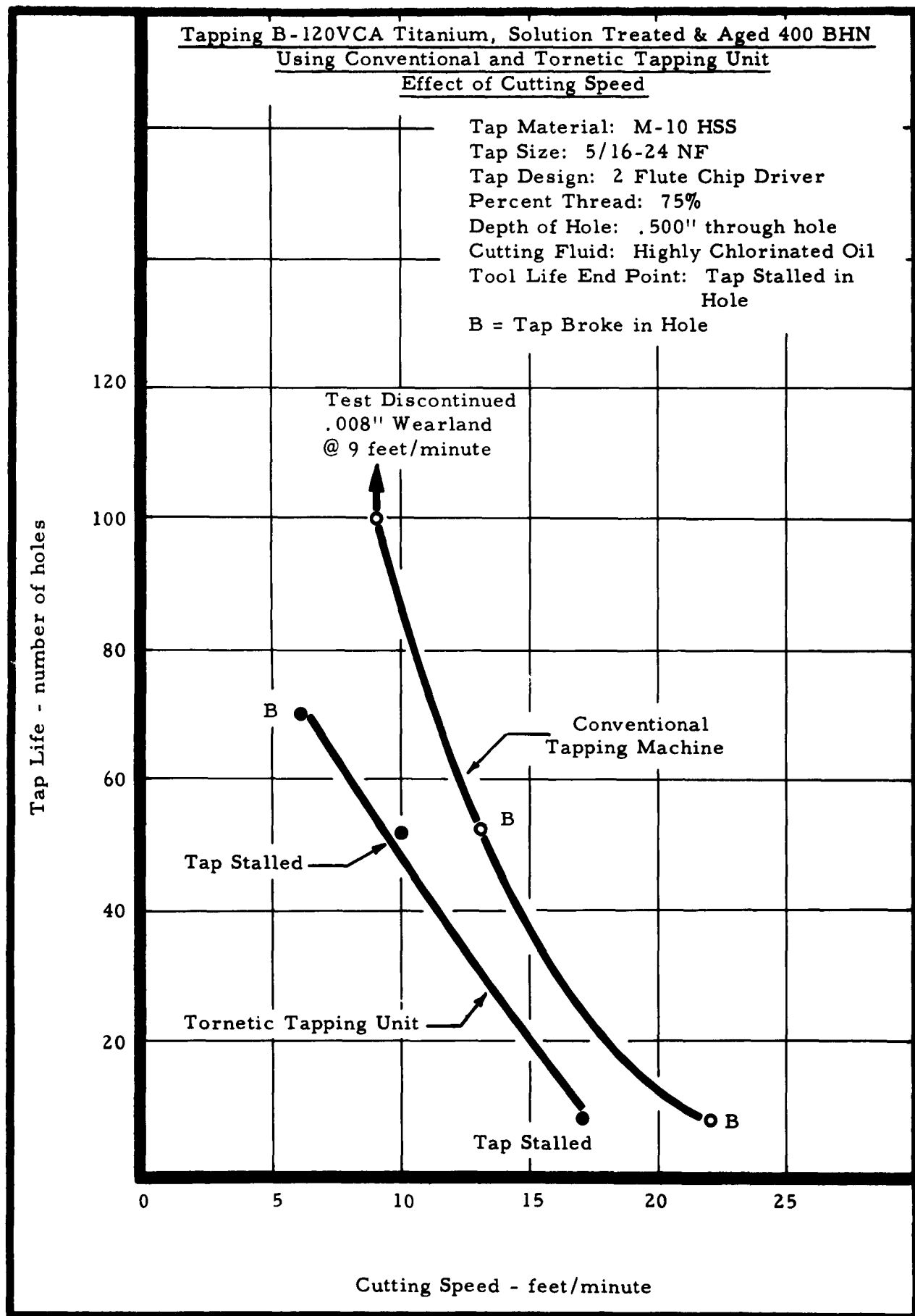
K-8  
(C-3)

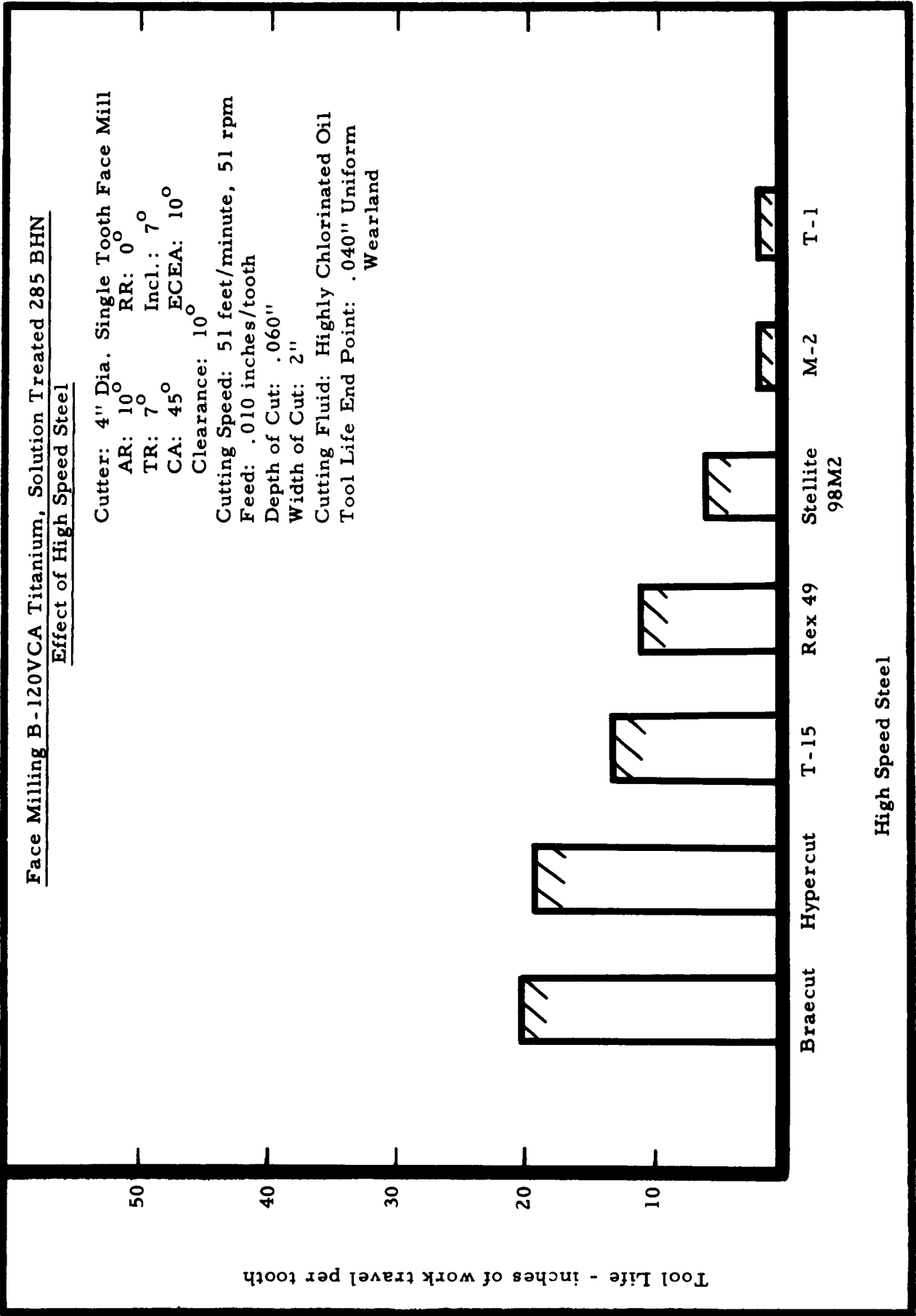
Carbide Grade

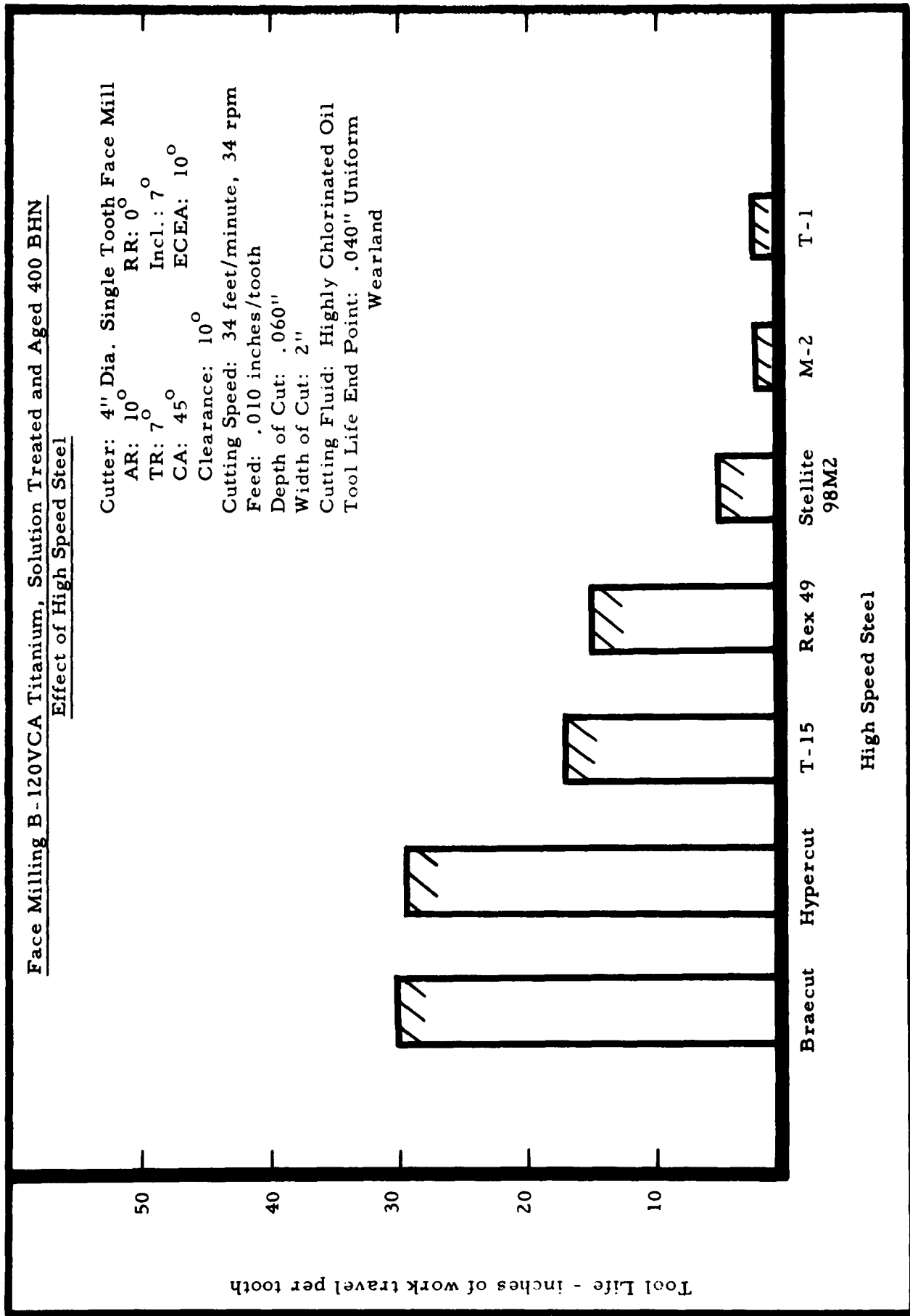




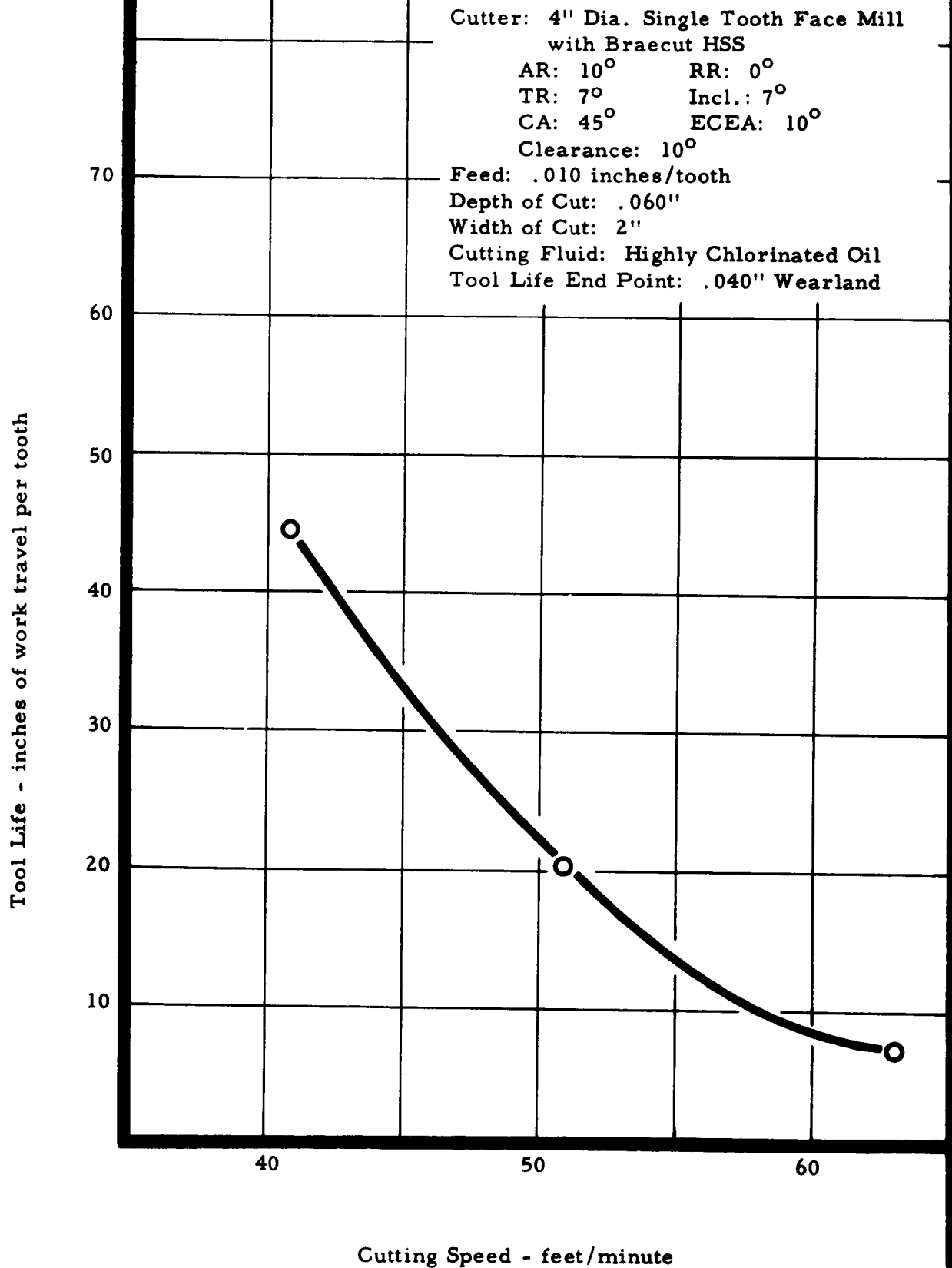




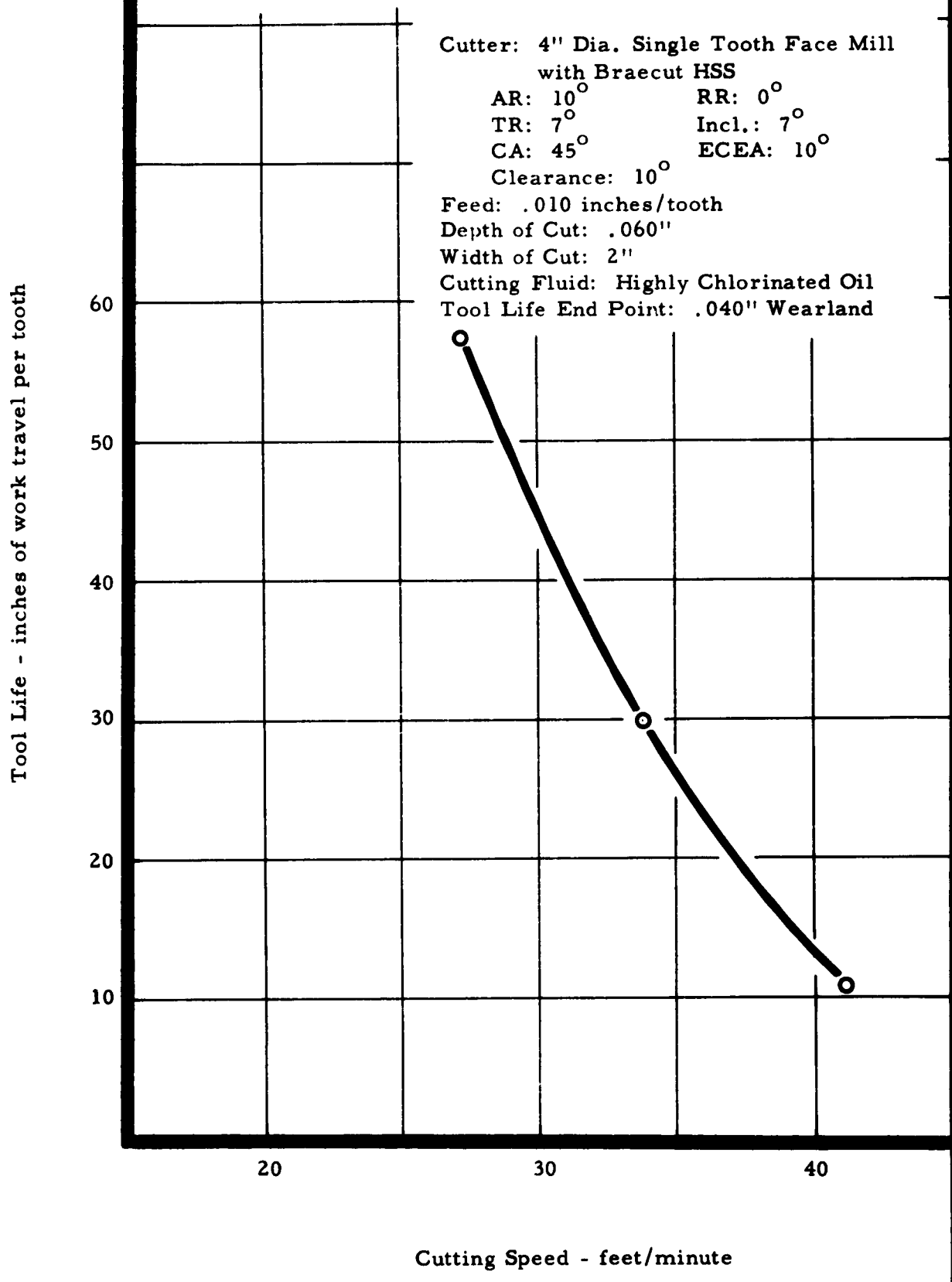




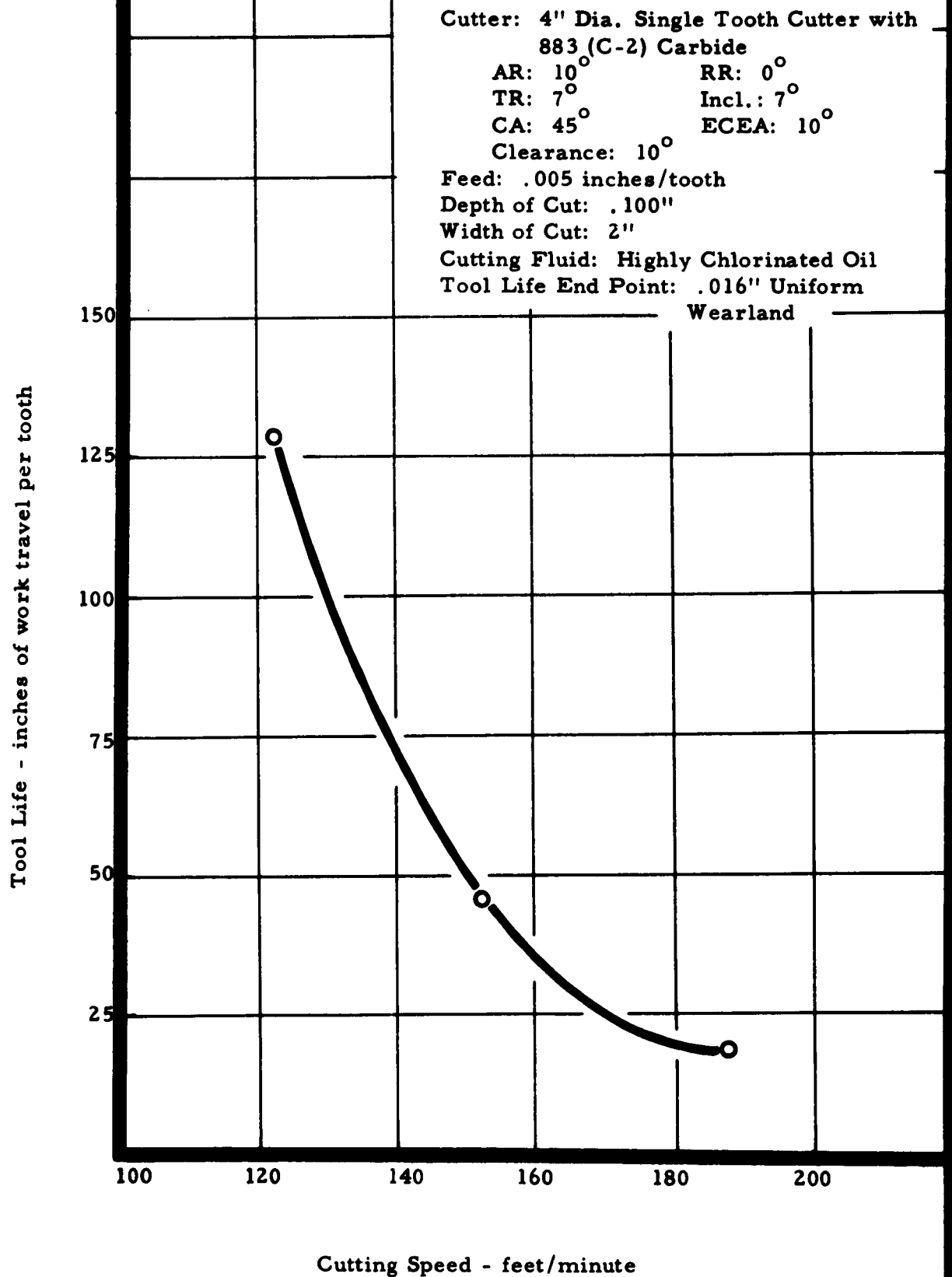
Face Milling B-120VCA Titanium, Solution Treated 285 BHN  
Effect of Cutting Speed with HSS Cutters



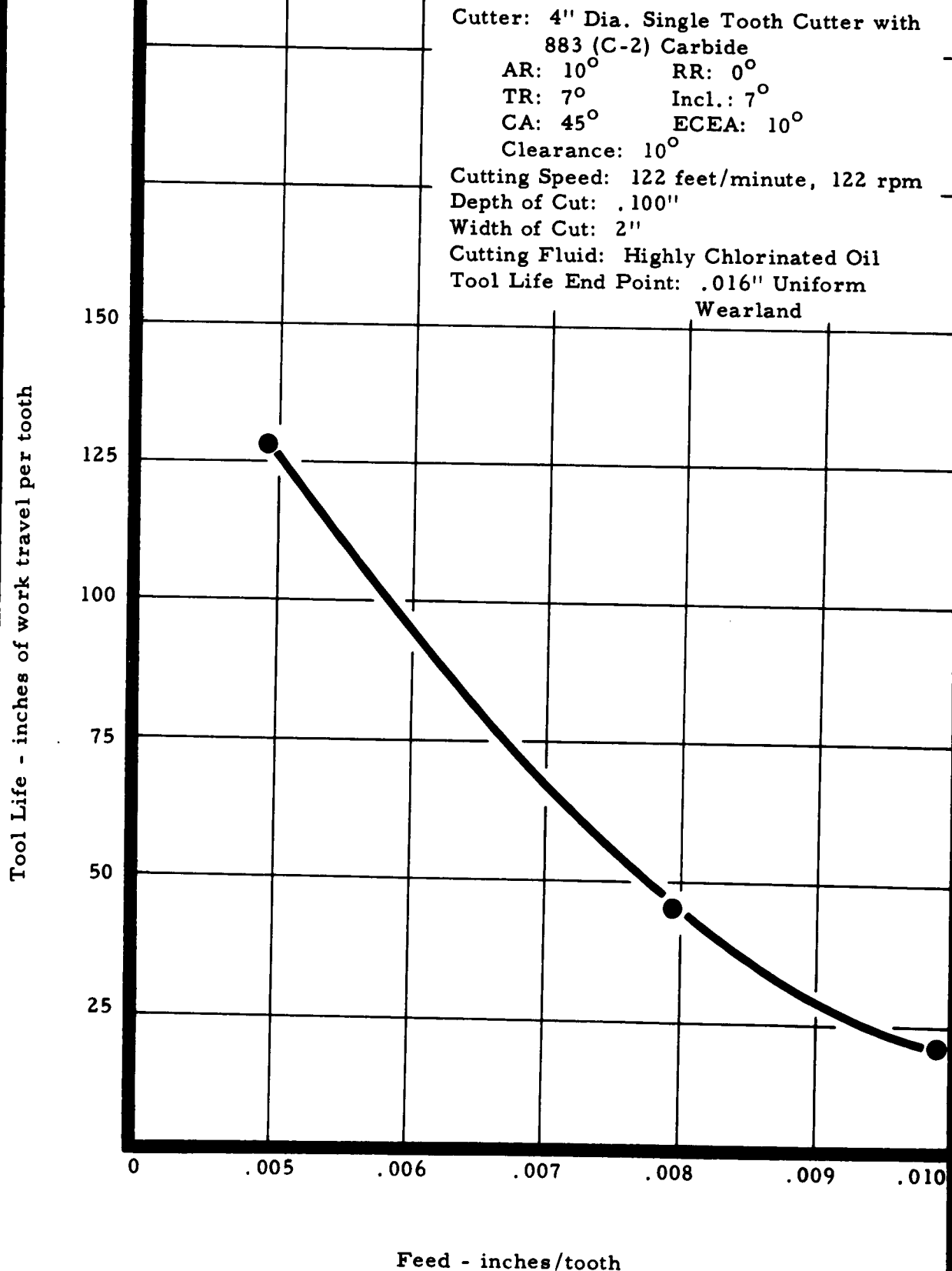
Face Milling B-120VCA Titanium  
Solution Treated and Aged 400 BHN  
Effect of Cutting Speed with HSS Cutters



**Face Milling B-120VCA Titanium, Solution Treated 285 BHN**  
**Effect of Cutting Speed with Carbide**



Face Milling B-120VCA Titanium, Solution Treated 285 BHN  
Effect of Feed with Carbide



Face Milling B-120VCA Titanium, Solution Treated 285 BHN  
Effect of Carbide Grade

Cutter: 4" Dia. Single Tooth Face Mill

AR:  $10^{\circ}$  RR:  $0^{\circ}$

TR:  $7^{\circ}$  Incl.:  $7^{\circ}$

CA:  $45^{\circ}$  ECEA:  $10^{\circ}$

Clearance:  $10^{\circ}$

Cutting Speed: 122 feet/minute, 122 rpm

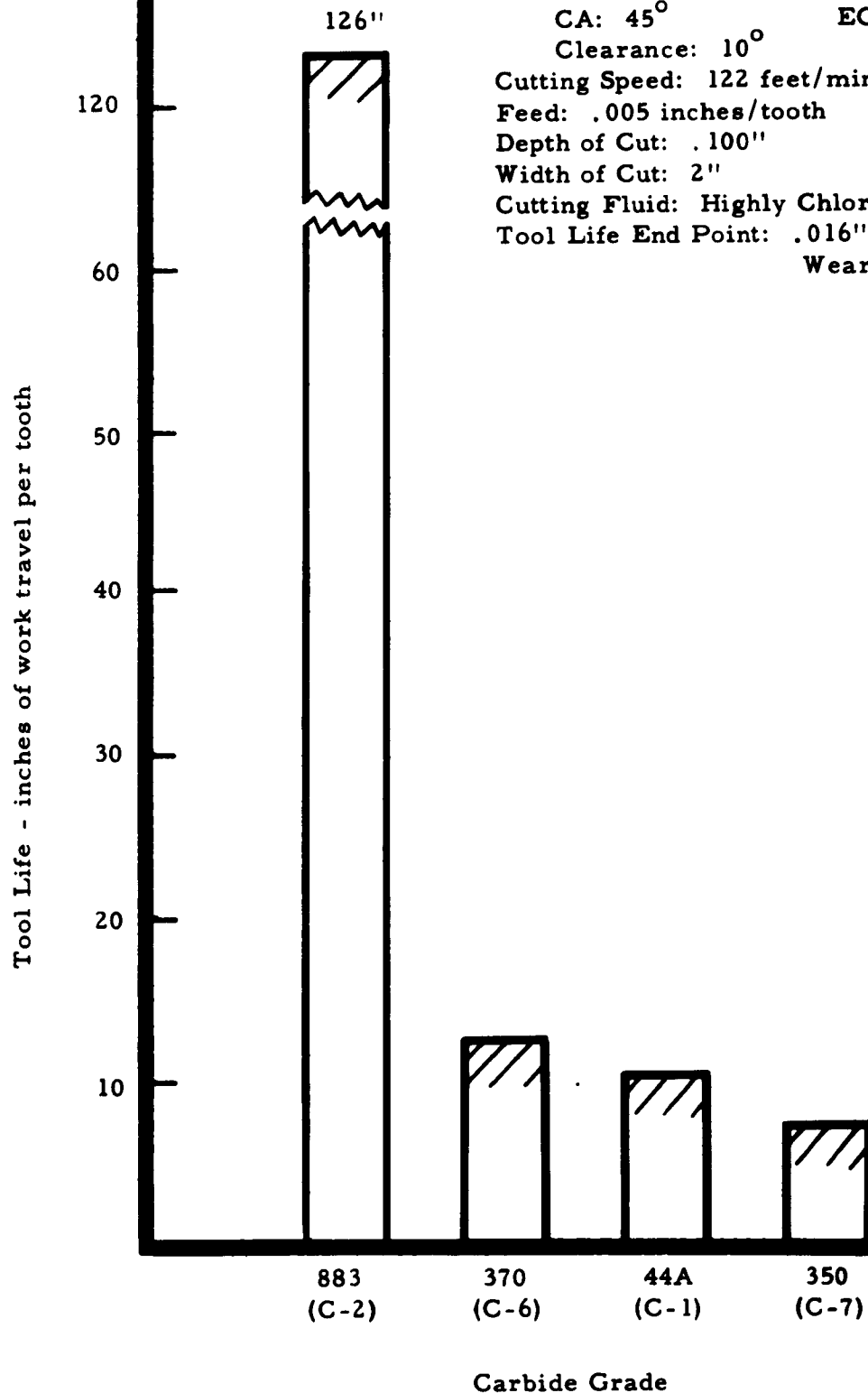
Feed: .005 inches/tooth

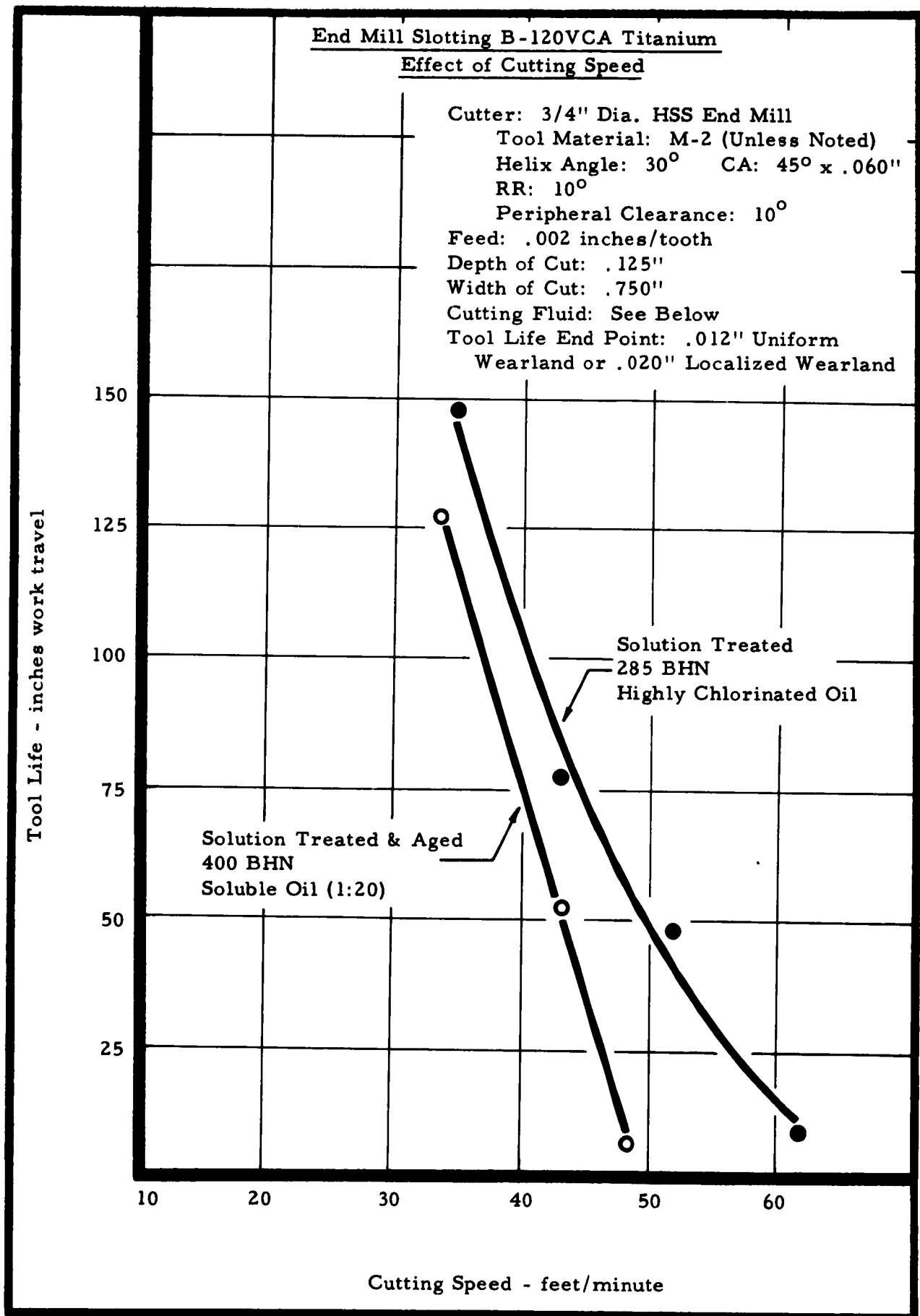
Depth of Cut: .100"

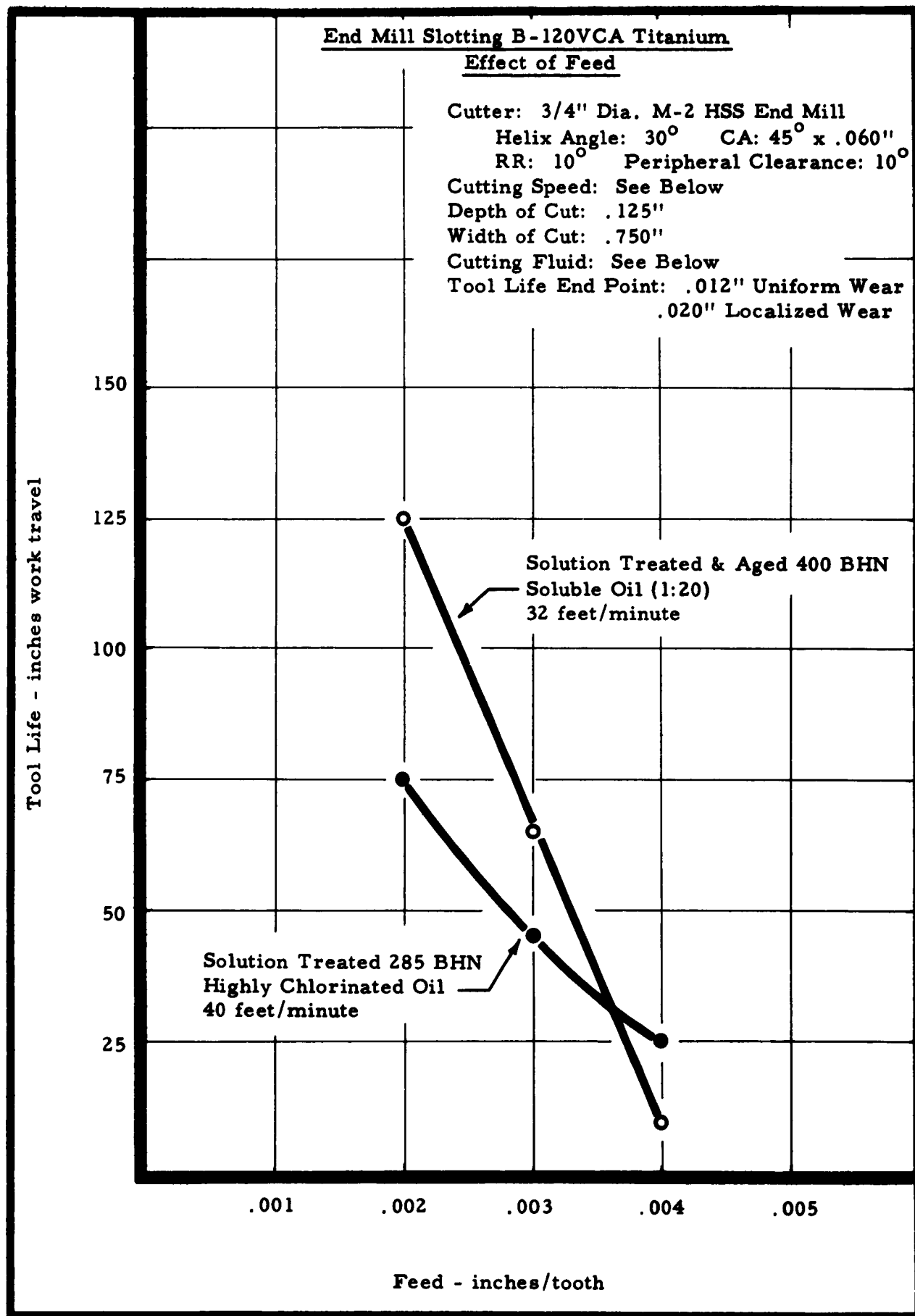
Width of Cut: 2"

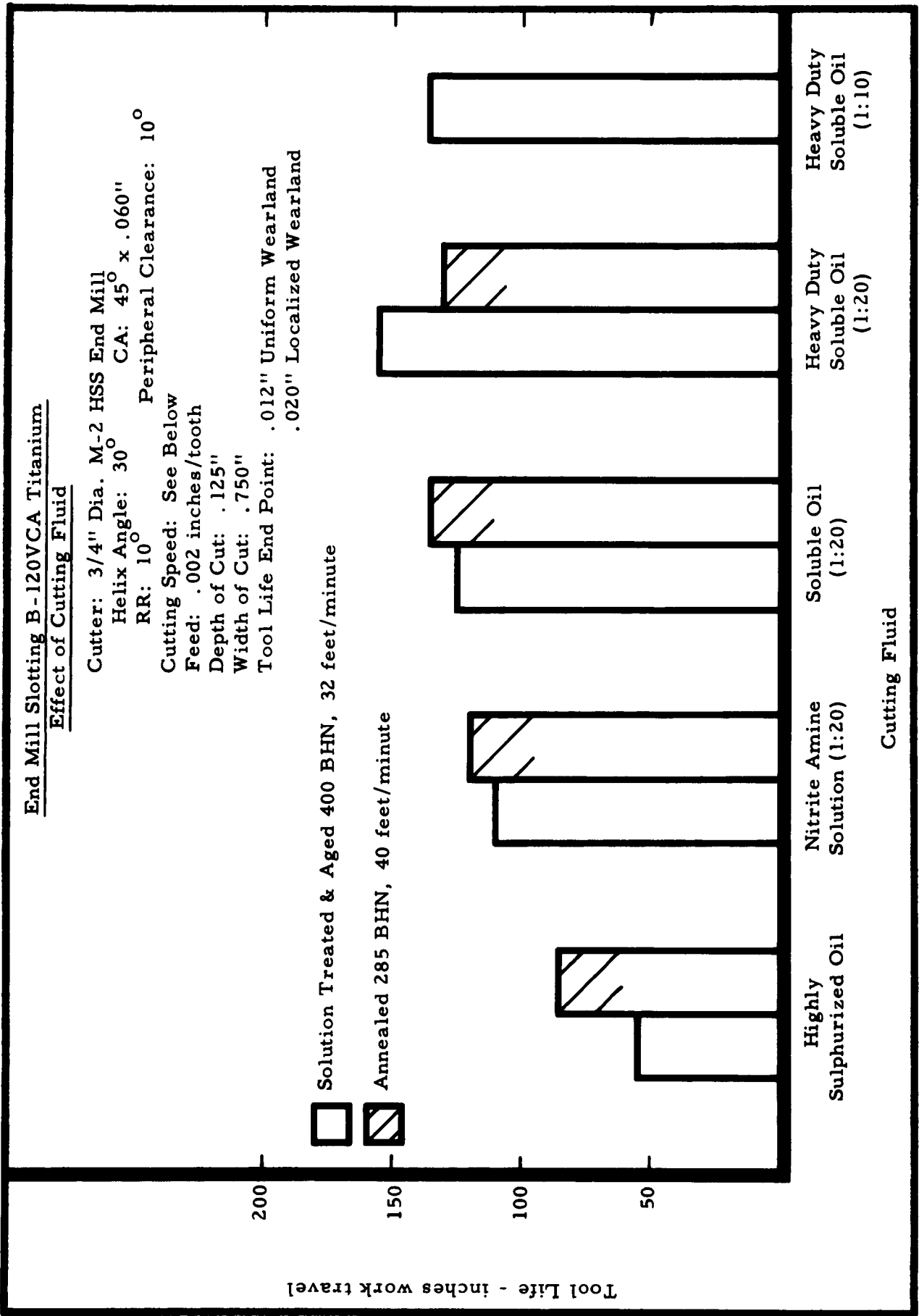
Cutting Fluid: Highly Chlorinated Oil

Tool Life End Point: .016" Uniform  
Wearland



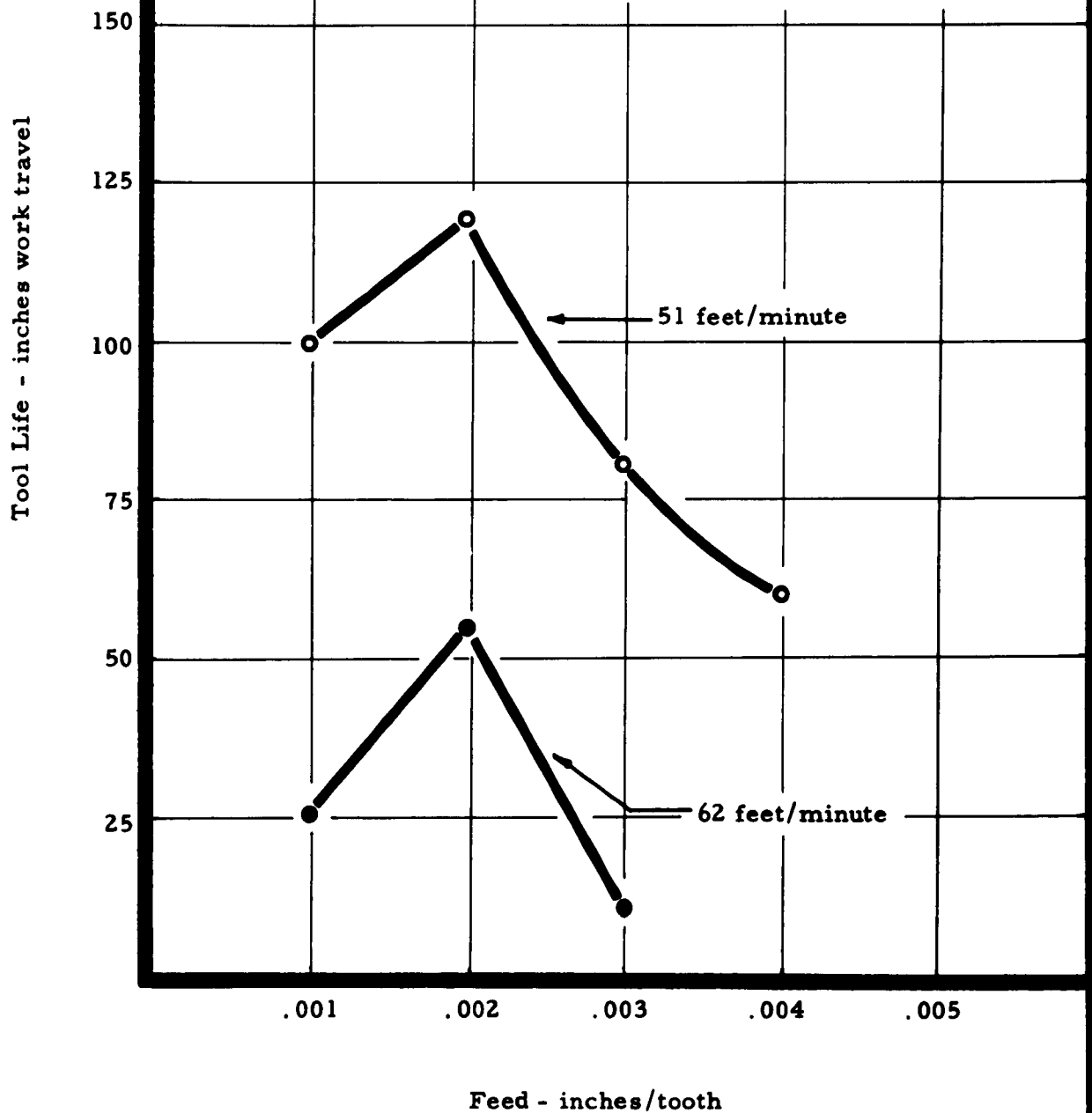






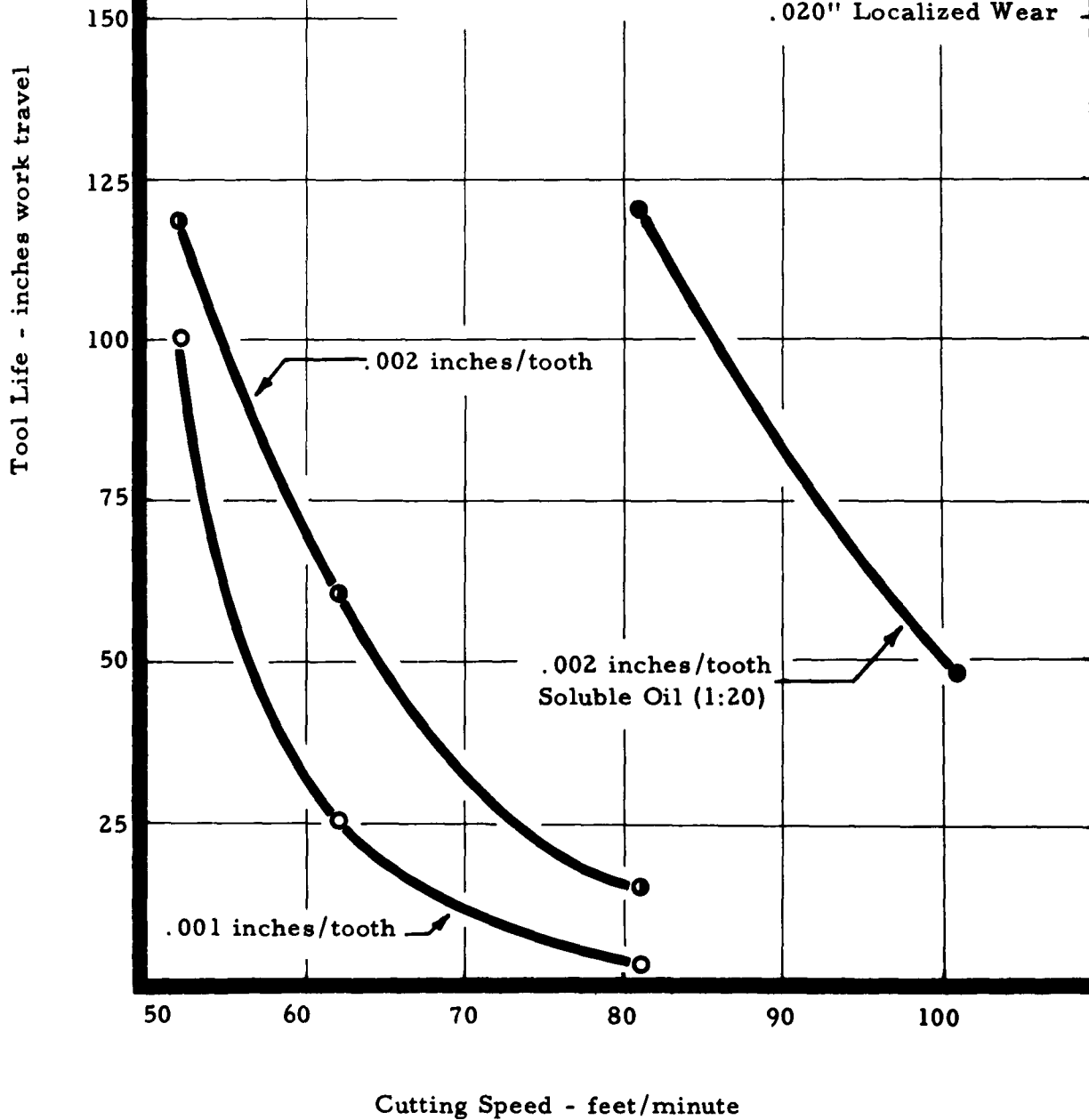
**Peripheral End Milling B-120VCA Titanium  
Solution Treated and Aged 400 BHN  
Effect of Feed**

Cutter: 3/4" Dia. 4 Tooth M-2 HSS  
End Mill  
Helix Angle: 30° CA: 45° x .060"  
RR: 10° Peripheral Clearance: 10°  
Depth of Cut: .125"  
Width of Cut: .750"  
Cutting Speed: See Below  
Cutting Fluid: Highly Chlorinated Oil  
Tool Life End Point: .012" Uniform Wear  
.020" Localized Wear



Peripheral End Milling B-120VCA Titanium  
Solution Treated and Aged 400 BHN  
Effect of Cutting Speed

Cutter: 3/4" Dia. 4 Tooth M-2 HSS  
 End Mill  
 Helix Angle: 30° CA: 45° x .060"  
 RR: 10° Peripheral Clearance: 10°  
 Feed: See Below  
 Depth of Cut: .125"  
 Width of Cut: .750"  
 Cutting Fluid: Highly Chlorinated Oil  
 (unless noted)  
 Tool Life End Point: .012" Uniform Wear  
 .020" Localized Wear



Turning TZM Molybdenum, 217 BHN  
Effect of Cutting Speed

Tool: Carbide (See Below)

BR: 0°

SR: 20°

SCEA: 15°

ECEA: 15°

Relief: 5°

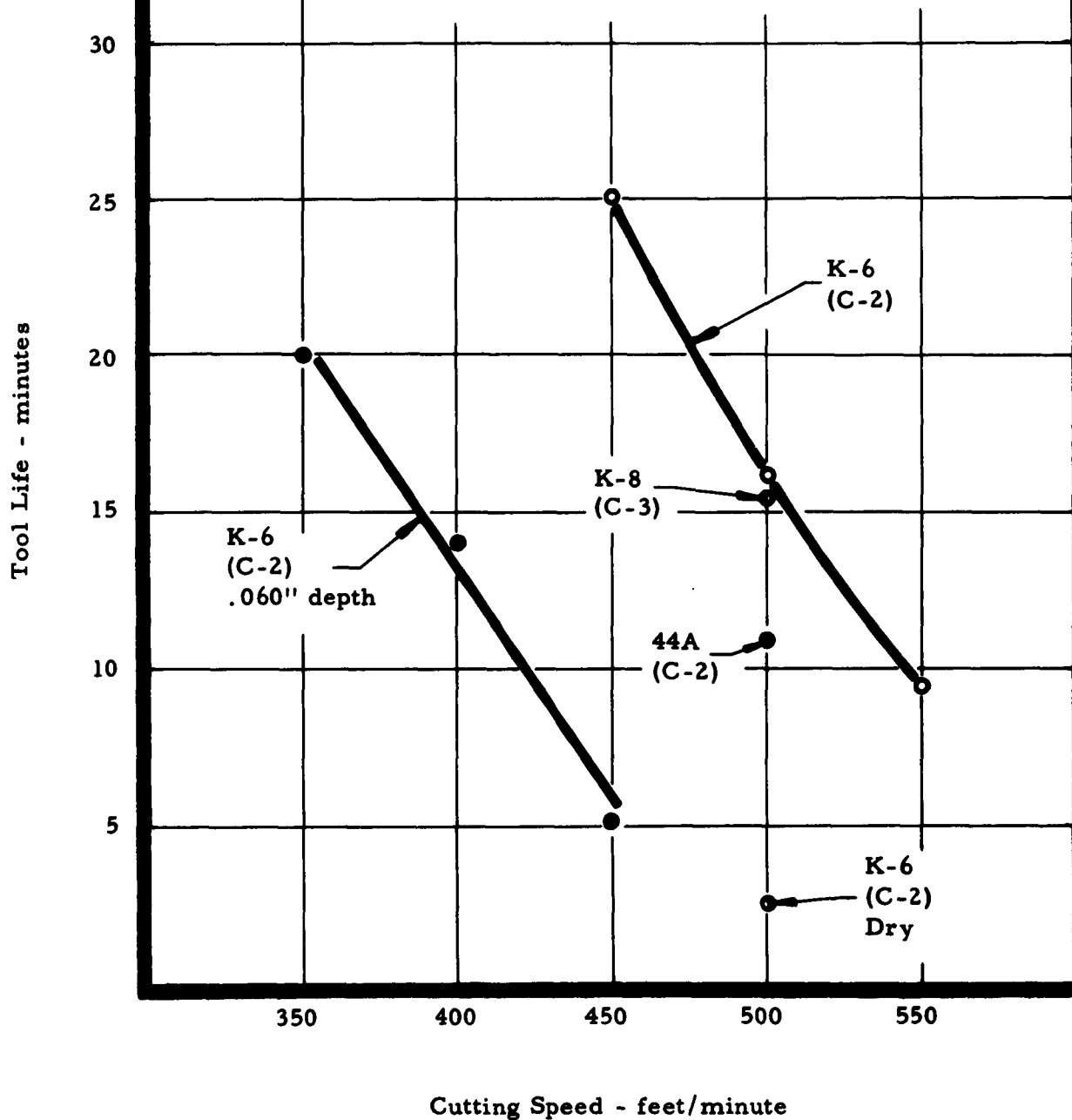
NR: 1/32"

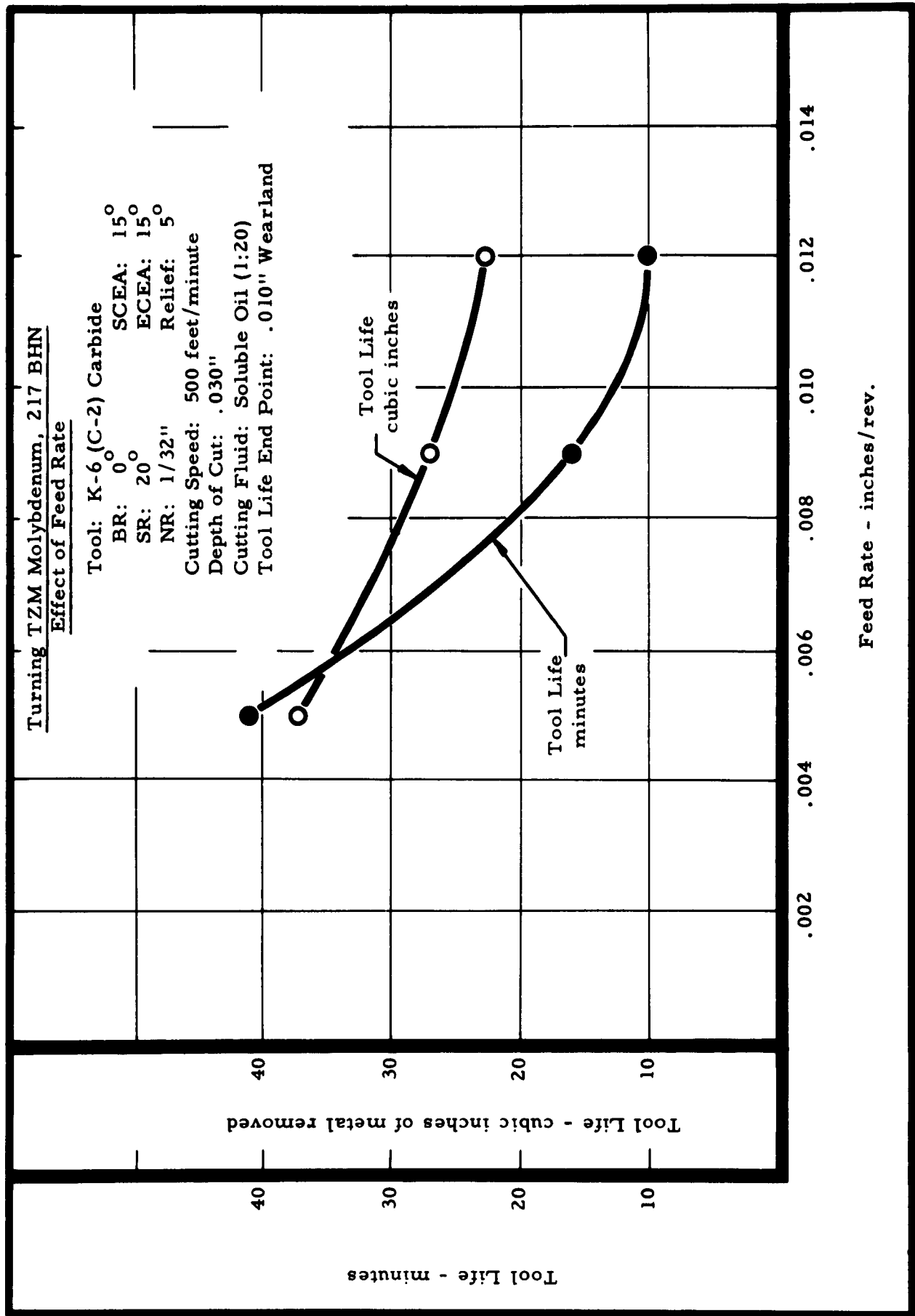
Feed: .009 inches/rev.

Depth of Cut: .030" (unless noted)

Cutting Fluid: Soluble Oil (1:20)  
(unless noted)

Tool Life End Point: .010" Wearland





Turning TZM Molybdenum, 217 BHN

Effect of Cutting Fluid

Tool: C-2 (K-6) Carbide

BR: 0°

SR: 20°

SCEA: 15°

ECEA: 15°

Relief: 5°

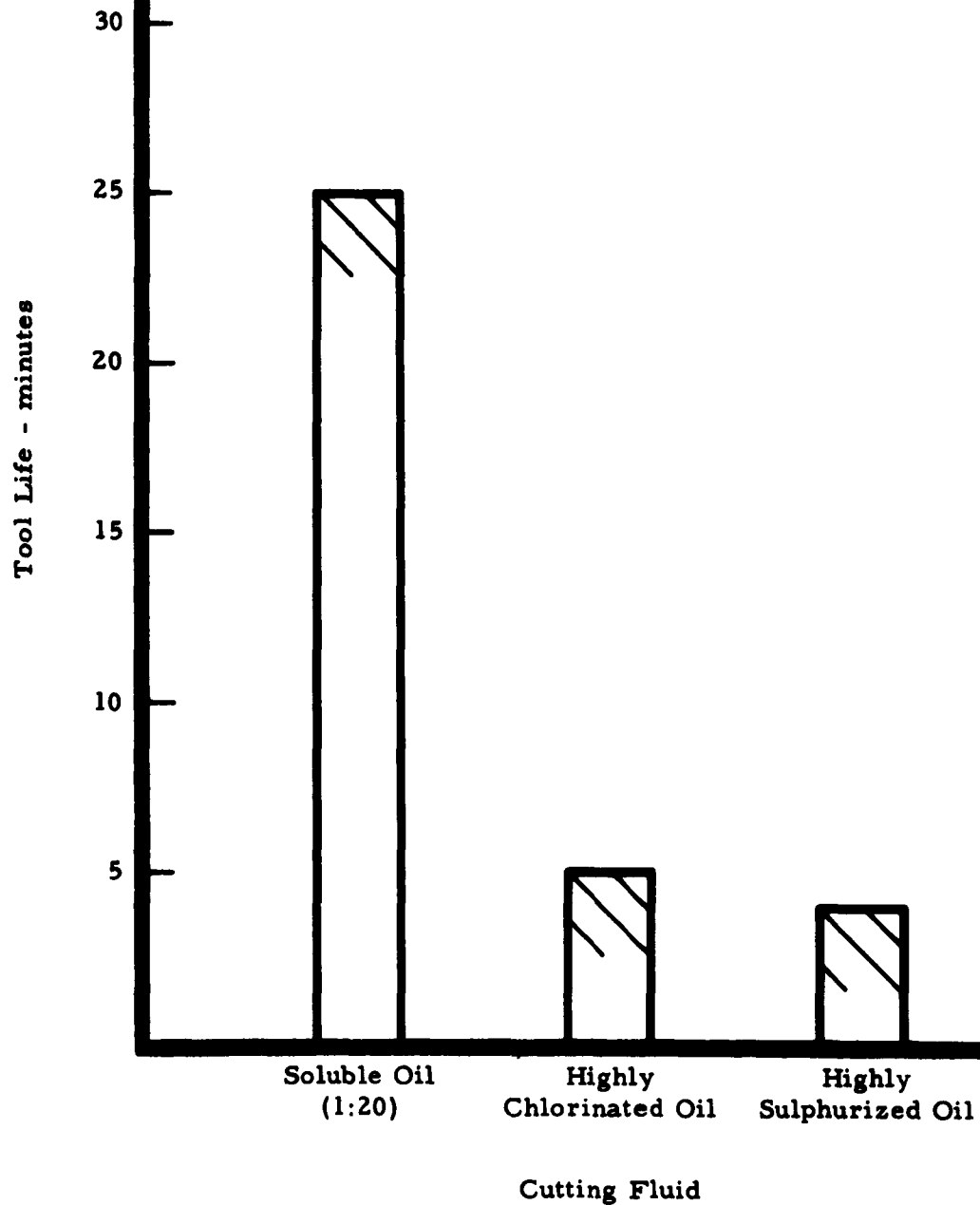
NR: 1/32"

Cutting Speed: 450 feet/minute

Feed: .009 inches/rev.

Depth of Cut: .030"

Tool Life End Point: .010" Wearland



Turning TZM Molybdenum, 217 BHN  
Effect of Side Rake Angle

Tool: C-2 (K-6) Carbide

BR: 0°

SR: See below

SCEA: 15°

ECEA: 15°

Relief: 5°

NR: 1/32"

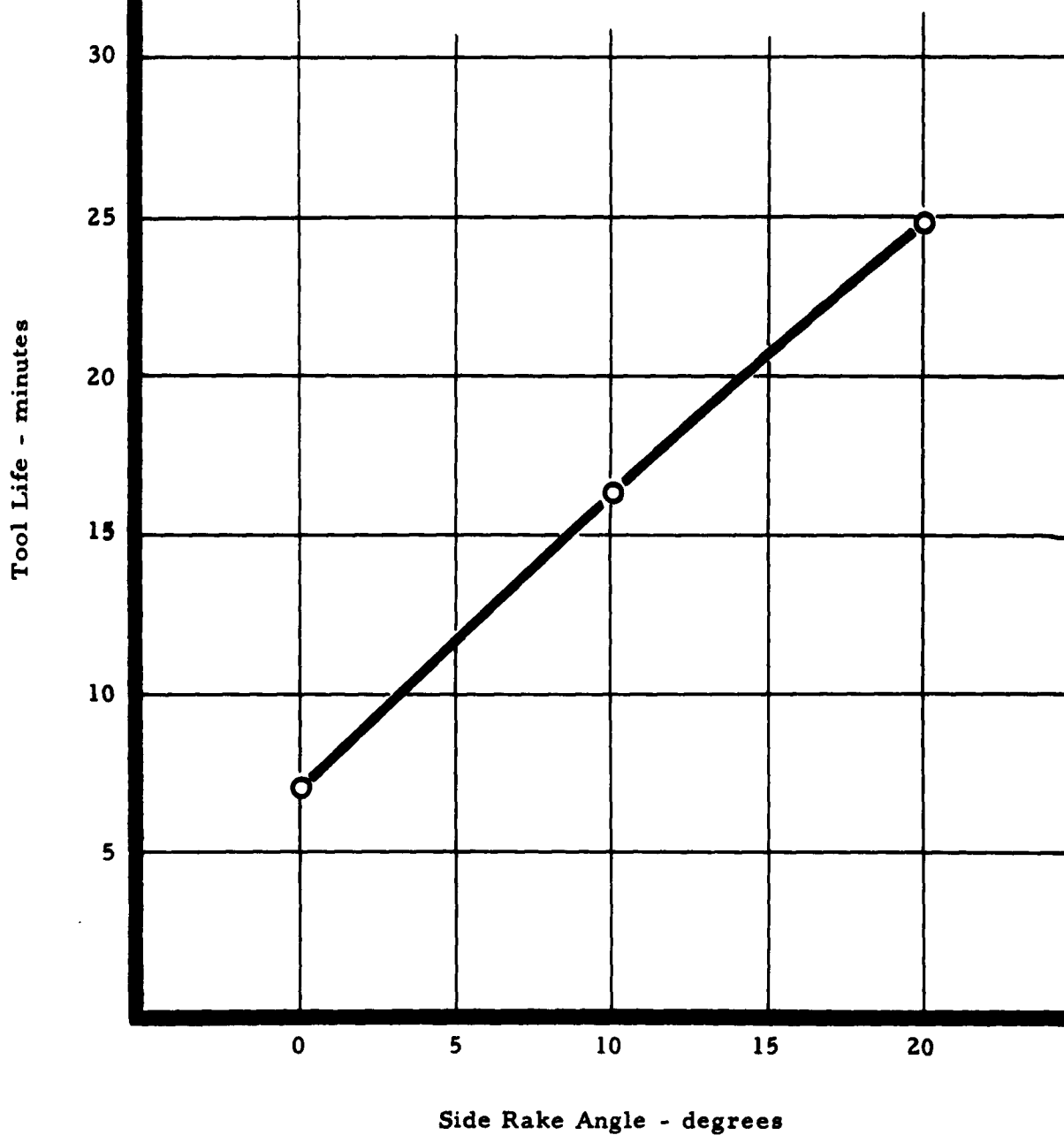
Cutting Speed: 450 feet/minute

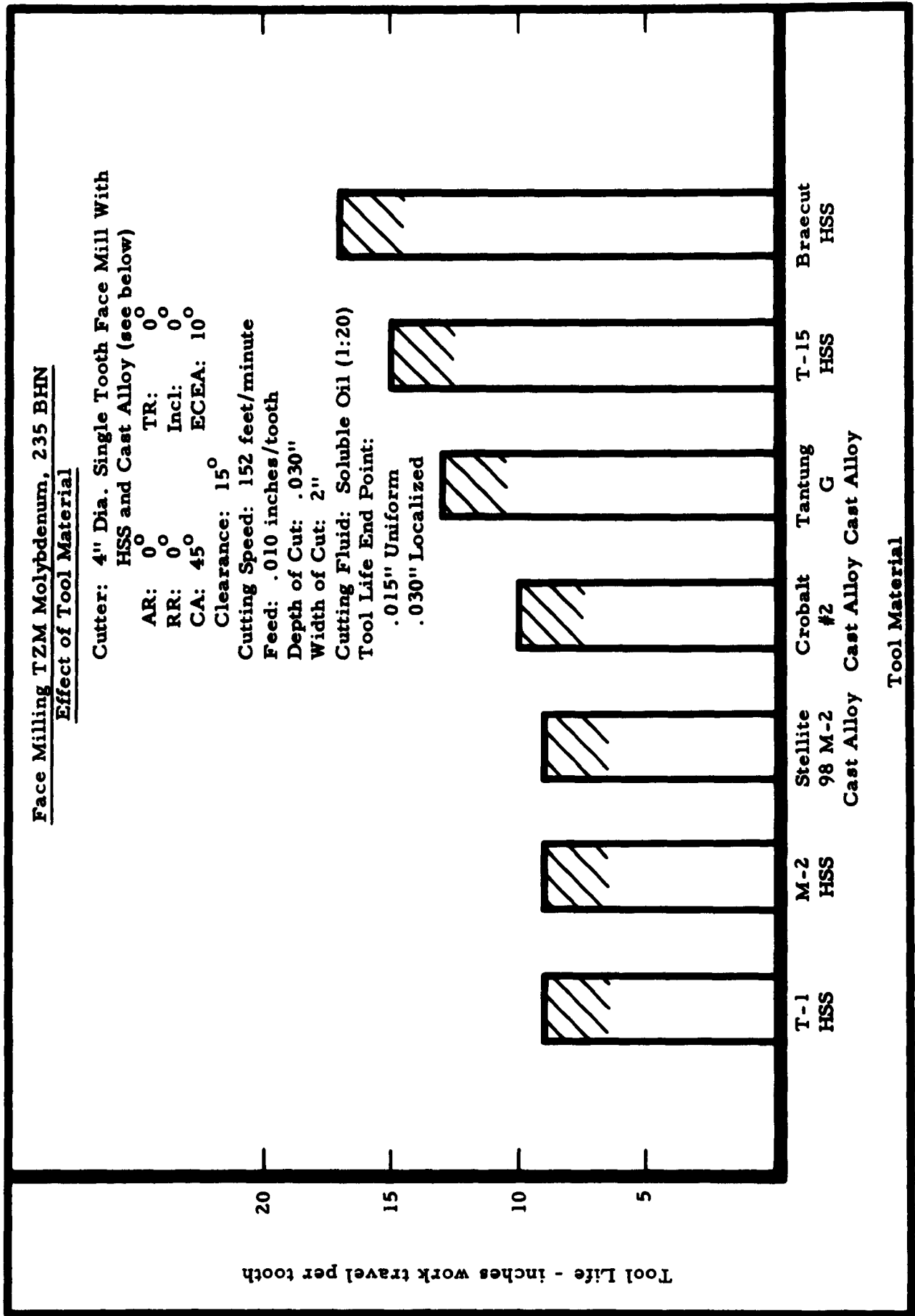
Feed: .009 inches/rev.

Depth of Cut: .030"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .010" Wearland





**Face Milling TZM Molybdenum, 235 BHN**

**Effect of Feed**

Cutter: 4" Dia. Single Tooth Face Mill  
With T-15 HSS

AR: 0° TR: 14°

RR: 20° Incl: -14°

CA: 45° ECEA: 10°

Clearance: 15°

Cutting Speed: 230 feet/minute

Depth of Cut: .030"

Width of Cut: 2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .015" Uniform Wear  
.030" Localized Wear

Tool Life - inches work travel per tooth

60

50

40

30

20

10

.005

.010

.015

Feed - inches/tooth

**Face Milling TZM Molybdenum, 229 BHN**  
**Effect of Depth of Cut**

Cutter: 4" dia. Single Tooth Face Mill  
 with T-15 HSS

AR: 0°      RR: 20°  
 TR: 14°      Incl.: -14°  
 CA: 45°      ECEA: 10°  
 Clearance: 15°

Feed: .010"/tooth

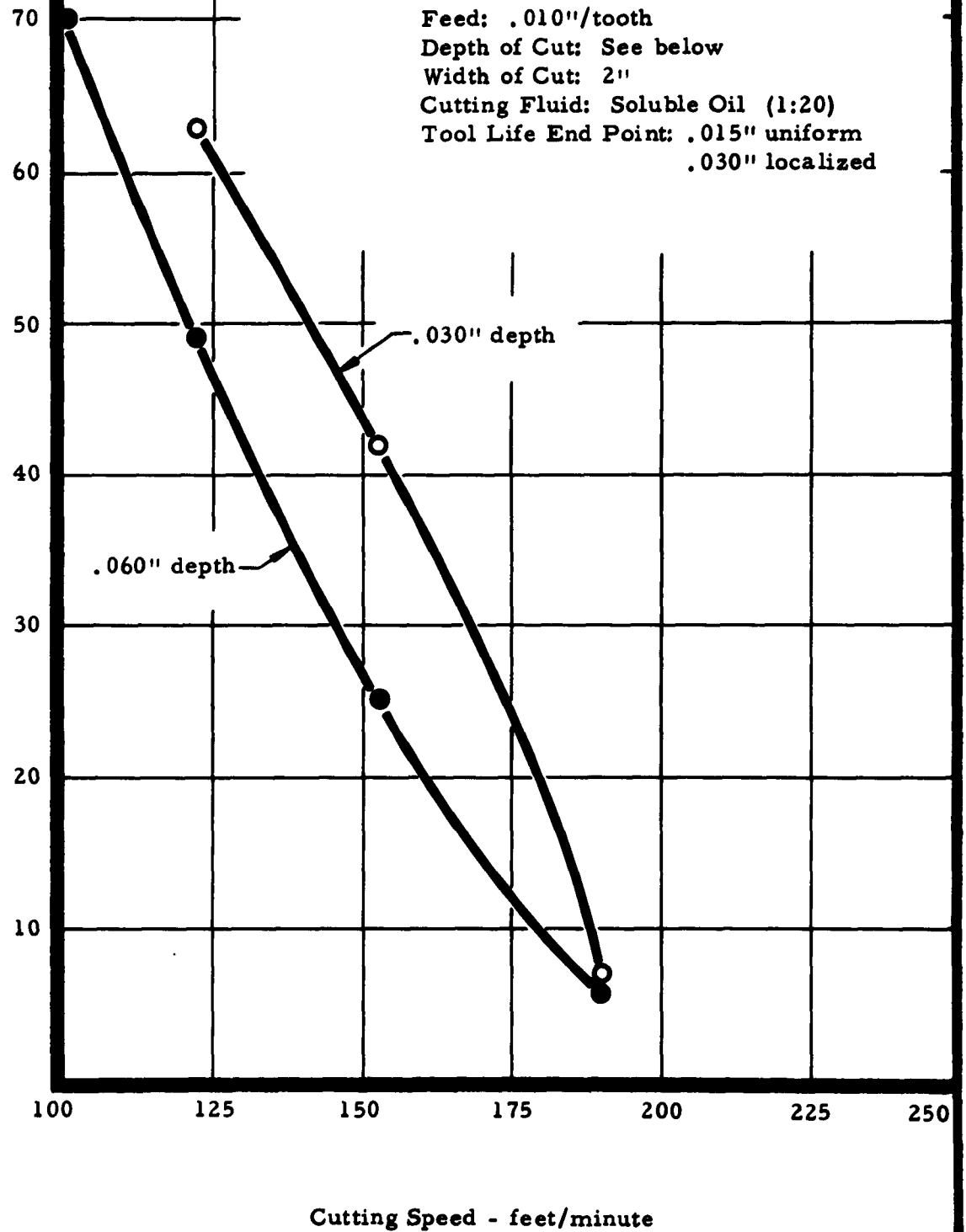
Depth of Cut: See below

Width of Cut: 2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .015" uniform  
 .030" localized

Tool Life - inches work travel/tooth



Face Milling T ZM Molybdenum, 235 BHN

Effect of Tool Geometry

Cutter: 4" Dia. Single Tooth Face Mill  
With T-15 HSS

CA:  $45^{\circ}$  ECEA:  $10^{\circ}$

Clearance:  $15^{\circ}$

Cutting Speed: 152 feet/minute

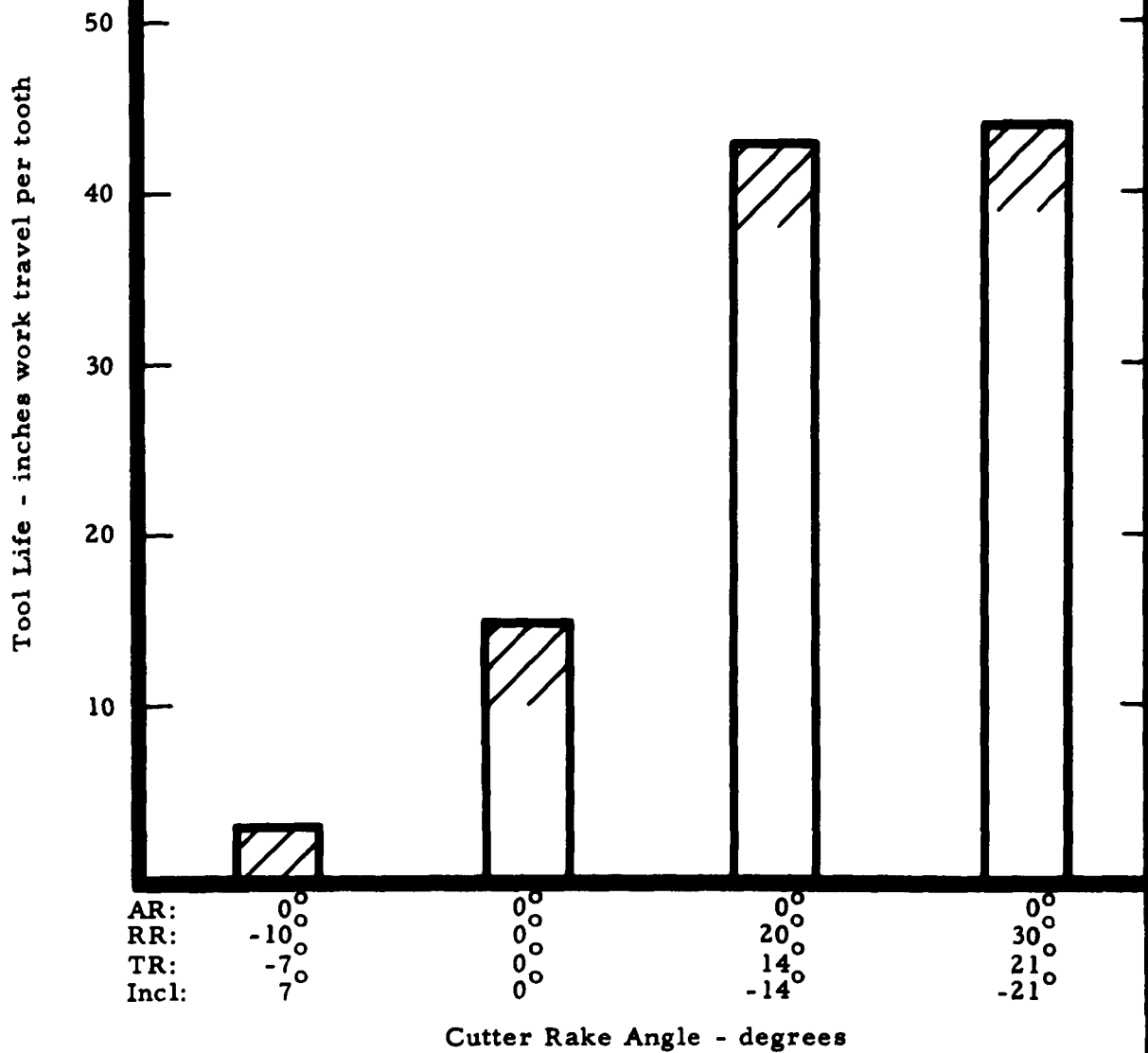
Feed: .010 inches/tooth

Depth of Cut: .030"

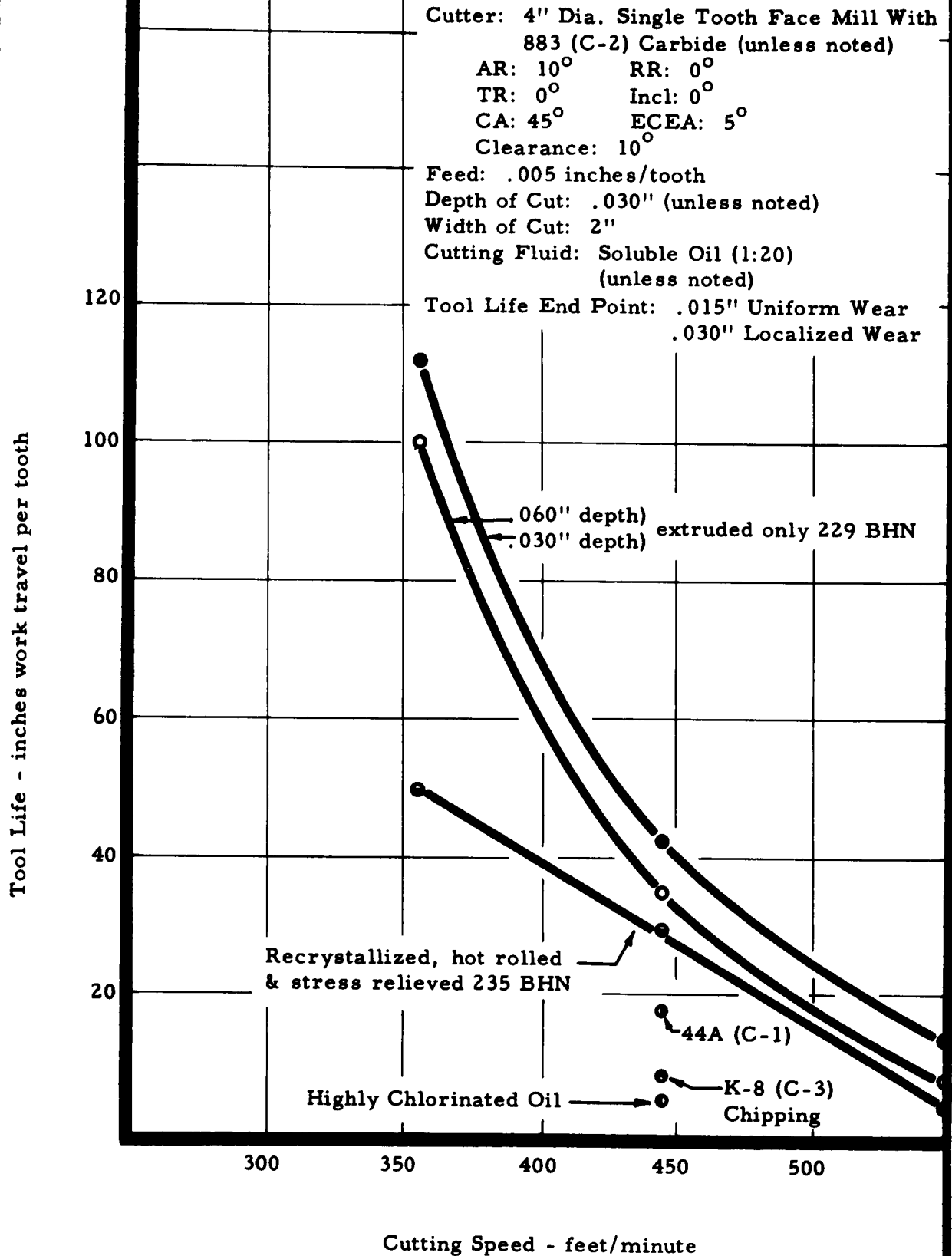
Width of Cut: 2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .015" Uniform Wear  
.030" Localized Wear



**Face Milling TZM Molybdenum**  
**Effect of Cutting Speed**





Face Milling TZM Molybdenum, 235 BHN  
Effect of Tool Geometry

Cutter: 4" Dia. Single Tooth Face Mill  
 With 883 (C-2) Carbide

CA: 45° ECEA: 5°

Clearance: 10°

Cutting Speed: 445 feet/minute

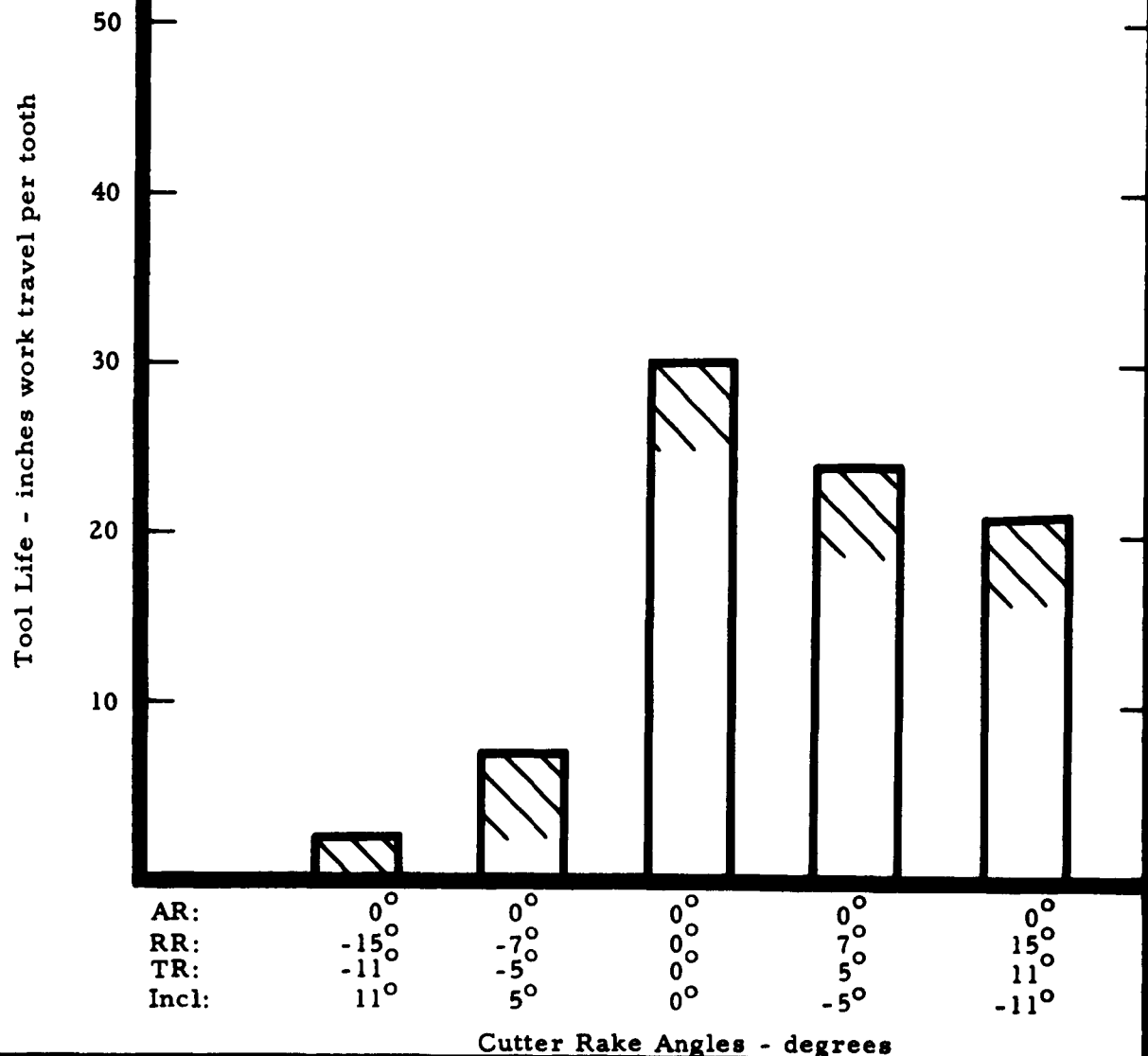
Feed: .005 inches/tooth

Depth of Cut: .030"

Width of Cut: 2"

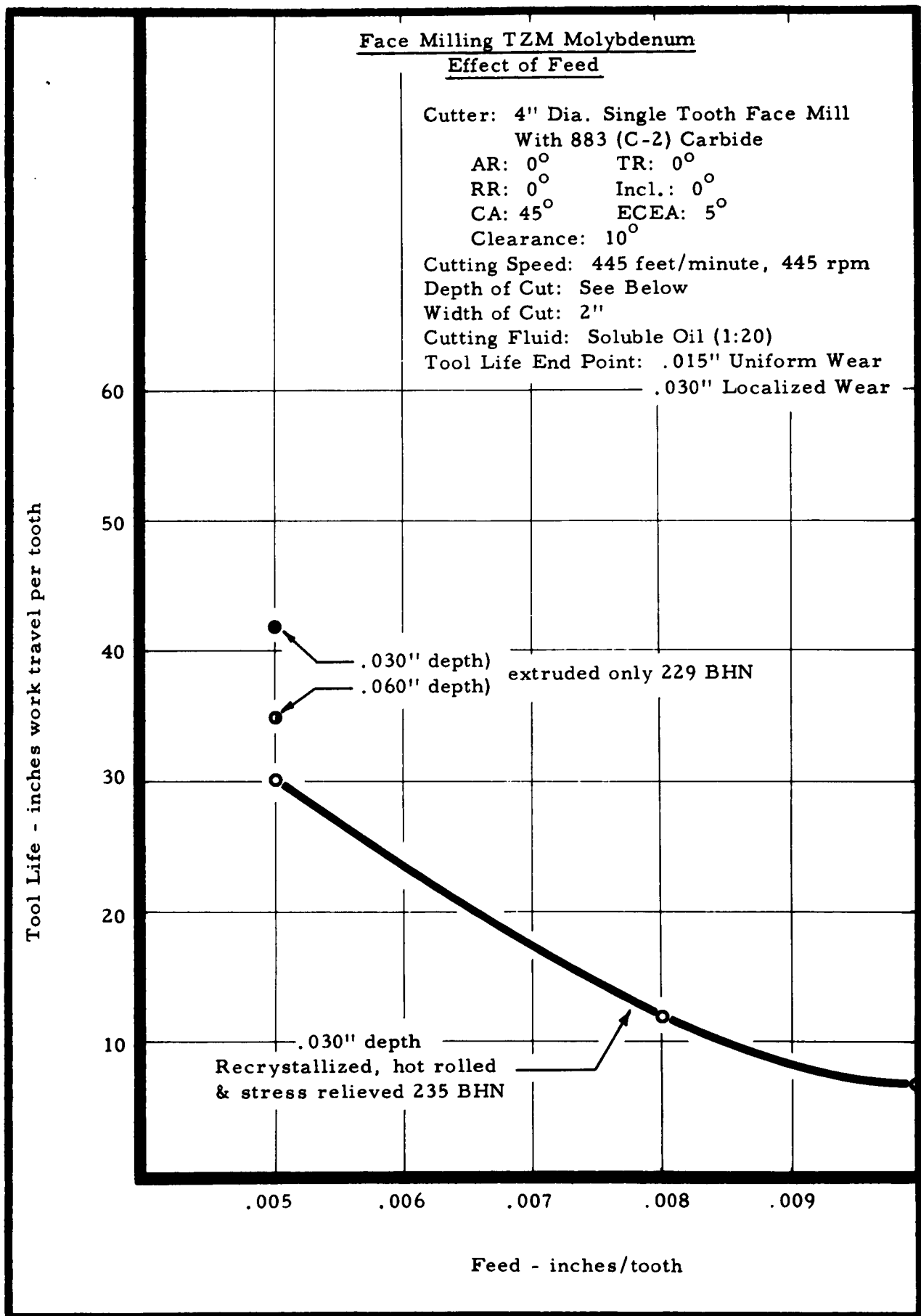
Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .015" Uniform Wear  
 .030" Localized Wear



See Text page 20

Figure 47



**End Mill Slotting TZM Molybdenum, 248 BHN**

**Effect of Cutting Speed**

Cutter: 3/4" Dia. 4 Tooth HSS End Mill  
(See Below)

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

Feed: .004 inches/tooth

Depth of Cut: .125"

Width of Cut: .750"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .012" Uniform Wear  
.030" Localized Wear

Tool Life - inches of work travel

100

80

60

40

20

M-3 HSS  
248 BHN

T-15 HSS  
248 BHN

100

150

200

250

300

Cutting Speed - feet/minute

**End Mill Slotting TZM Molybdenum, 248 BHN**  
**Effect of Cutting Fluid**

Cutter: 3/4" dia., 4 tooth HSS End Mill

Tool Material: M-3 HSS

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

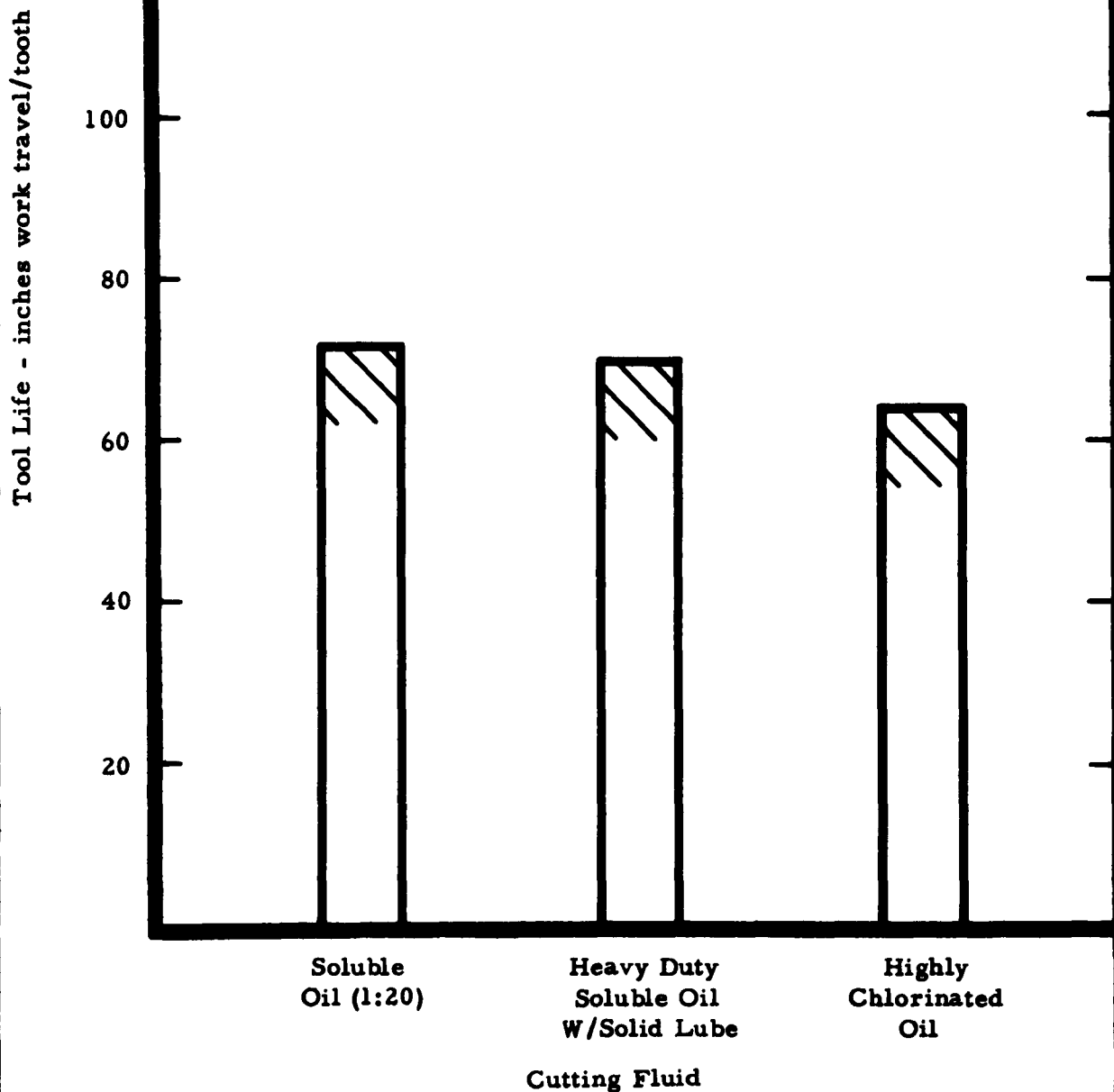
Cutting Speed: 150 feet/minute

Feed: .004 inches/tooth

Depth of Cut: .125"

Width of Cut: .750"

Tool Life End Point: .012" uniform wear  
.030" localized



End Mill Slotting TZM Molybdenum  
Effect of Feed

Cutter: 3/4" Dia. 4 Tooth HSS End Mill  
(See Below)

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

Cutting Speed: 152 feet/minute, 740 rpm

Depth of Cut: .125"

Width of Cut: 2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .012" Uniform Wear  
.030" Localized Wear

Tool Life - inches work travel

100

80

60

40

20

M-3 HSS  
248 BHN

T-15 HSS  
229 BHN

M-2 HSS  
229 BHN

.001

.002

.003

.004

.005

Feed - inches/tooth

End Mill Slotting TZM Molybdenum, 229 BHN  
Effect of Depth of Cut

Cutter: 3/4" dia., 4 tooth HSS End Mill

Tool Material: T-15 HSS

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

Feed: .004 inches/tooth

Cutting Speed: 152 feet/minute, 760 rpm

Width of Cut: .750"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .012" uniform wear

.030" localized

B: Breakdown

Tool Life - inches work travel

100

80

60

40

20

.125

.250

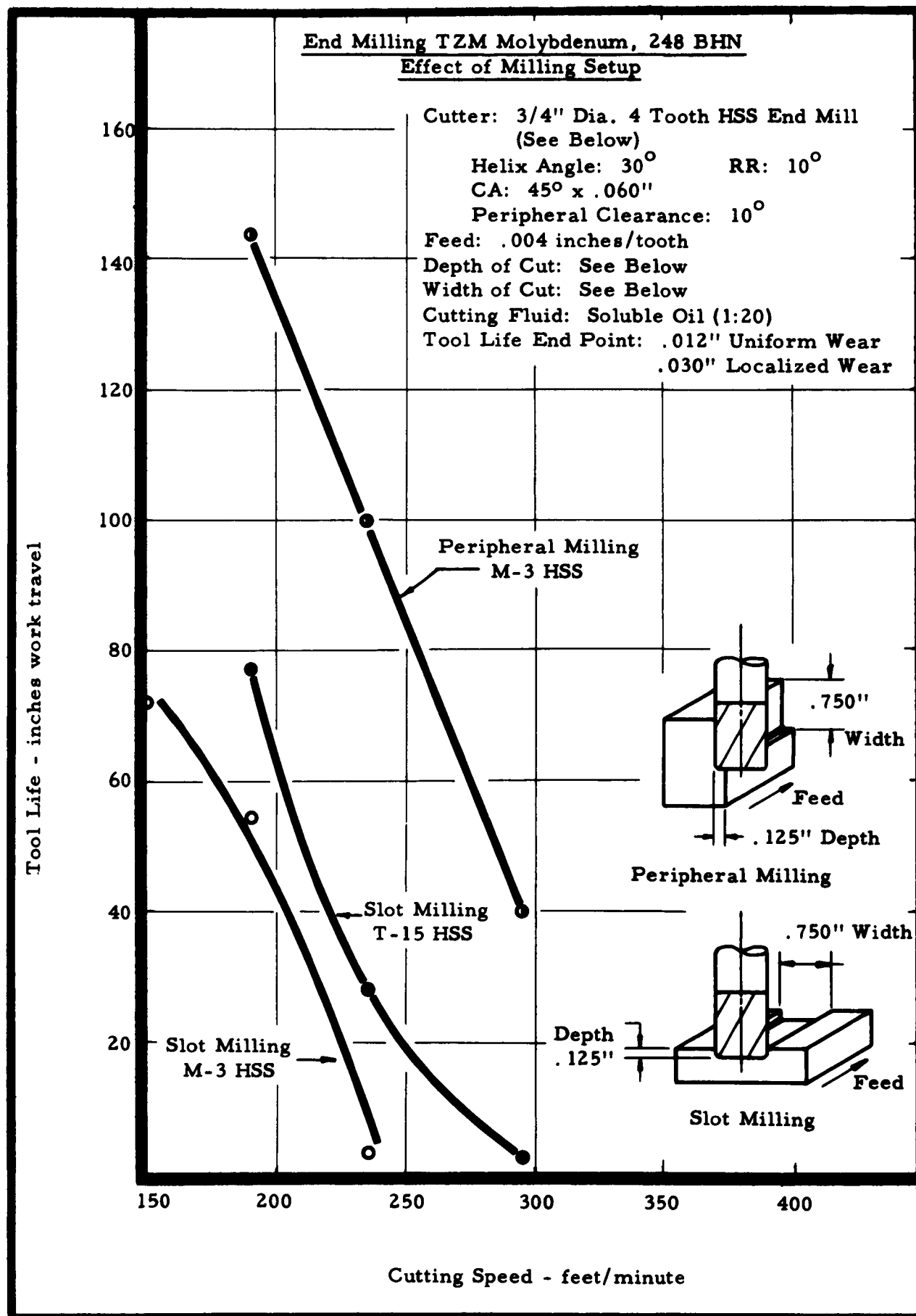
.375

.500

.625

Depth of Cut - inches

B



Drilling T2M Molybdenum, 229 BHN  
Effect of Cutting Speed and Drill Point Geometry

Drill Material: M-1 HSS

Dia.: .250" Length: 2-1/2"

Helix Angle: 29° Clearance: 7°

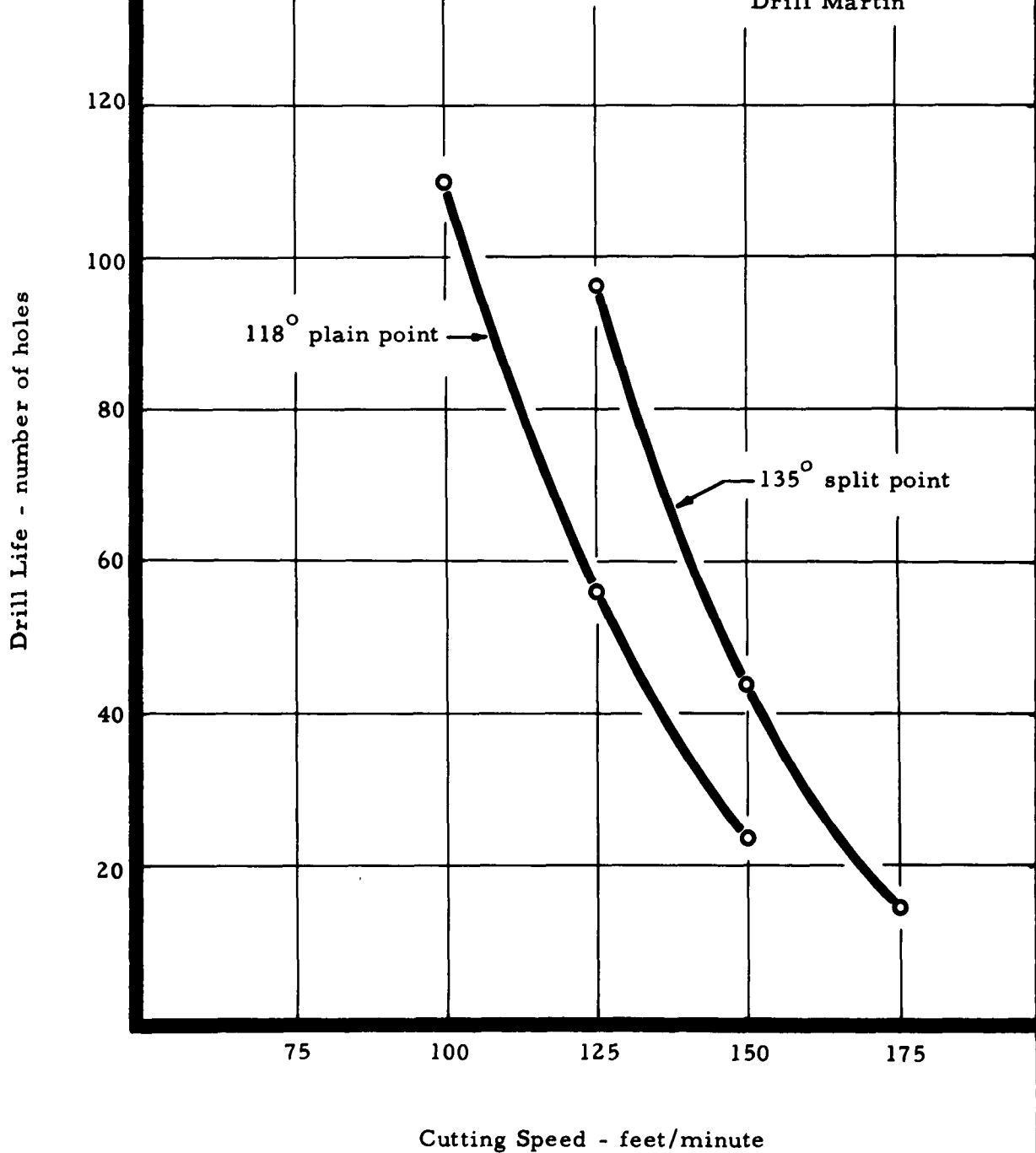
Style: Standard Screw Machine Length

Feed: .005 inches/rev.

Depth of Hole: .500" through hole

Cutting Fluid: Highly Chlorinated Oil

Drill Life End Point: .015" Wearland on  
Drill Martin



Drilling TZM Molybdenum, 248 BHN  
Effect of Feed

Drill Material: Type M-1 HSS

Dia.: .250" Length: 2-1/2"

Point Angle: 118° Helix Angle: 29°

Clearance: 7° Point Grind: Plain

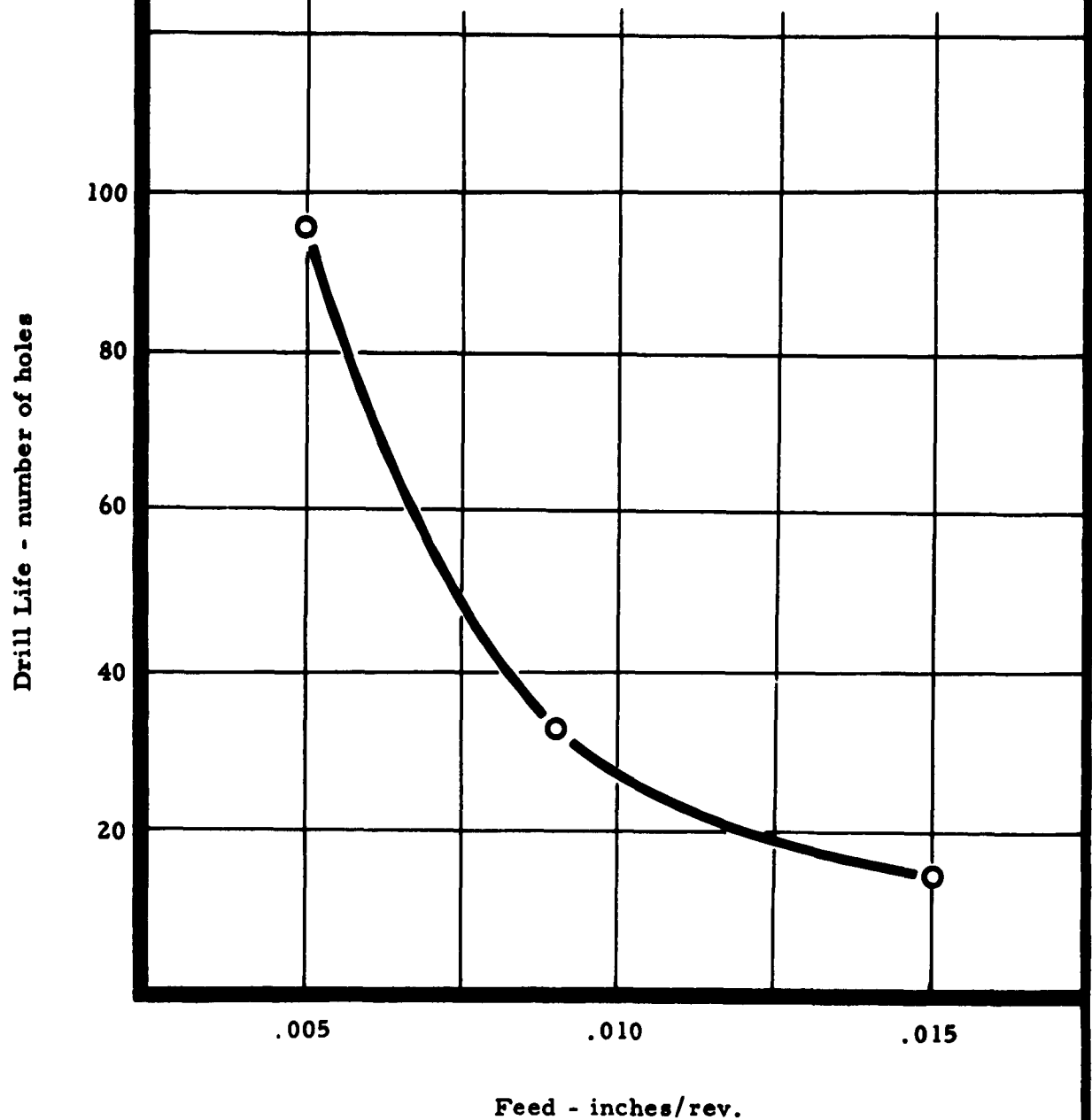
Style: Standard Screw Machine Length

Cutting Speed: 125 feet/minute

Depth of Hole: .500" thru

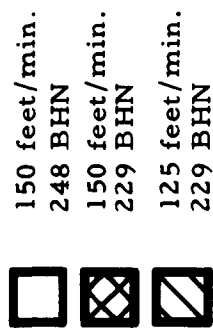
Cutting Fluid: Highly Chlorinated Oil

Drill Life End Point: .015" Wearland on  
Drill Margin



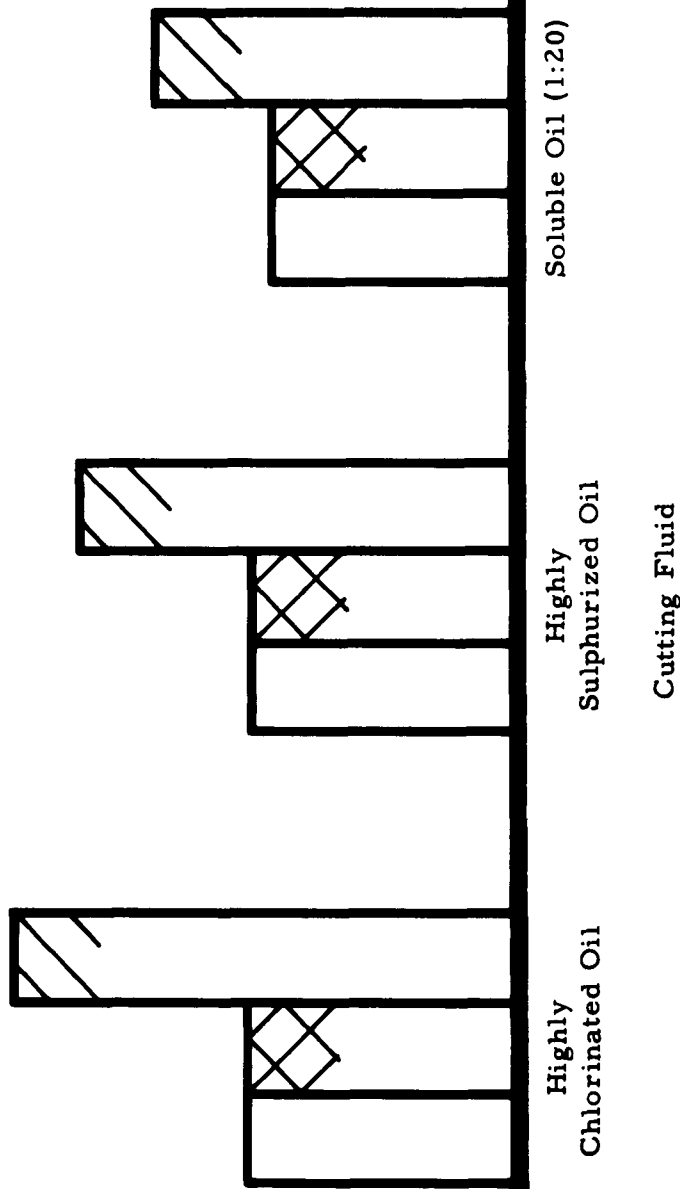
Drilling TZM Molybdenum Alloy  
Effect of Cutting Fluid

Drill Material: M-1 HSS  
 Dia.: .250" Length: 2-1/2"  
 Helix Angle: 29° Point Grind: Plain  
 Point Angle: 118° Clearance: 7°  
 Style: Standard Screw Machine Length  
 Cutting Speed: See Below  
 Feed: .005 inches/rev.  
 Depth of Hole: .500" through hole  
 Cutting Fluid: See Below  
 Drill Life End Point: .015" Wearland on Drill Margin



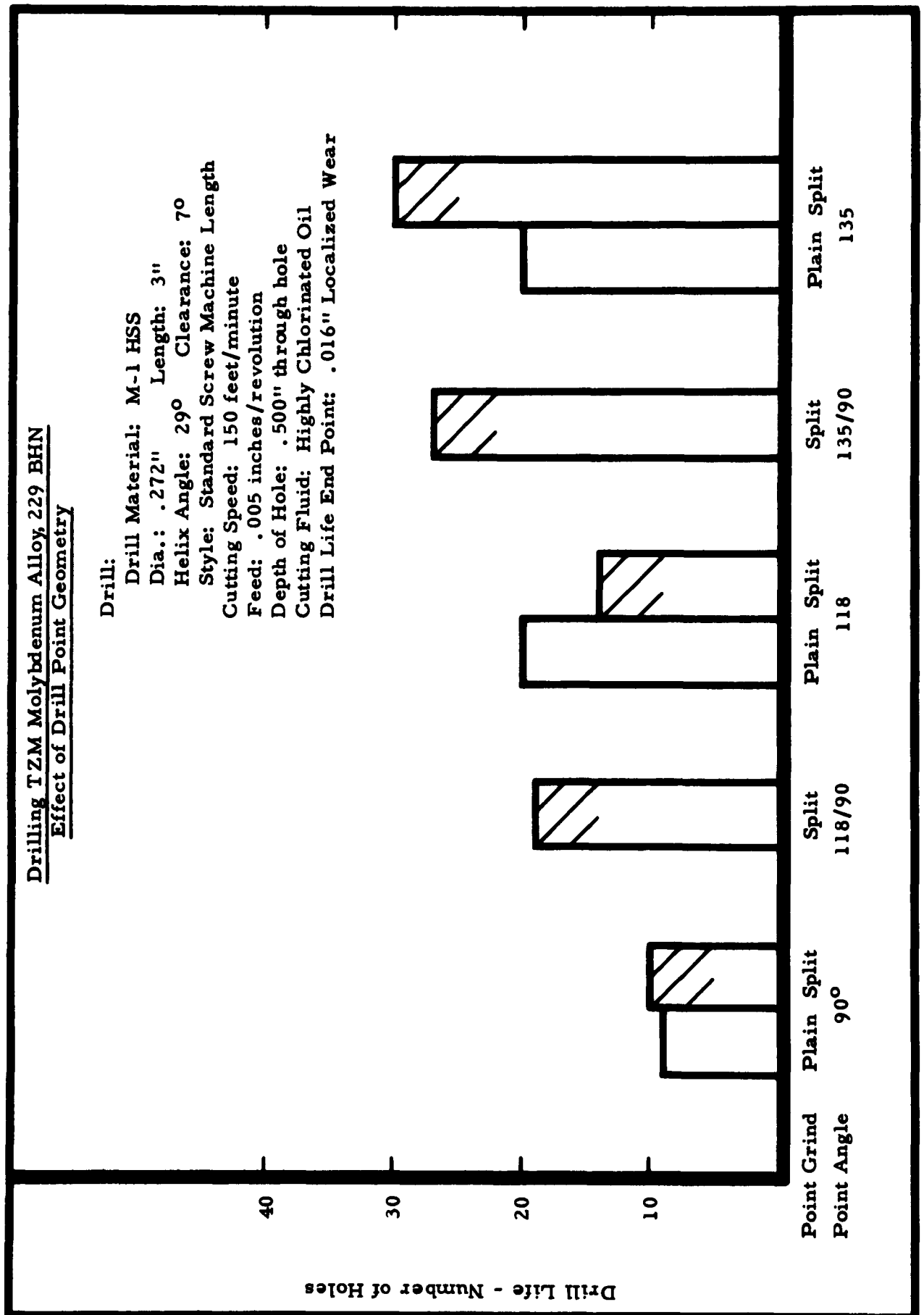
Drill Life - number of holes

100  
80  
60  
40  
20



Drilling T2M Molybdenum Alloy 229 BHN  
Effect of Drill Point Geometry

Drill:  
 Drill Material: M-1 HSS  
 Dia.: .272" Length: 3"  
 Helix Angle: 29° Clearance: 7°  
 Style: Standard Screw Machine Length  
 Cutting Speed: 150 feet/minute  
 Feed: .005 inches/revolution  
 Depth of Hole: .500" through hole  
 Cutting Fluid: Highly Chlorinated Oil  
 Drill Life End Point: .016" Localized Wear



Drilling TZM Molybdenum Alloy, 229 BHN  
Effect of HSS Type

Drill:

Dia.: 1/4"      Length: 2-1/2"

Helix Angle: 29°      Clearance: 7°

Point Angle: 118°      Point Type: Plain Point

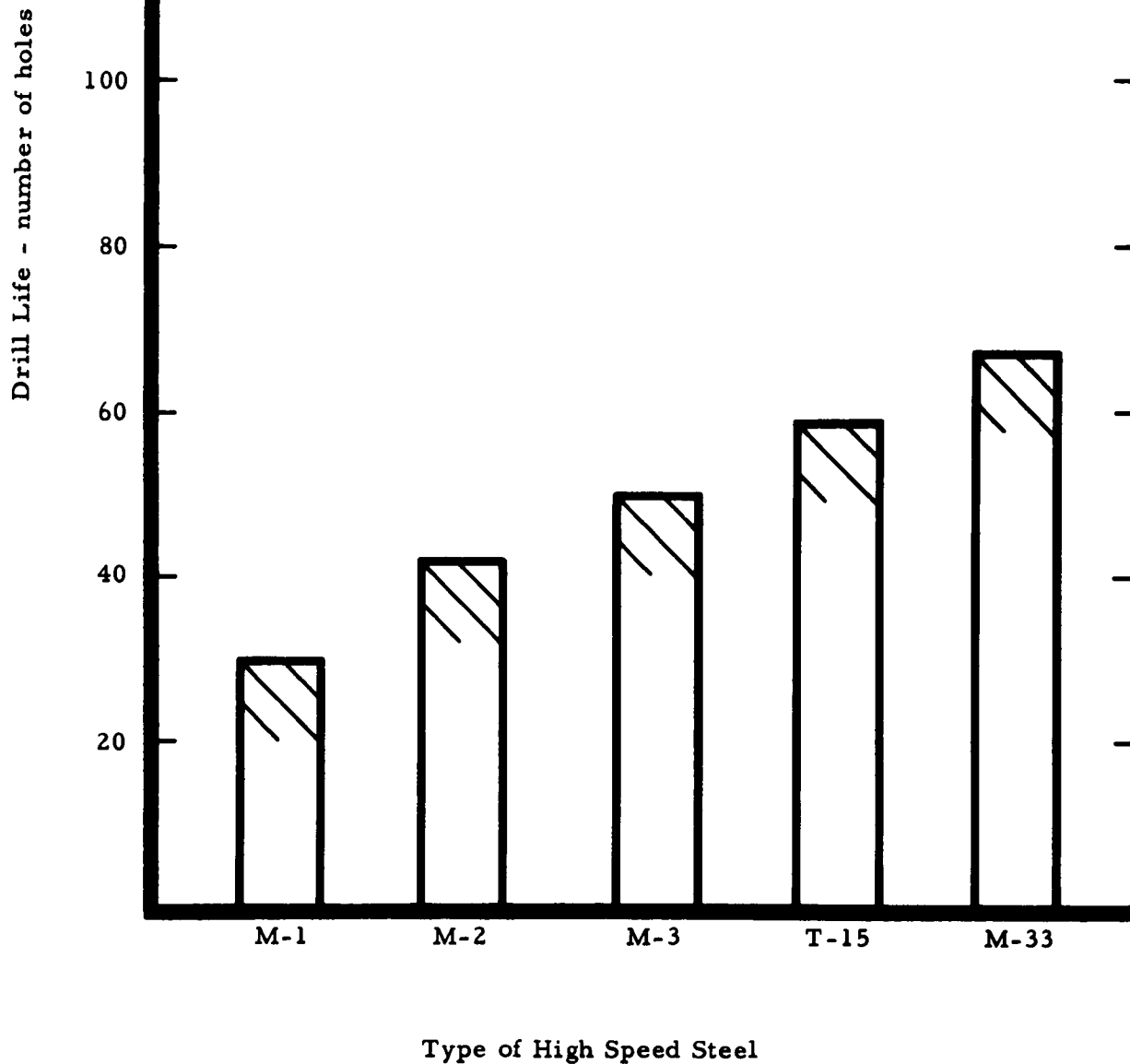
Cutting Speed: 150 feet/minute

Feed: .005 inches/revolution

Depth of Hole: 1/2" through hole

Cutting Fluid: Highly Chlorinated Oil

Drill Life End Point: .015" wearland



Drilling T2M Molybdenum Alloy  
Effect of Feed & Work Material

Drill:

Drill Material: M-1 HSS  
 Dia.: .250 Length: 2-1/2"  
 Helix Angle: 29° Clearance: 7°  
 Style: Standard Screw Machine Length  
 Depth of Hole: .500" through hole  
 Cutting Fluid: Highly Chlorinated Oil  
 Drill Life End Point: .016" localized wear

Material Condition

- Extruded, recrystallized  
hot rolled & Stress relieved  
248 BHN
- Extruded & recrystallized  
220 BHN
- Extruded only, 229 BHN

Drill Life - number of holes

120  
100  
80  
60  
40  
20

75

100

125

150

175

Cutting Speed - feet/minute

.009  
in./rev.

.005 in./rev.

Reamer Life End Point: .012" wear on reamer O.D.

**Cutting Speed - feet/minute**

Reaming TZM Molybdenum, 229 BHN  
Effect of Cutting Fluid

Reamer:

Reamer Material: M-2 HSS, straight 6 flute  
chucking reamer

Dia.: .272" Clearance: 10°

Corner Angle: 45°

Cutting Speed: 85 feet/minute

Feed: .015 inches/revolution

Depth of Hole: .500" through hole

Stock Removed: .010" on radius

Reamer Life End Point: .012" wear on reamer O.D.

Reamer Life - number of holes

50

40

30

20

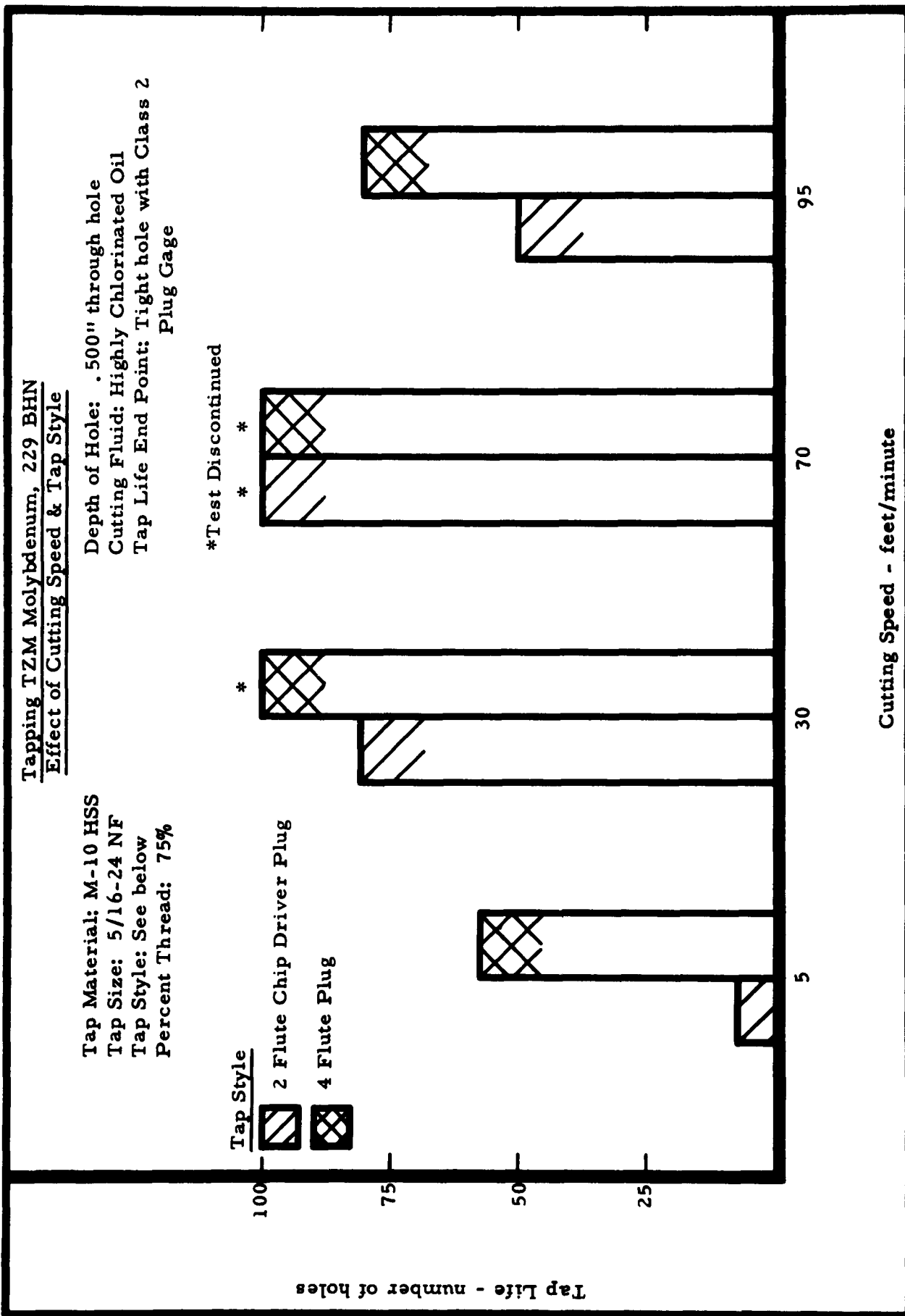
10

Highly  
Chlorinated  
Oil

Highly  
Sulphurized  
Oil

Soluble  
Oil (1:20)

Cutting Fluid



Tapping TZM Molybdenum, 229 BHN  
Effect of Cutting Fluid

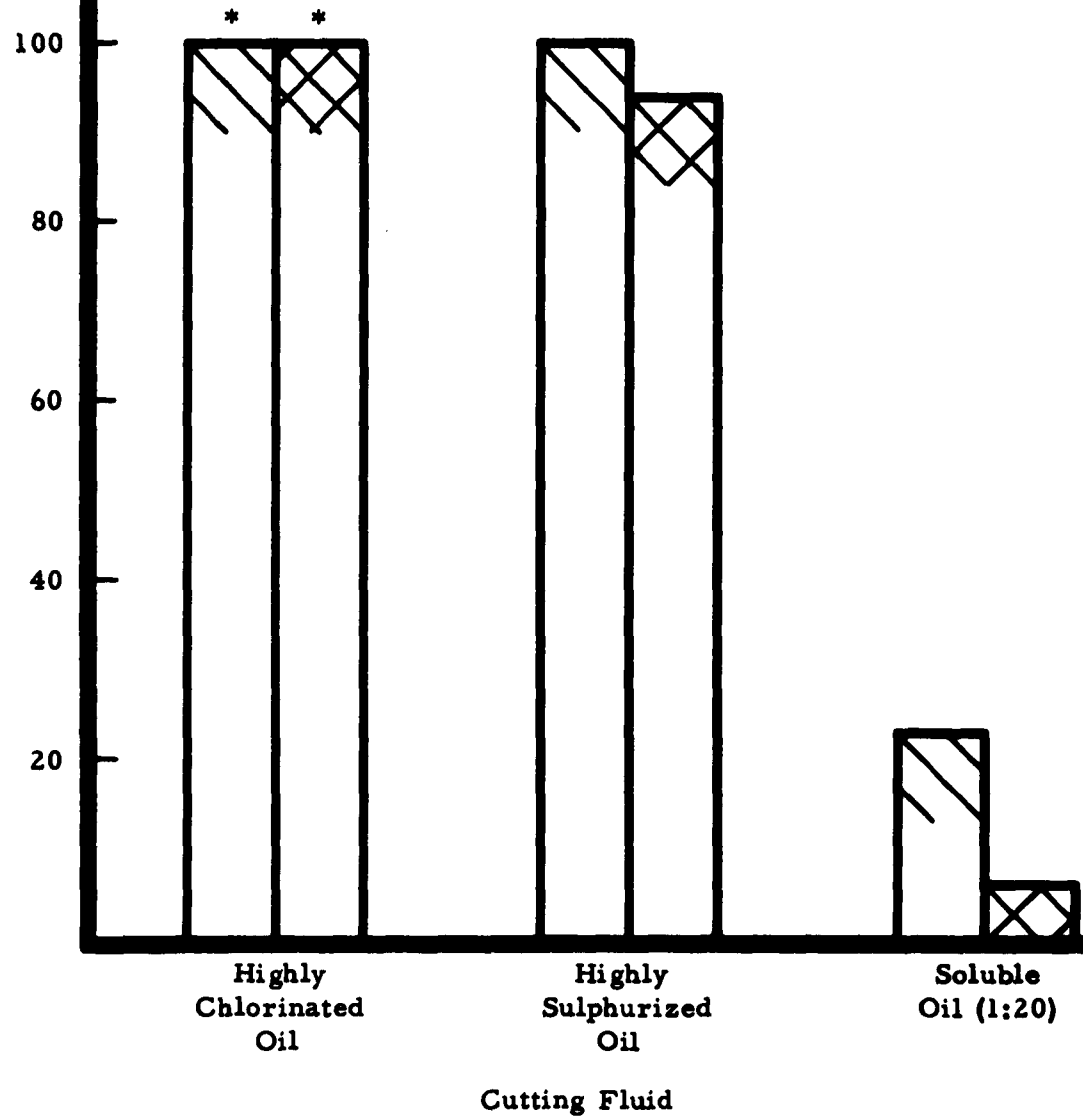
Tap Material: M-10 HSS  
Tap Size: 5/16-24 NF  
Tap Style: See below  
Percent Thread: 75%  
Depth of Hole: .500" through hole  
Tap Life End Point: Tight hole with  
Class 2 Plug Gage  
Cutting Speed: 70 feet/minute, 856 rpm

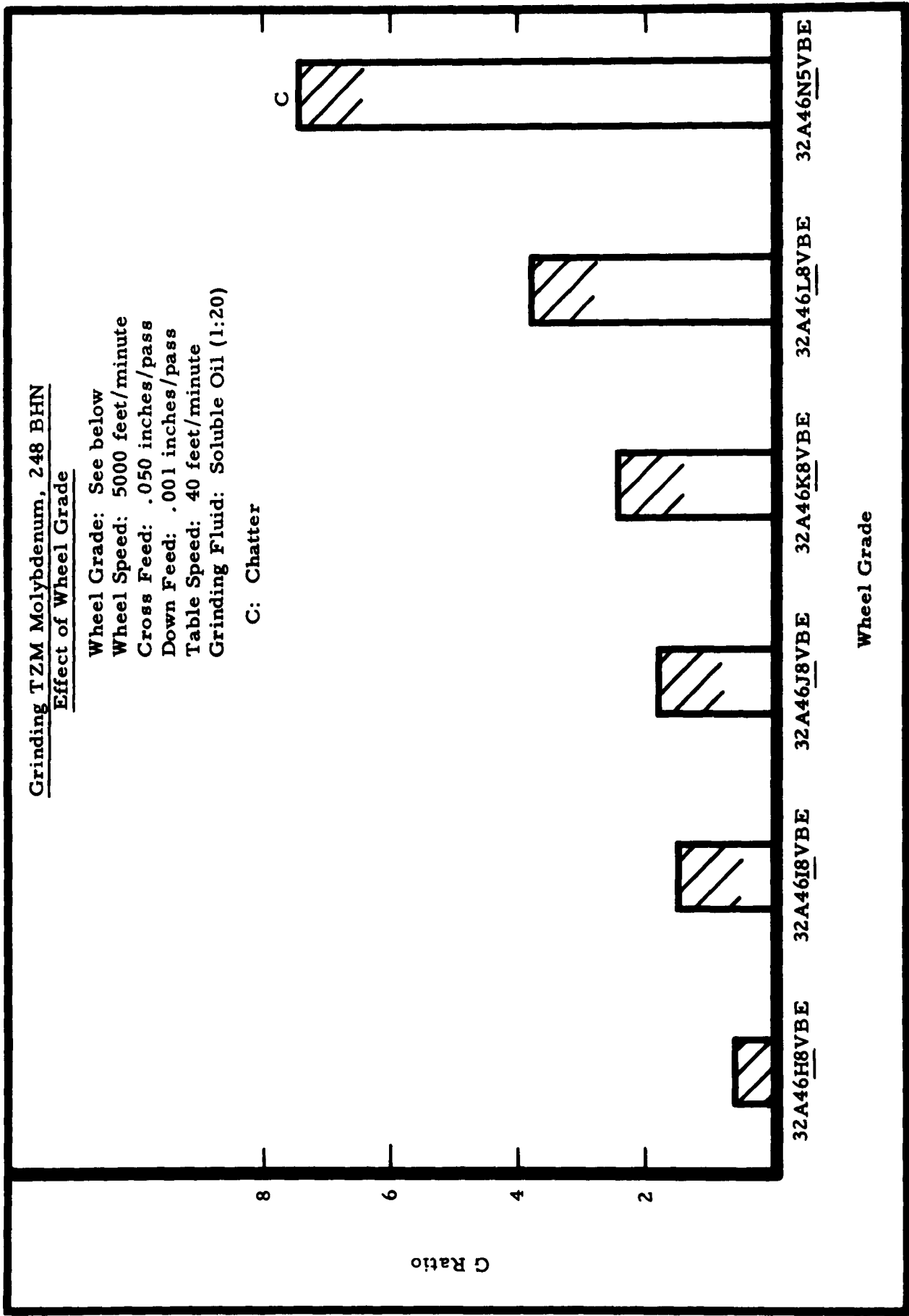
Tap Style

-  2 Flute Chipdriver Plug  
 4 Flute Plug

\*Test Discontinued

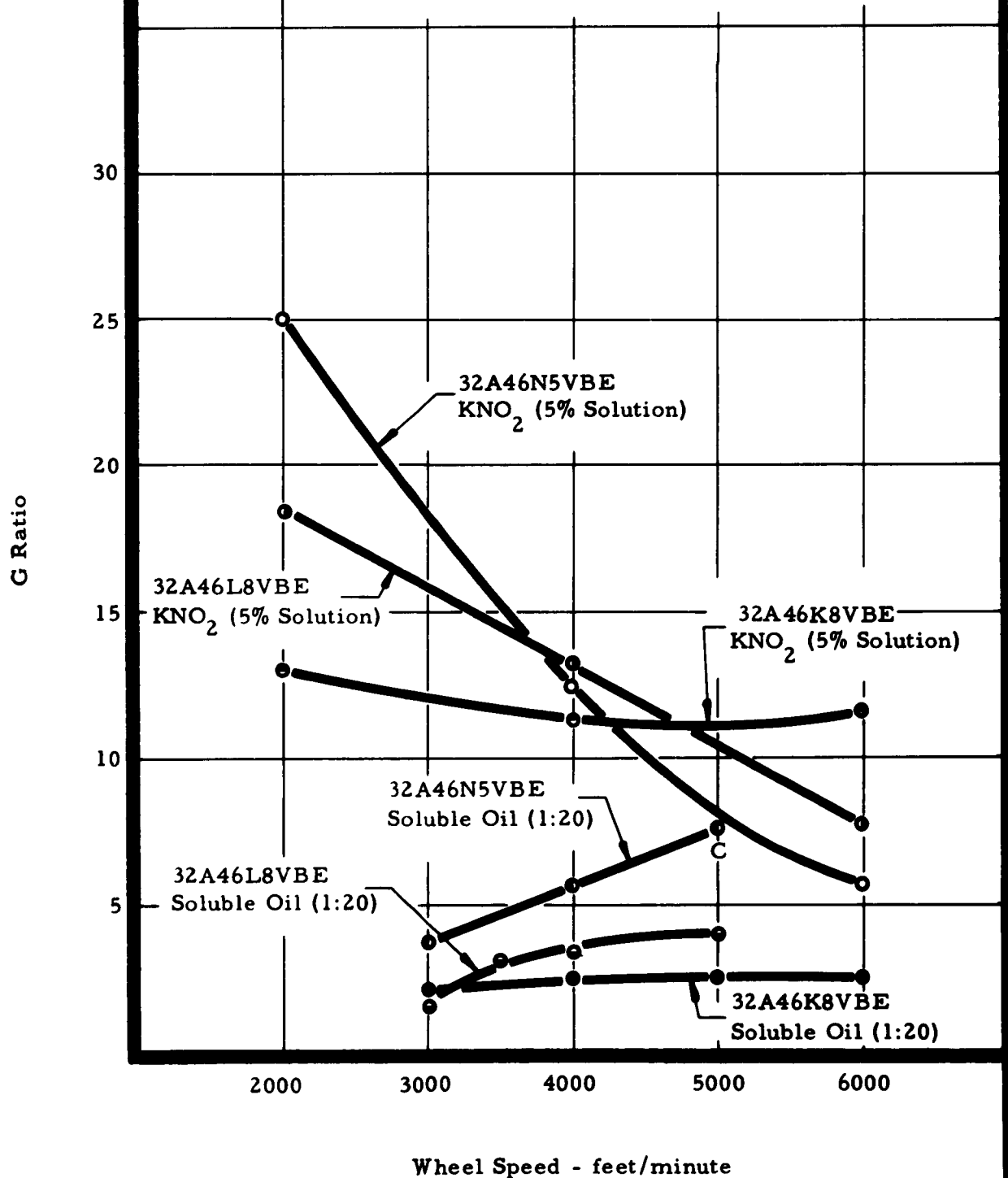
Tap Life - number of holes

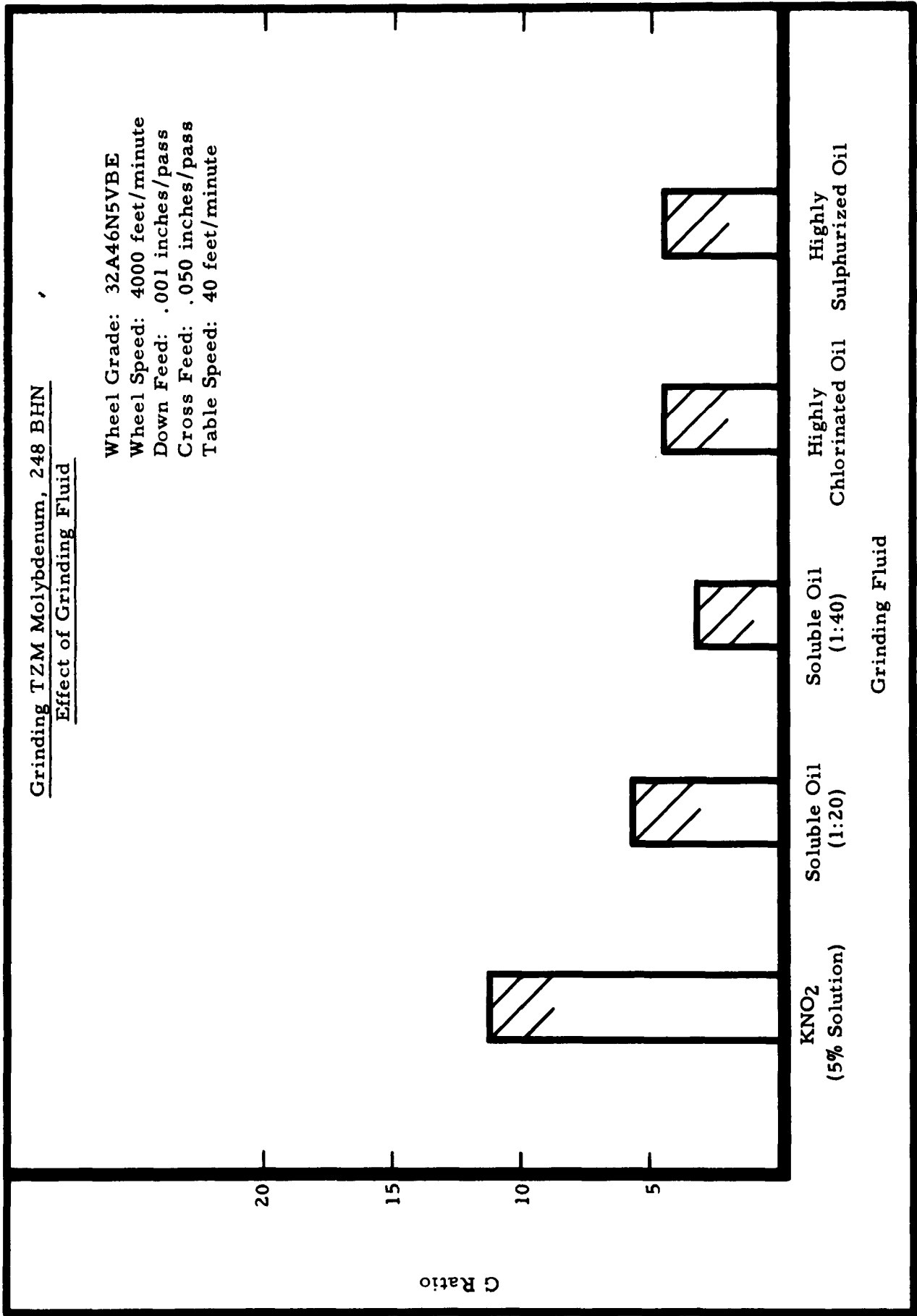




Grinding TZM Molybdenum, 248 BHN  
Effect of Wheel Grade and Grinding Fluid

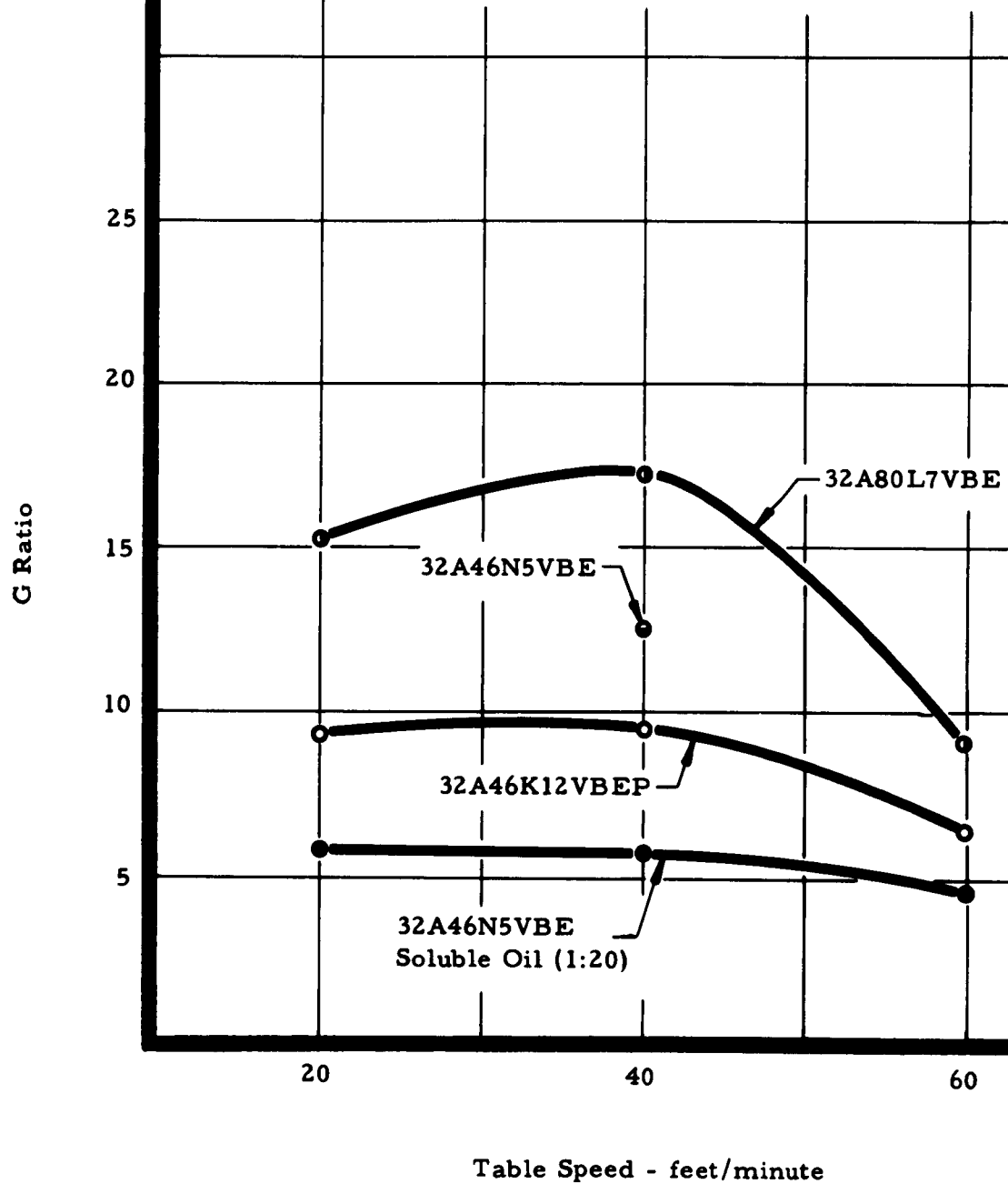
Down Feed: .001 inches/pass  
 Cross Feed: .050 inches/pass  
 Table Speed: 40 feet/minute  
 Grinding Fluid: See Below  
 C: Chatter





Grinding TzM Molybdenum, 248 BHN  
Effect of Table Speed

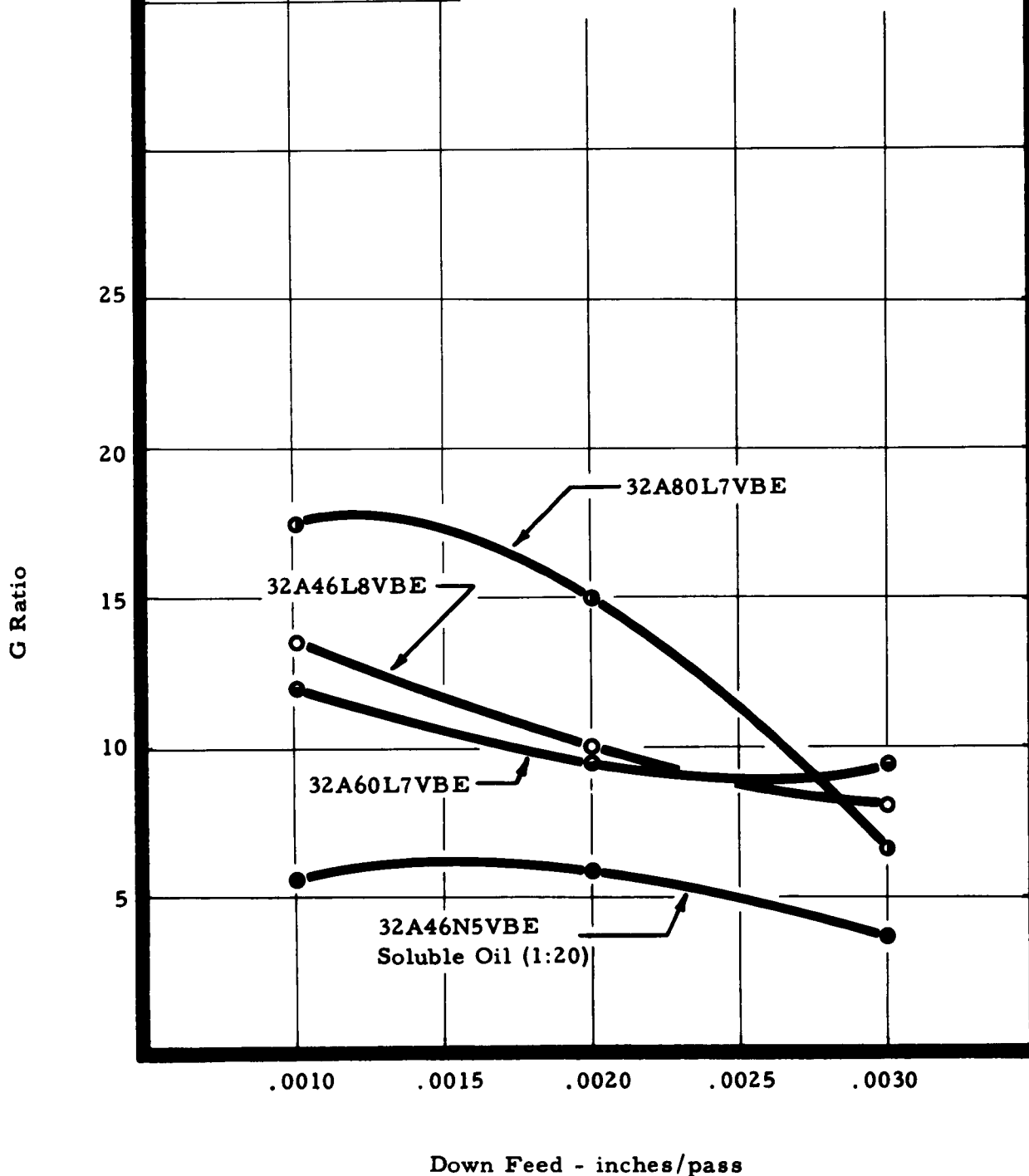
Wheel Grade: See Below  
Wheel Speed: 4000 feet/minute  
Down Feed: .001 inches/pass  
Cross Feed: .050 inches/pass  
Grinding Fluid:  $\text{KNO}_2$  (5% Solution)  
(unless noted)



Grinding TZM Molybdenum, 248 BHN

Effect of Down Feed

Wheel Grade: See Below  
Wheel Speed: 4000 feet/minute  
Cross Feed: .050 inches/pass  
Table Speed: 40 feet/minute  
Grinding Fluid:  $\text{KNO}_2$  (5% Solution)  
(unless noted)



Grinding TZM Molybdenum, 248 BHN

Effect of Cross Feed

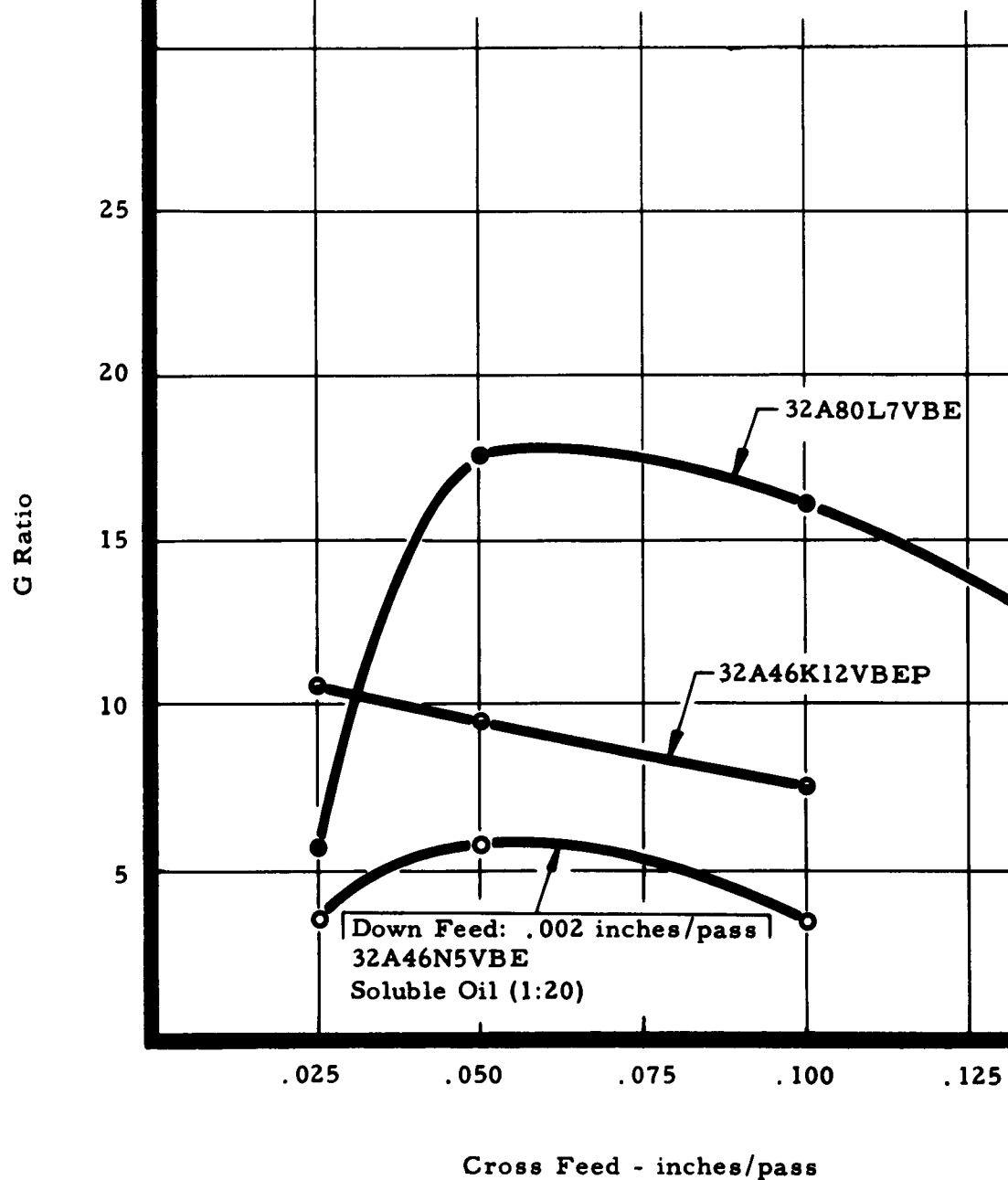
Wheel Grade: See Below

Wheel Speed: 4000 feet/minute

Down Feed: .001 inches/pass  
(unless noted)

Table Speed: 40 feet/minute

Grinding Fluid:  $\text{KNO}_2$  (5% Solution)  
(unless noted)



Turning D-31 Columbium Alloy, 207 BHN  
Effect of Carbide Grade

Tool Material: See Below

Tool: BR: 0° SR: 20°

SCEA: 0° ECEA: 5°

Relief: 5° NR: 1/64

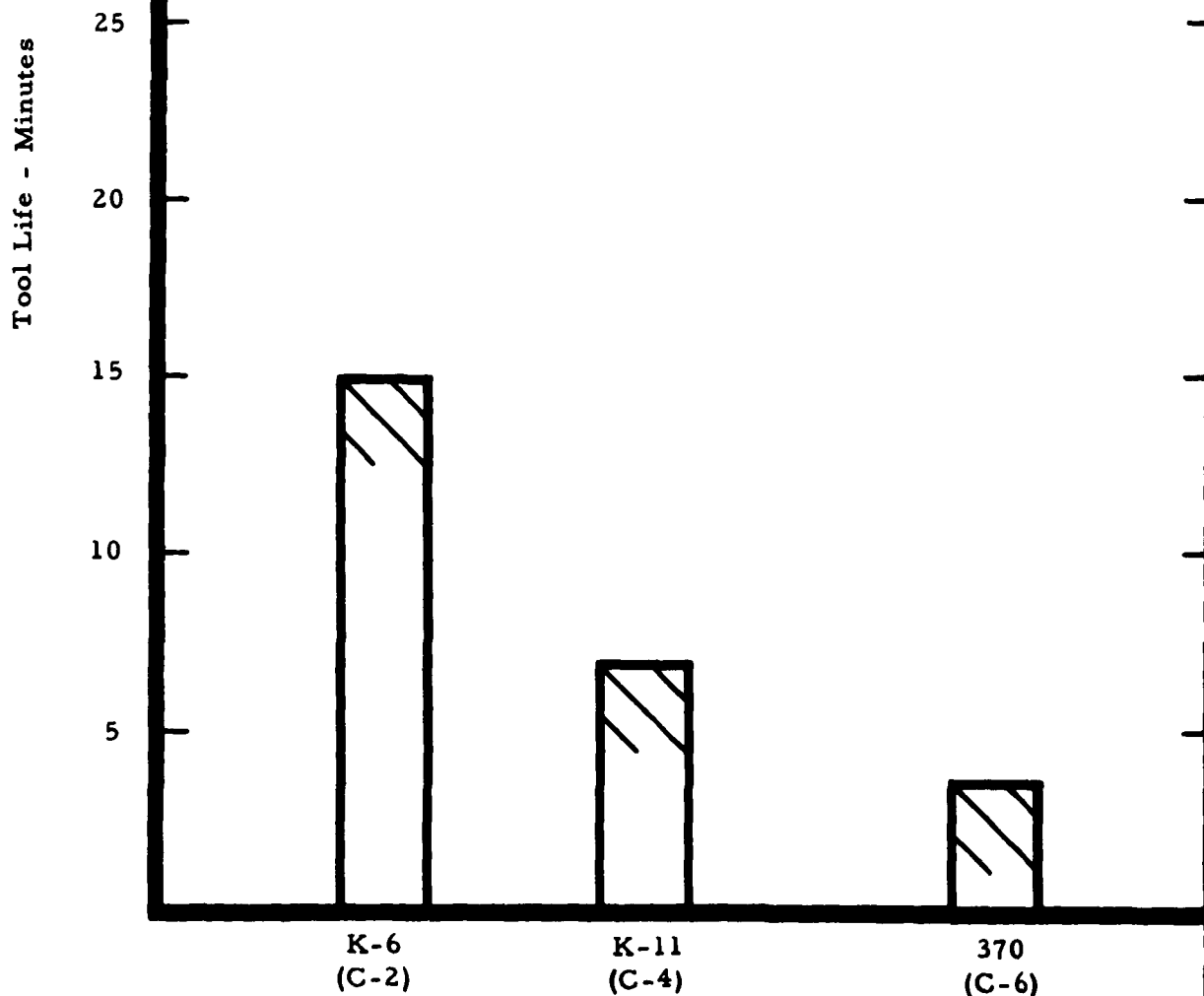
Cutting Speed: 350 feet/minute

Feed: .005 inches/revolution

Depth of Cut: .030"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .010" Wearland



Turning D-31 Columbium Alloy, 207 BHN  
Effect of Cutting Speed and Tool Material

Tool Material: see below

Tool: BR: 0° SR: 20°

SCEA: 0° ECEA: 5°

Relief: 5° NR: 1/64

Feed: .005 inches/revolution

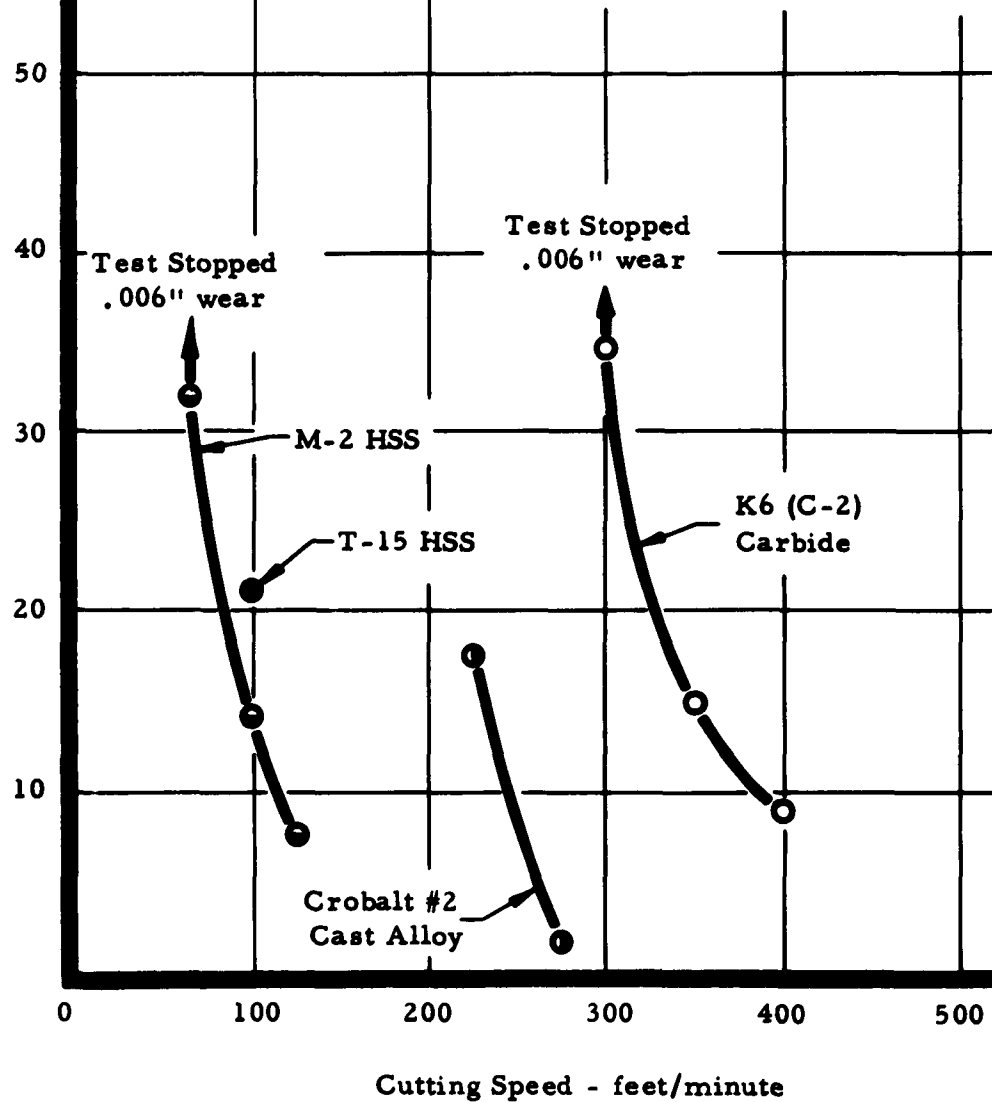
Depth of Cut: .030"

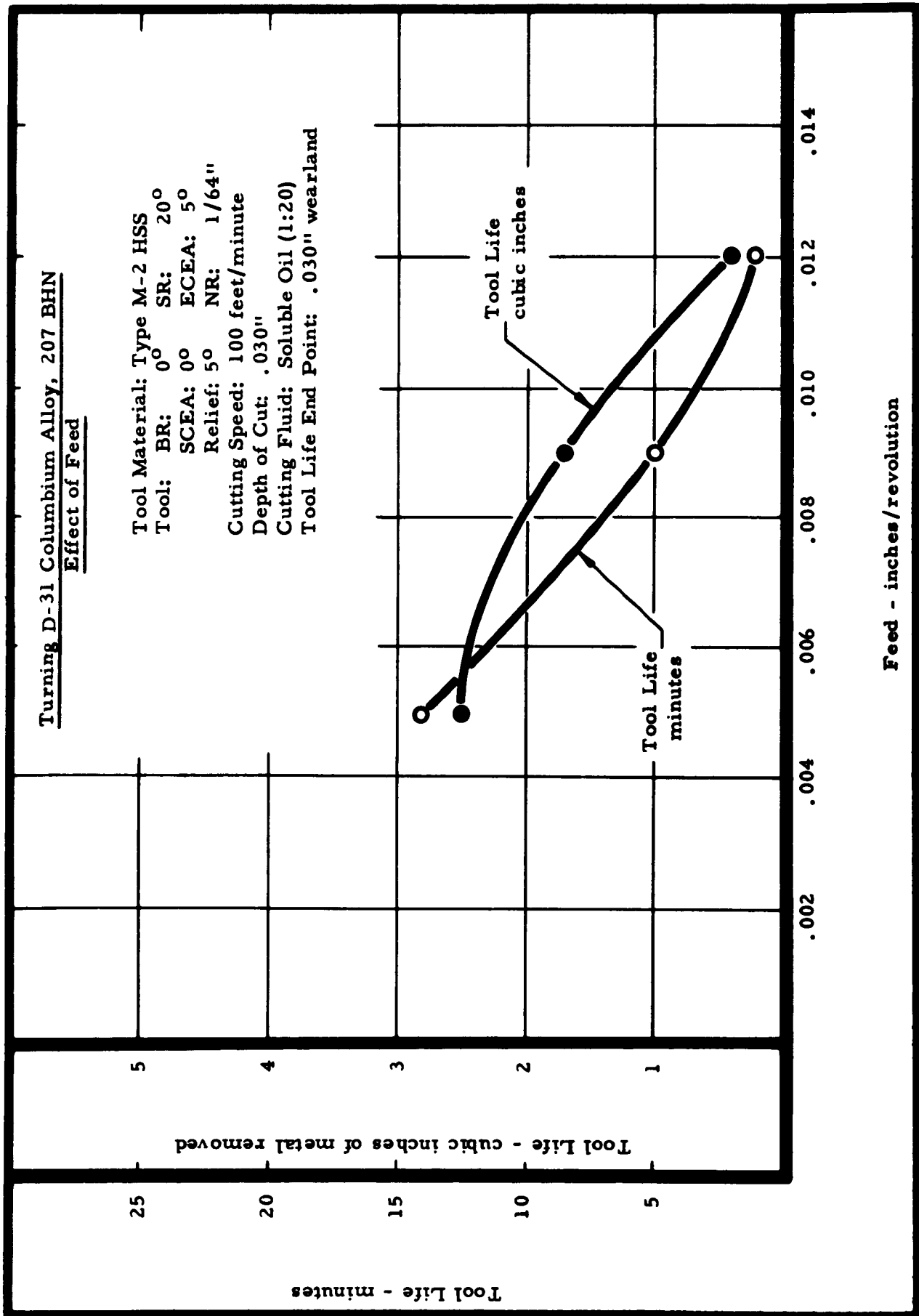
Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .010" wearland for  
carbide.

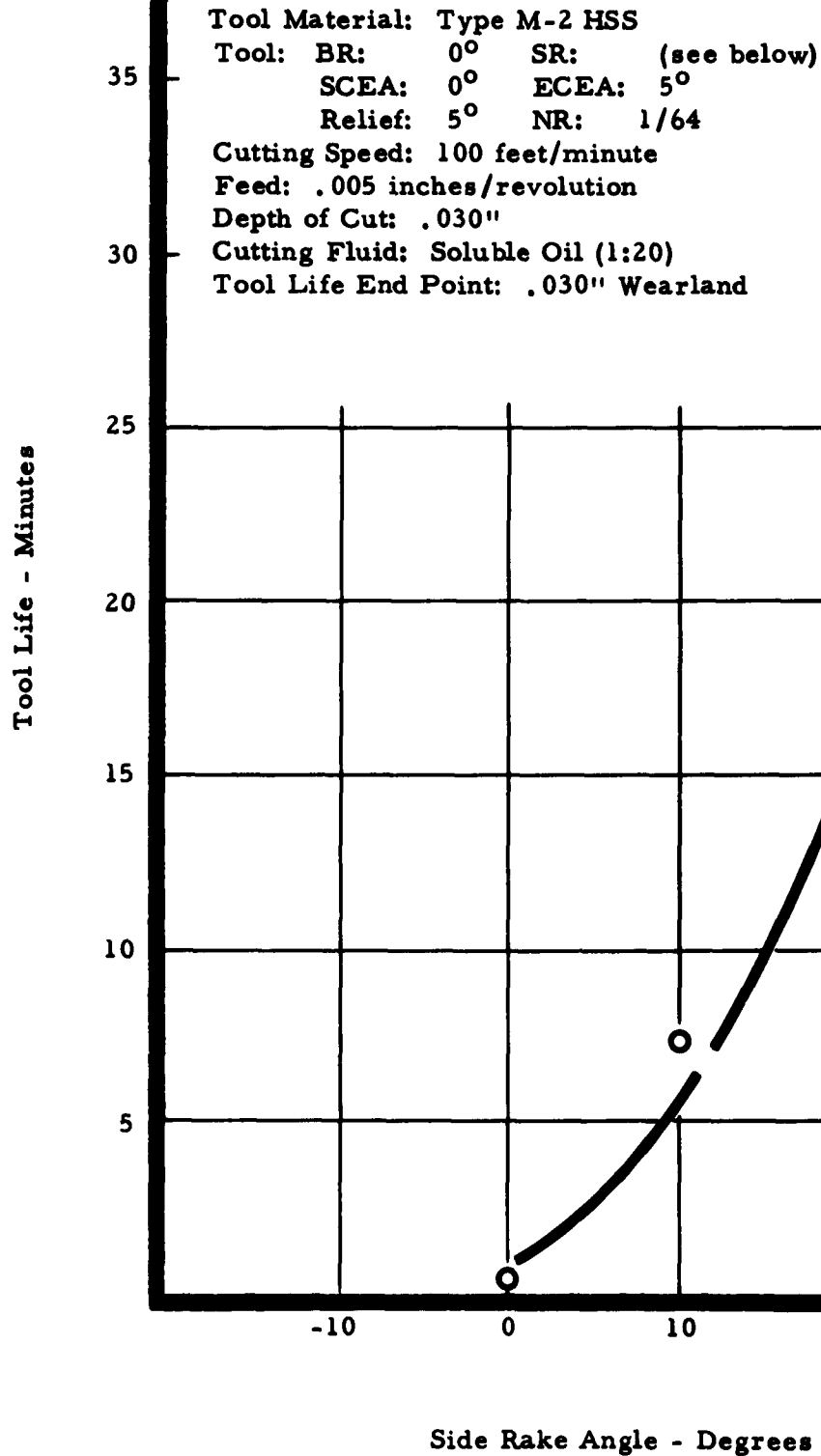
.030" wearland for  
HSS.

Tool Life - minutes





Turning D-31 Columbium Alloy, 207 BHN  
Effect of Rake Angle



Face Milling D-31 Columbium, 217 BHN  
Effect of Cutting Speed and Feed

Cutter: 4" Dia. Single Tooth Face Mill  
 With M-2 HSS

AR: 0°                      RR: 0°

TR: 14°                    Incl.: -14°

CA: 45°                   ECEA: 5°

Clearance: 10°

Feed: See Below

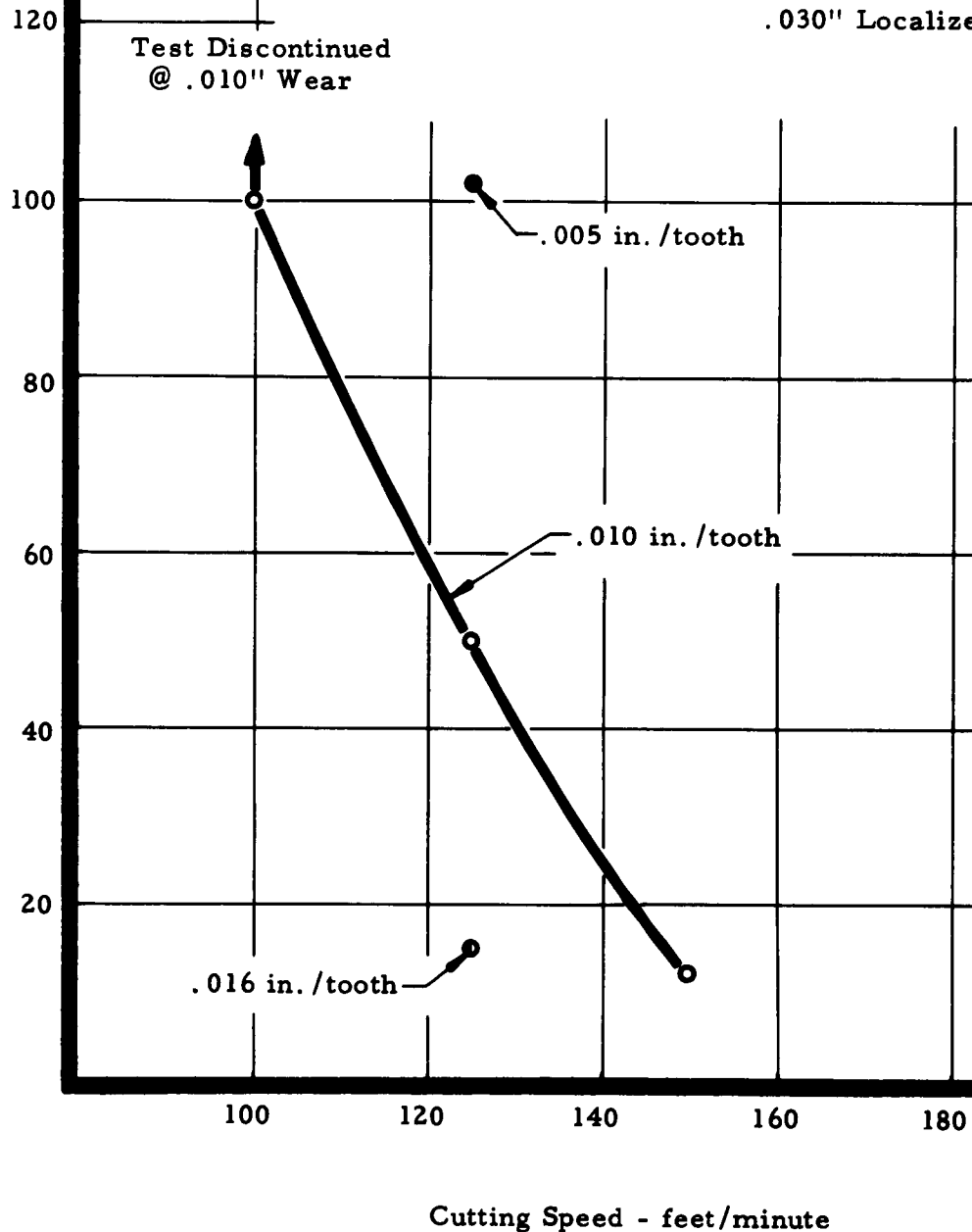
Depth of Cut: .030"

Width of Cut: 1-1/2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .016" Uniform Wear  
 .030" Localized Wear

Tool Life - inches work travel per tooth



Face Milling D-31 Columbium, 217 BHN  
Effect of Tool Material

Cutter: 4" dia. Single Tooth Face Mill  
with HSS

AR: 0° RR: 20°

TR: 14° Incl.: -14°

CA: 45° ECEA: 5°

Clearance: 10°

Cutting Speed: 152 feet/minute

Feed: .010 inches/tooth

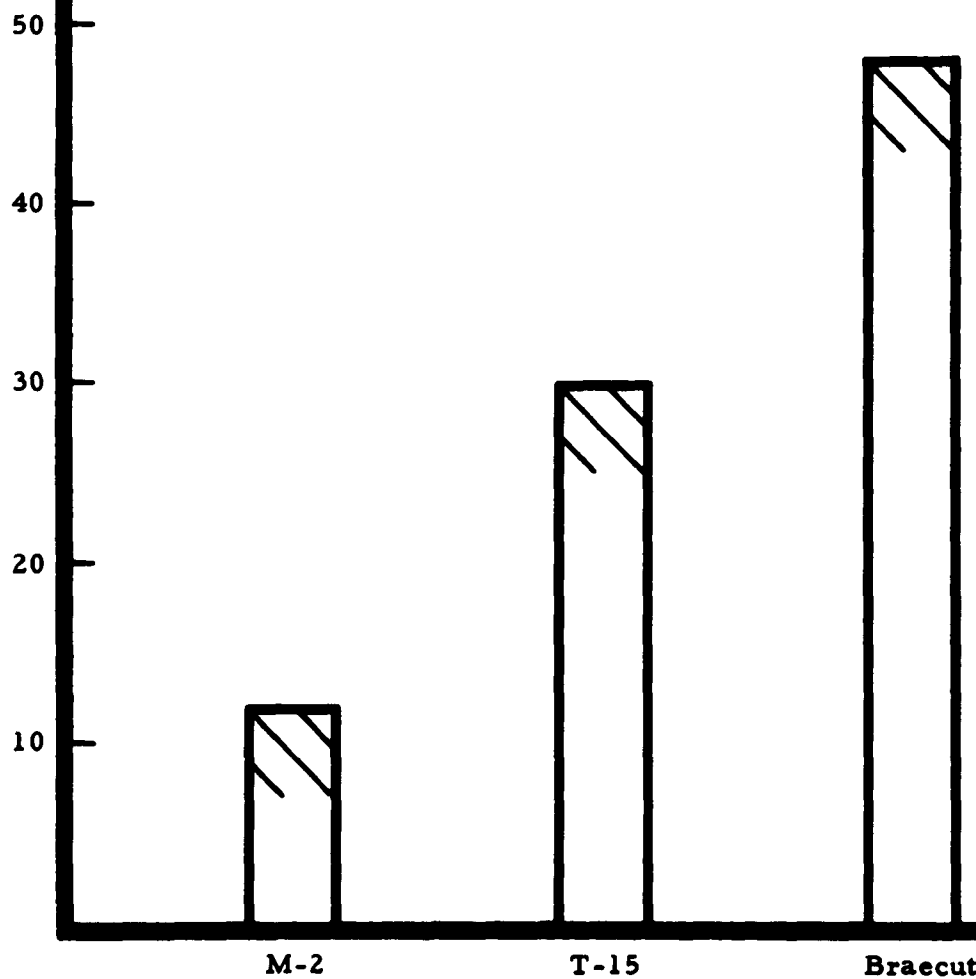
Depth of Cut: .030"

Width of Cut: 1-1/2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .016" Uniform Wear  
.030" Localized

Tool Life - inches work travel/tooth



**Face Milling D-31 Columbium, 217 BHN**

**Effect of Cutting Fluid**

Cutter: 4" dia. Single Tooth Face Mill  
with M-2 HSS

AR: 0° RR: 20°

TR: 14° Incl.: -14°

CA: 45° ECEA: 5°

Clearance: 10°

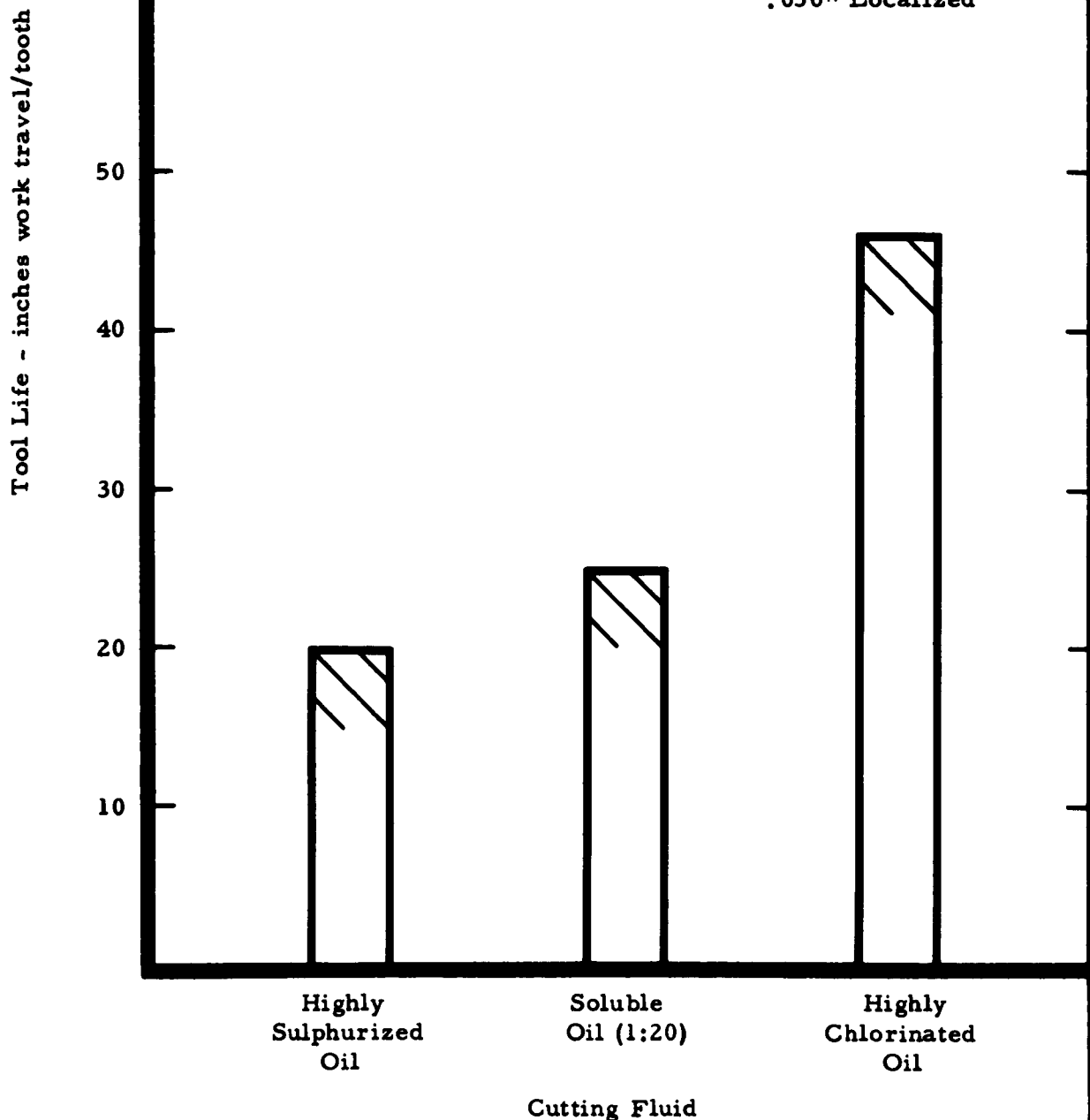
Cutting Speed: 142 feet/minute

Feed: .010 inch/tooth

Depth of Cut: .030"

Width of Cut: 1-1/2"

Tool Life End Point: .016" Uniform wear  
.030" Localized



**Face Milling D-31 Columbium, 217 BHN**  
**Effect of Cutter Rake Angles**

Cutter: 4" dia. Single Tooth Face Mill  
 with M-2 HSS

CA: 45° ECEA: 5°

Clearance: 10°

Cutting Speed: 122 feet/minute

Feed: .010 inch/tooth

Depth of Cut: .030"

Width of Cut: 1-1/2"

Cutting Fluid: Soluble Oil (1:20)

Tool Life End Point: .016" Uniform Wear

.030" Localized

Tool Life - inches work travel/tooth

100

80

60

40

20

AR

0

0

0

0

20

RR

0

10

20

30

0

TR

0

7

14

22

14

Incl.

0

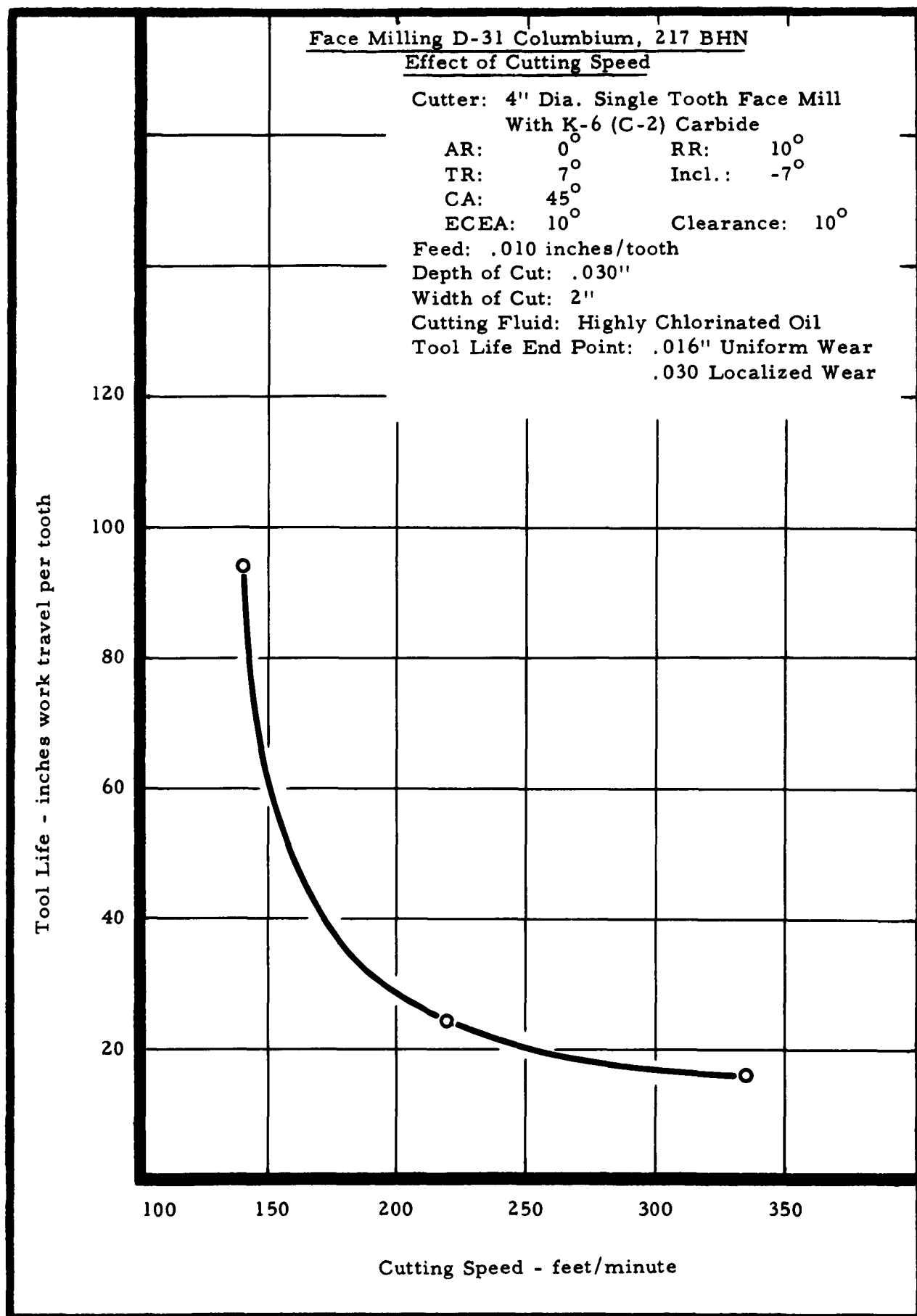
-7

-14

-22

14

Cutter Rake Angles - degrees



End Mill Slotting D-31 Columbium, 217 BHN

Effect of Cutting Fluid

Cutter: 1/2" Dia. 4 Tooth, M-2 HSS  
End Mill

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

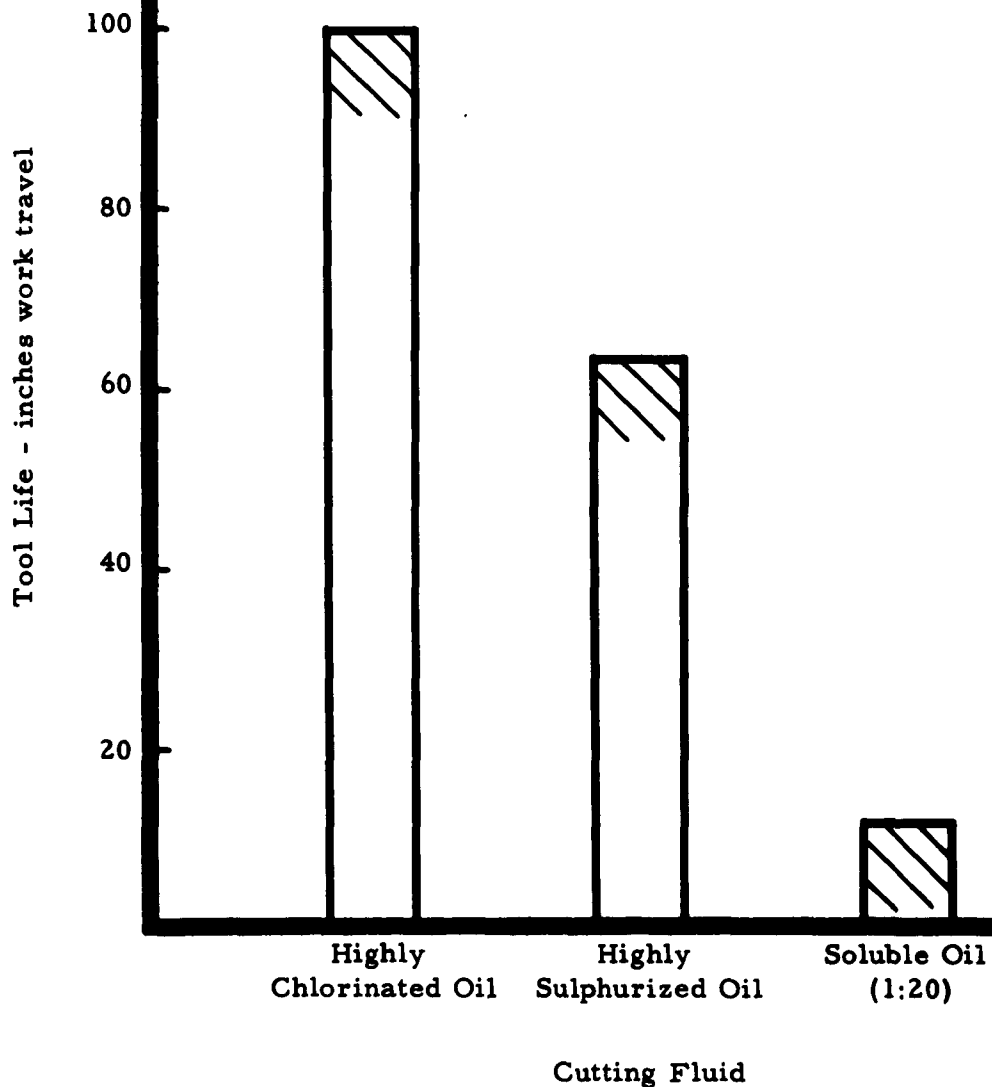
Cutting Speed: 83 feet/minute, 635 rpm

Feed: .003 inches/tooth

Depth of Cut: .060"

Cutting Fluid: See below

Tool Life End Point: .012" Uniform Wear  
.030" Localized Wear



End Mill Slotting D-31 Columbium, 217 BHN

Effect of Feed

Cutter: 1/2" Dia. 4 Tooth M-2 HSS End Mill

Helix Angle: 30° RR: 10°

CA: 45° x .060"

Peripheral Clearance: 10°

Cutting Speed: 102 feet/minute, 780 rpm

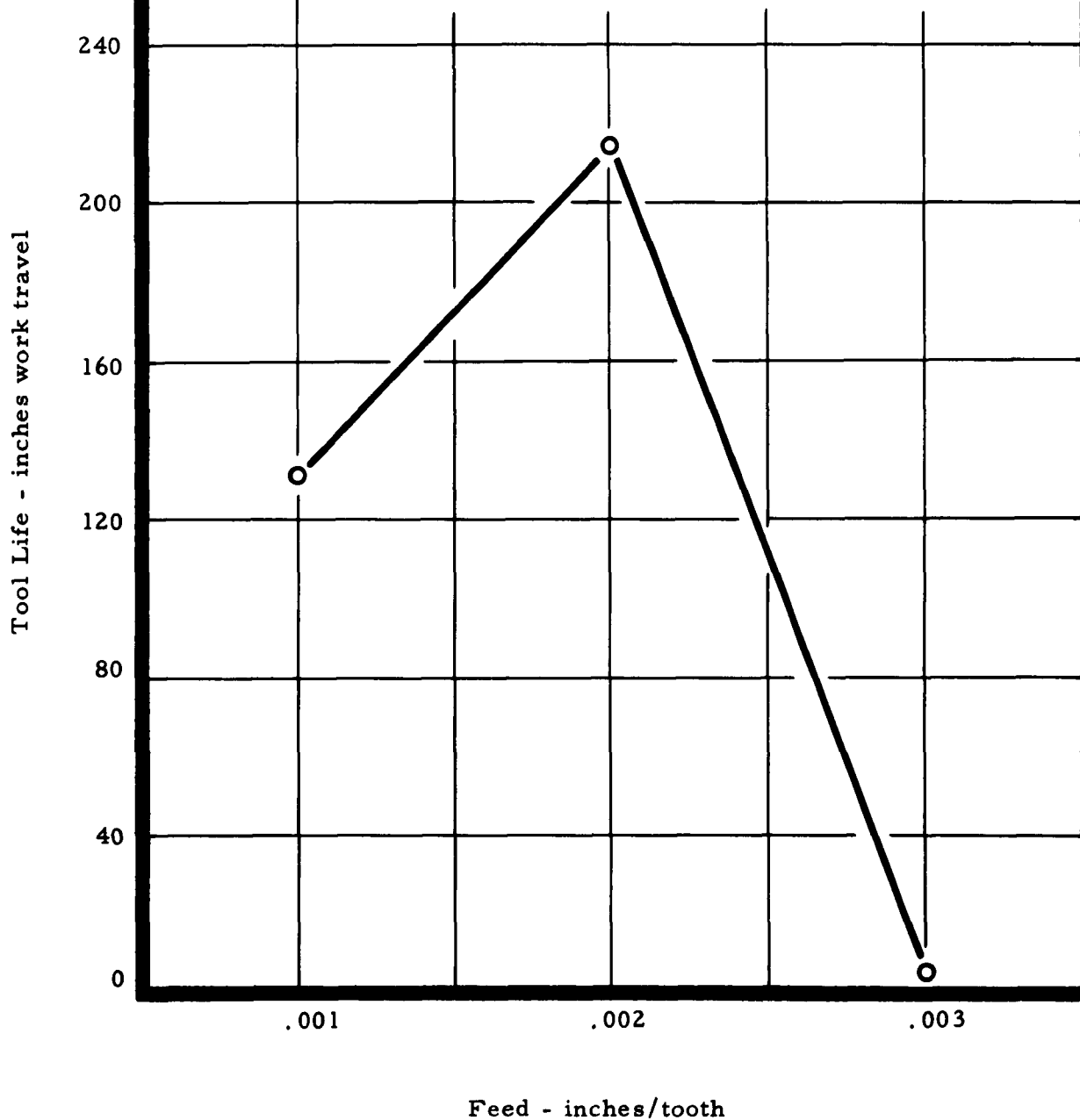
Depth of Cut: .060"

Width of Cut: .500"

Cutting Fluid: Highly Chlorinated Oil

Tool Life End Point: .012" Uniform Wear

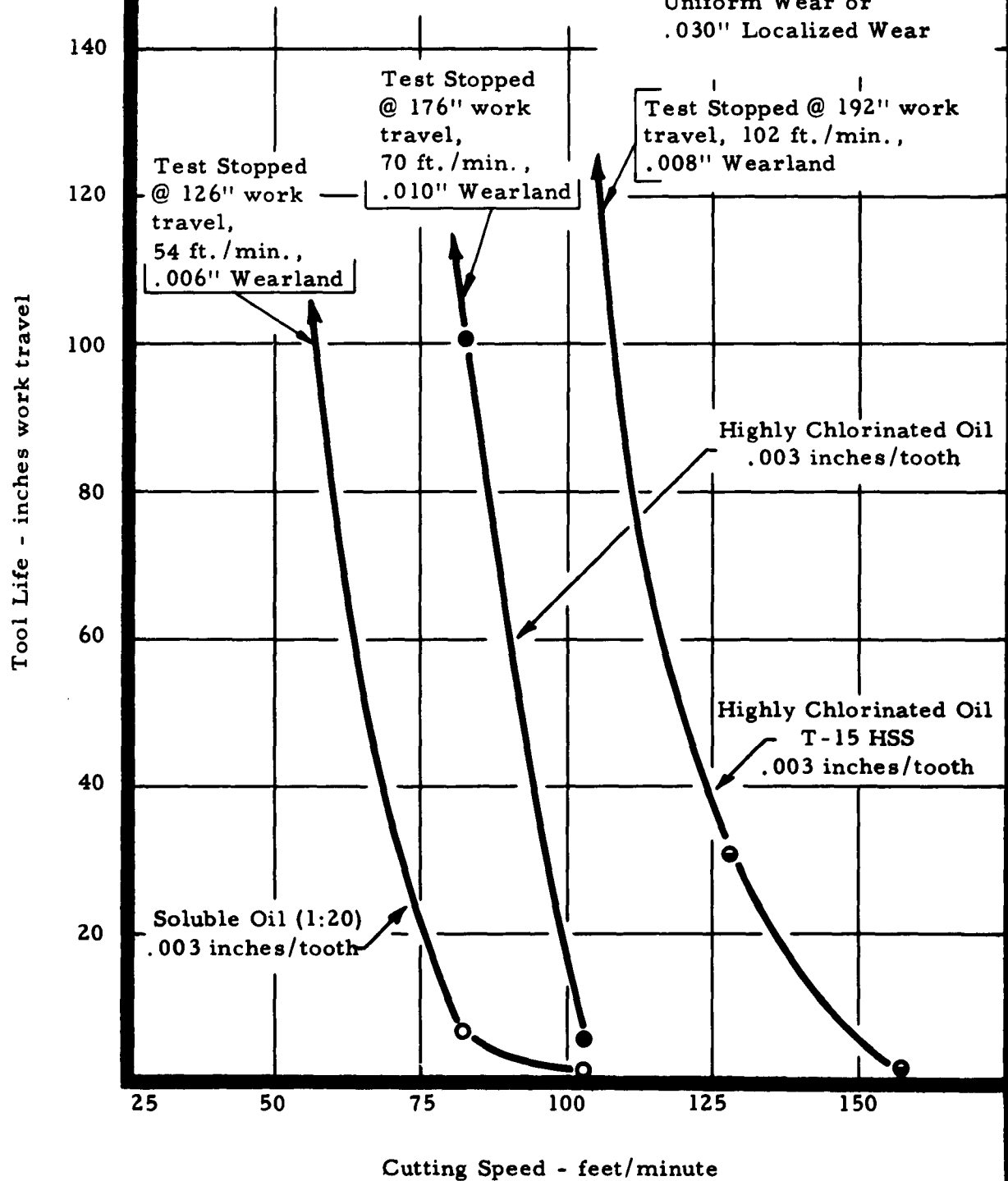
.030" Localized Wear

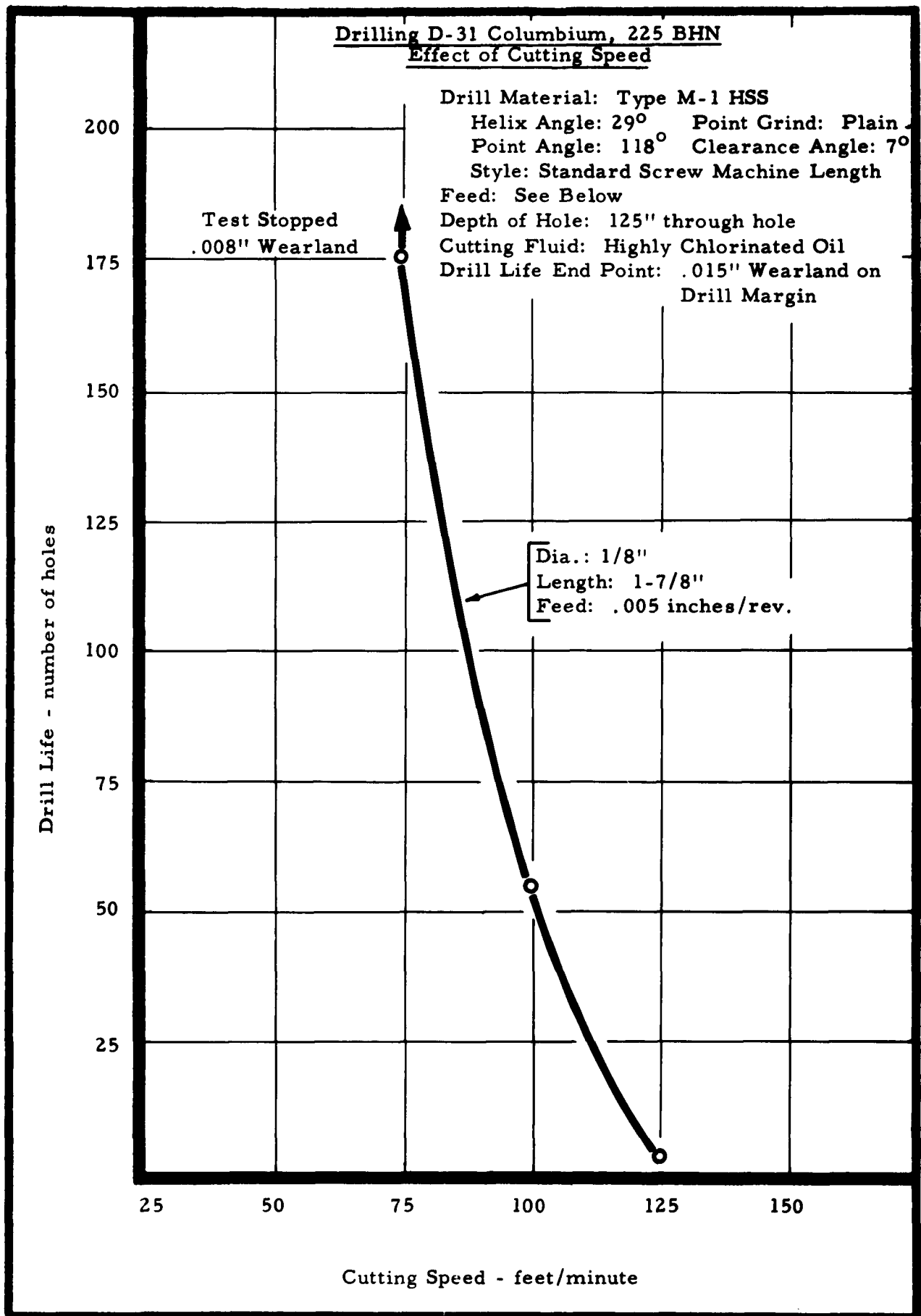


End Mill Slotting D-31 Columbium, 217 BHN  
Effect of Speed and Cutting Fluid

Cutter: 1/2" Dia. 4 Tooth M-2  
HSS End Mill  
Helix Angle: 30° RR: 10°  
CA: 45° x .040"  
Peripheral Clearance: 6°

Feed: See below  
Depth of Cut: .060"  
Width of Cut: .500"  
Cutting Fluid: See below  
Tool Life End Point: .012"  
Uniform Wear or  
.030" Localized Wear





Drilling D-31 Columbium, 225 BHN  
Effect of Drill Length

Drill Material: Type M-1 HSS

Dia.: 1/16" Point Grind: Plain

Helix Angle: 29°

Point Angle: 118°

Clearance Angle: 7°

Cutting Speed: 75 feet/minute, 4600 rpm

Feed: .002 inches/rev.

Depth of Hole: .125" through hole

Cutting Fluid: Highly Chlorinated Oil

Drill Life End Point: .015" Wearland on  
Drill Margin

Drill Life - number of holes

70

60

50

40

30

20

10

Standard  
Length

1-1/4

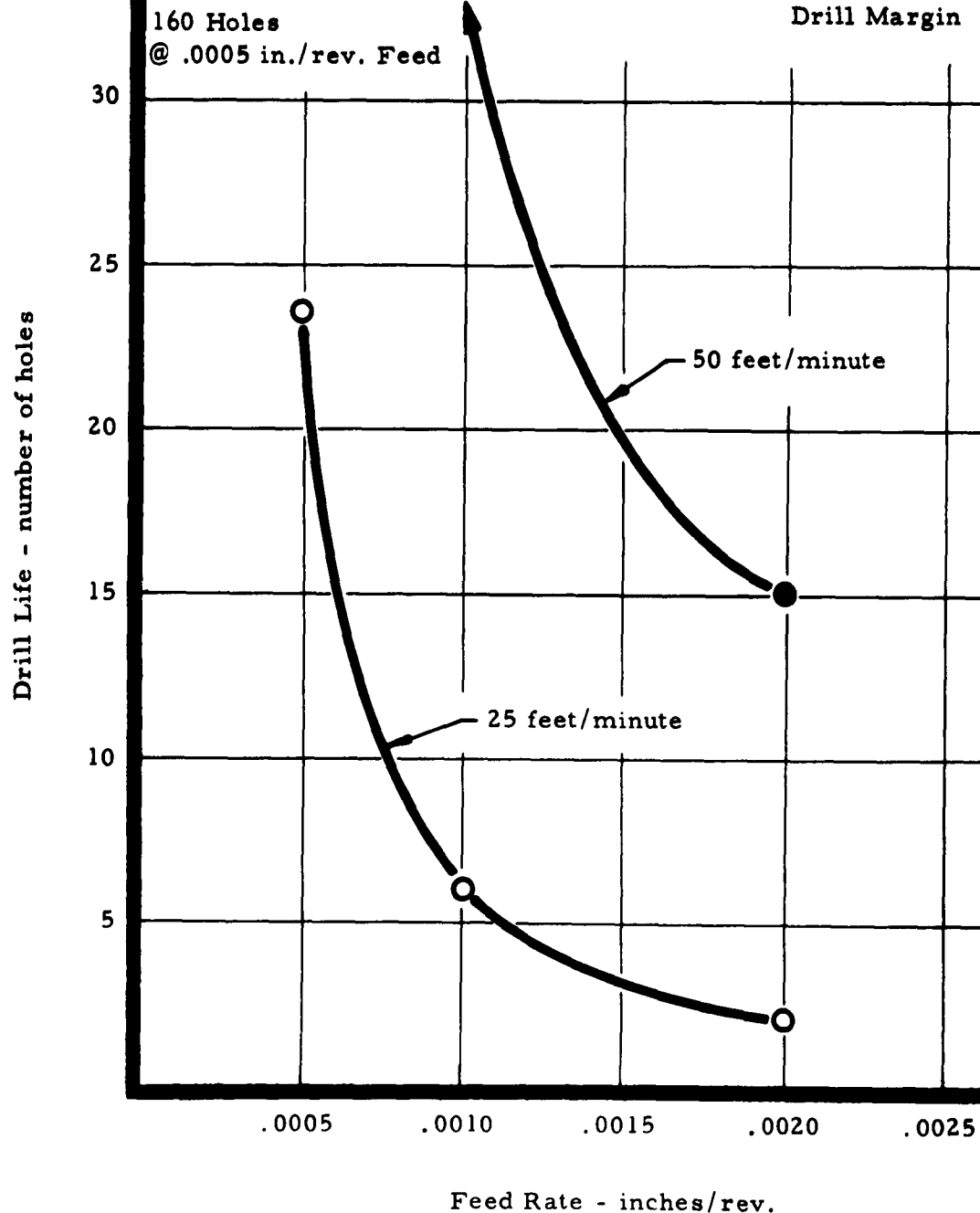
1-3/8

1-5/8

Drill Length - inches

Drilling D-31 Columbium, 225 BHN  
Effect of Feed Rate

Drill Material: Type M-1 HSS  
 Dia.: 1/16" Length: 1-5/8"  
 Helix Angle: 29° Point Grind: Plain  
 Point Angle: 118° Clearance Angle: 7°  
 Style: Standard Screw Machine Length  
 Cutting Speed: See below  
 Depth of Hole: .125" thru  
 Cutting Fluid: Highly Chlorinated Oil  
 Tool Life End Point: .015" Wearland on Drill Margin



**Drilling D-31 Columbium, 225 BHN**  
**Effect of Cutting Speed and Feed**

Drill Material: Type M-1 HSS

Dia.: #21 (.159") Length: 2-1/8"

Helix Angle: 29° Point Grind: Plain

Point Angle: 118° Clearance Angle: 7°

Style: Standard Screw Machine Length

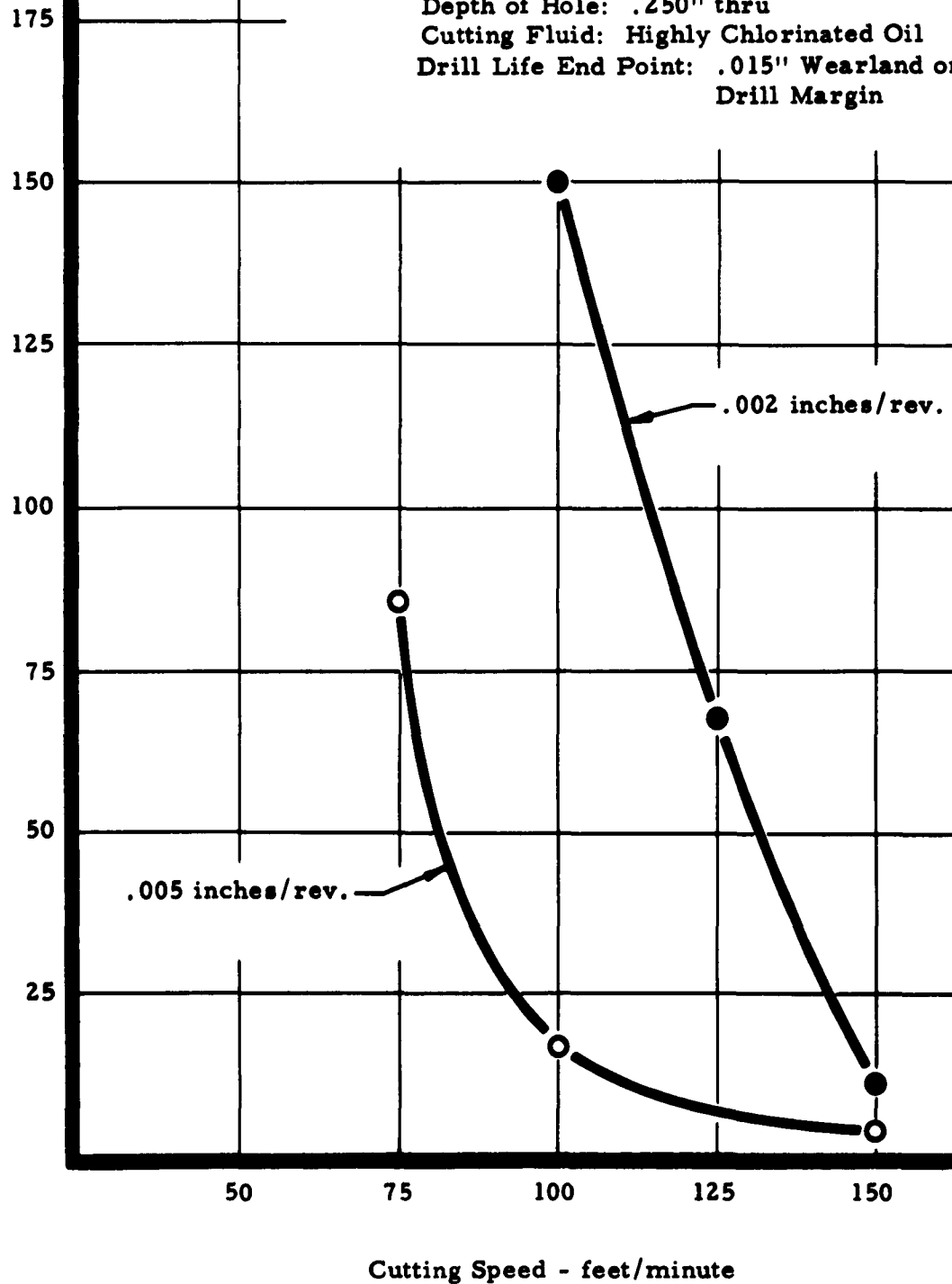
Feed: See below

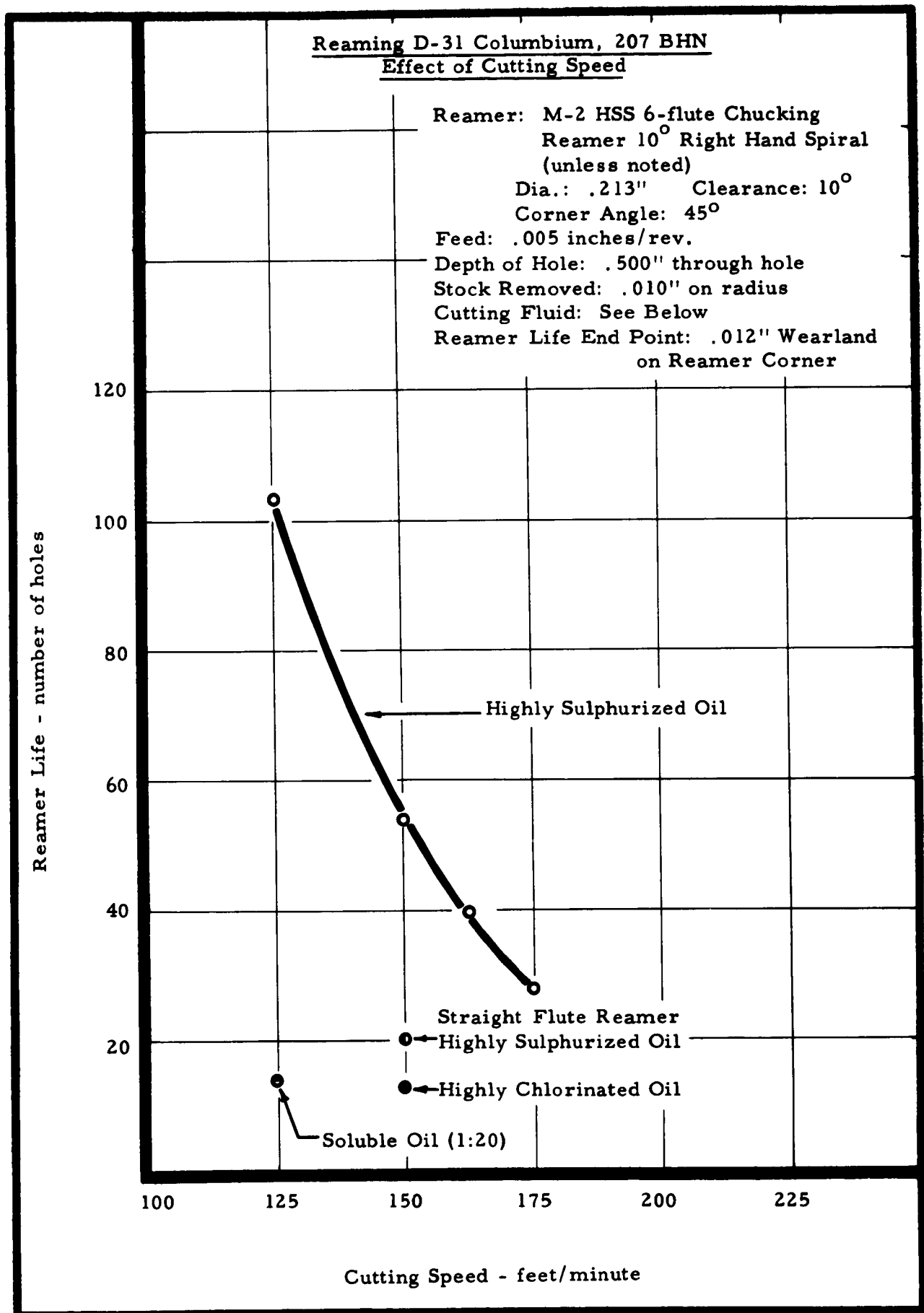
Depth of Hole: .250" thru

Cutting Fluid: Highly Chlorinated Oil

Drill Life End Point: .015" Wearland on  
Drill Margin

Drill Life - number of holes





Reaming D-31 Columbium, 207 BHN  
Effect of Feed

Reamer: M-2 HSS 6 Flute Chucking Reamer  
10° Right-Hand Spiral

Dia.: .213" Clearance: 10°

Corner Angle: 45°

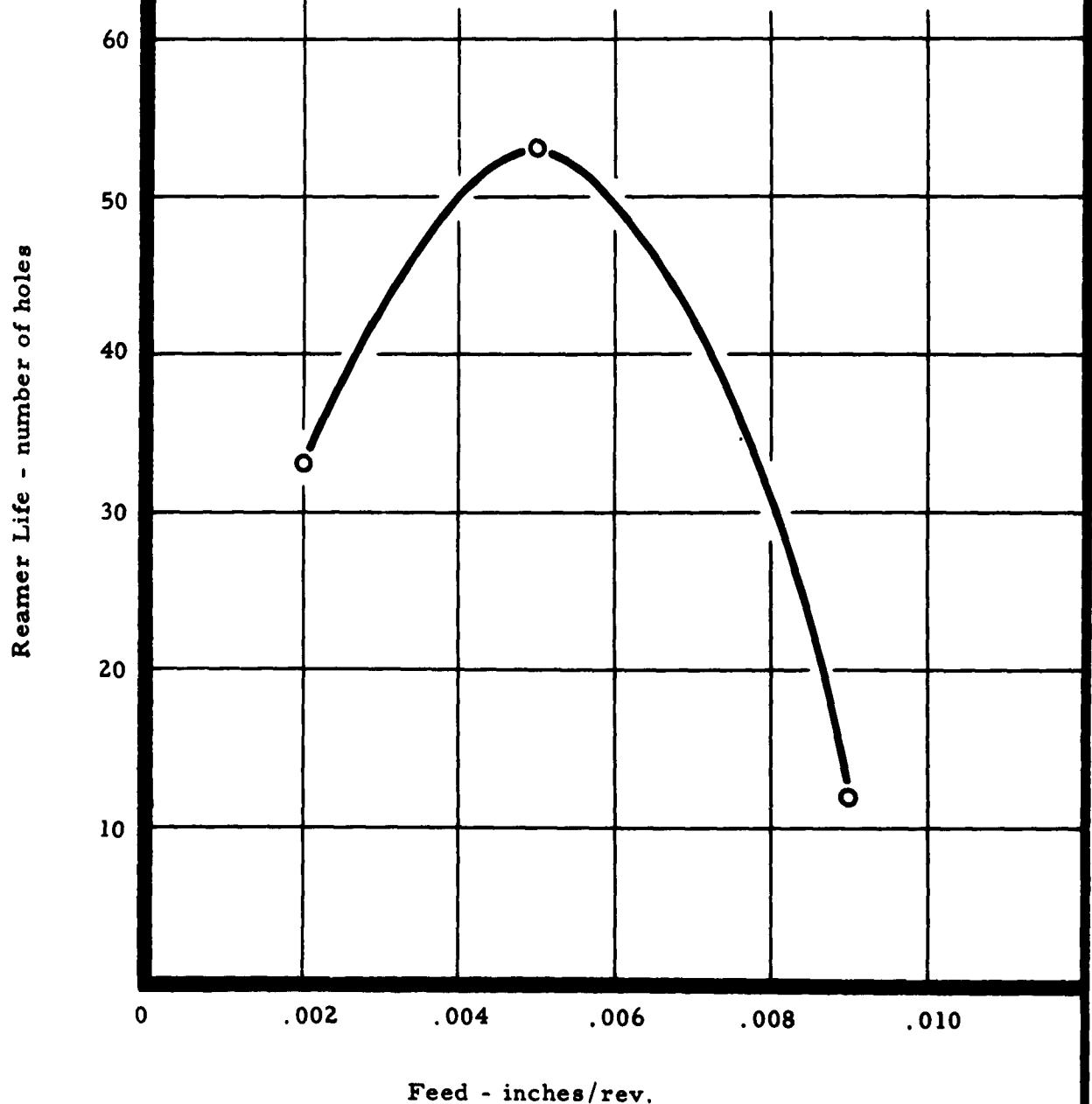
Cutting Speed: 150 feet/minute, 2690 rpm

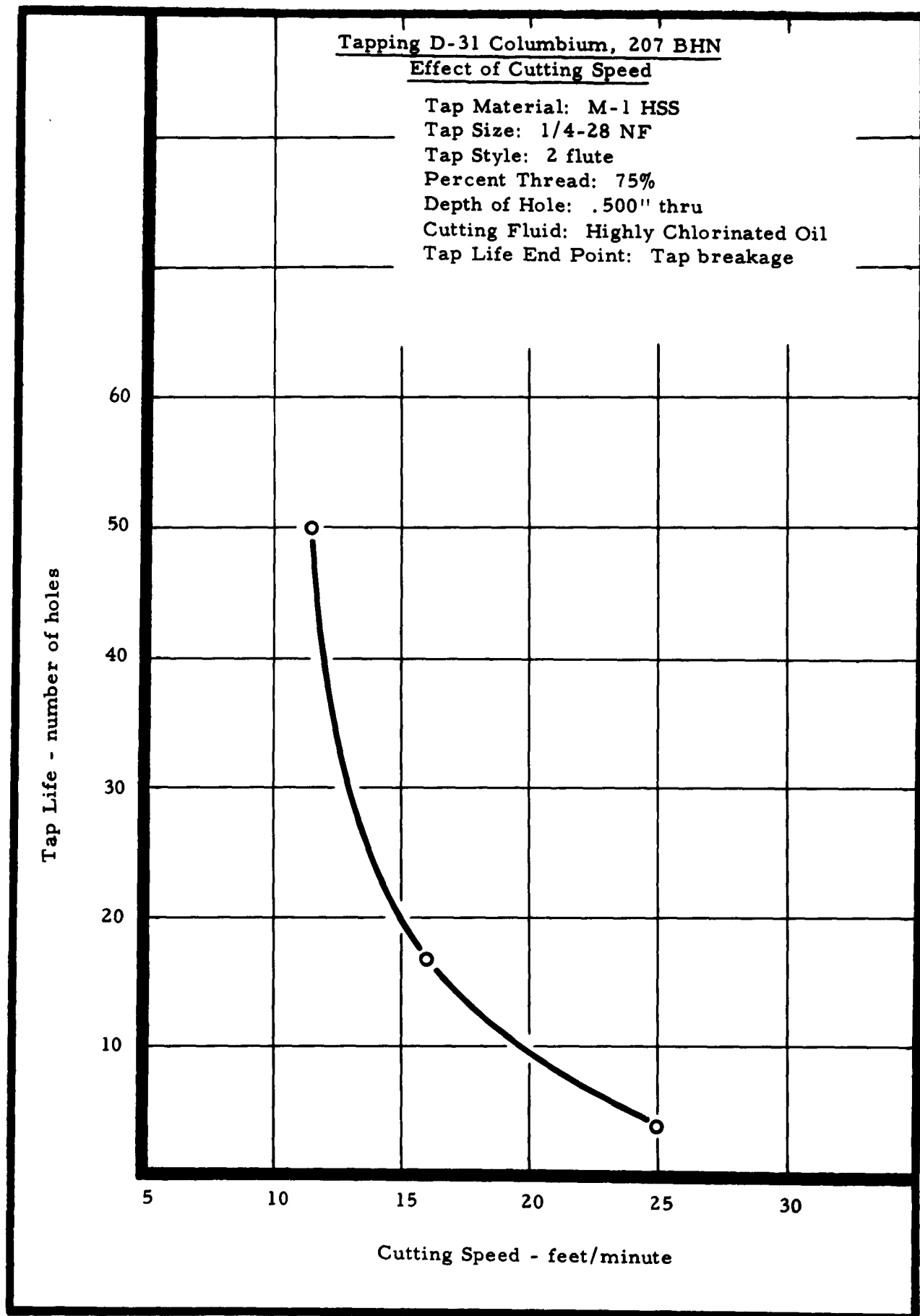
Depth of Hole: .500" thru

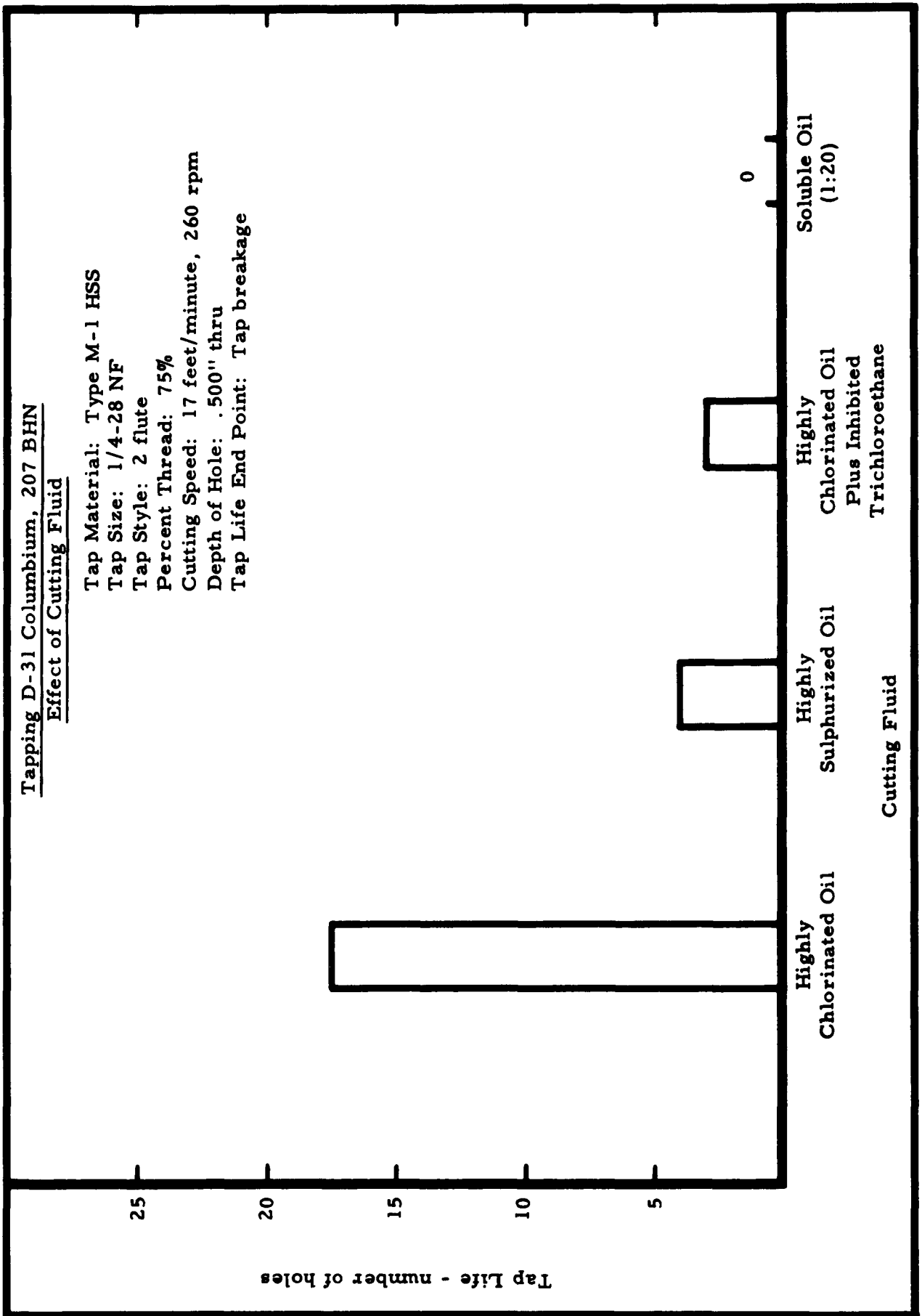
Stock Removed: .010" on Radius

Cutting Fluid: Highly Sulphurized Oil

Reamer Life End Point: .012" Wearland on  
Reamer Corner





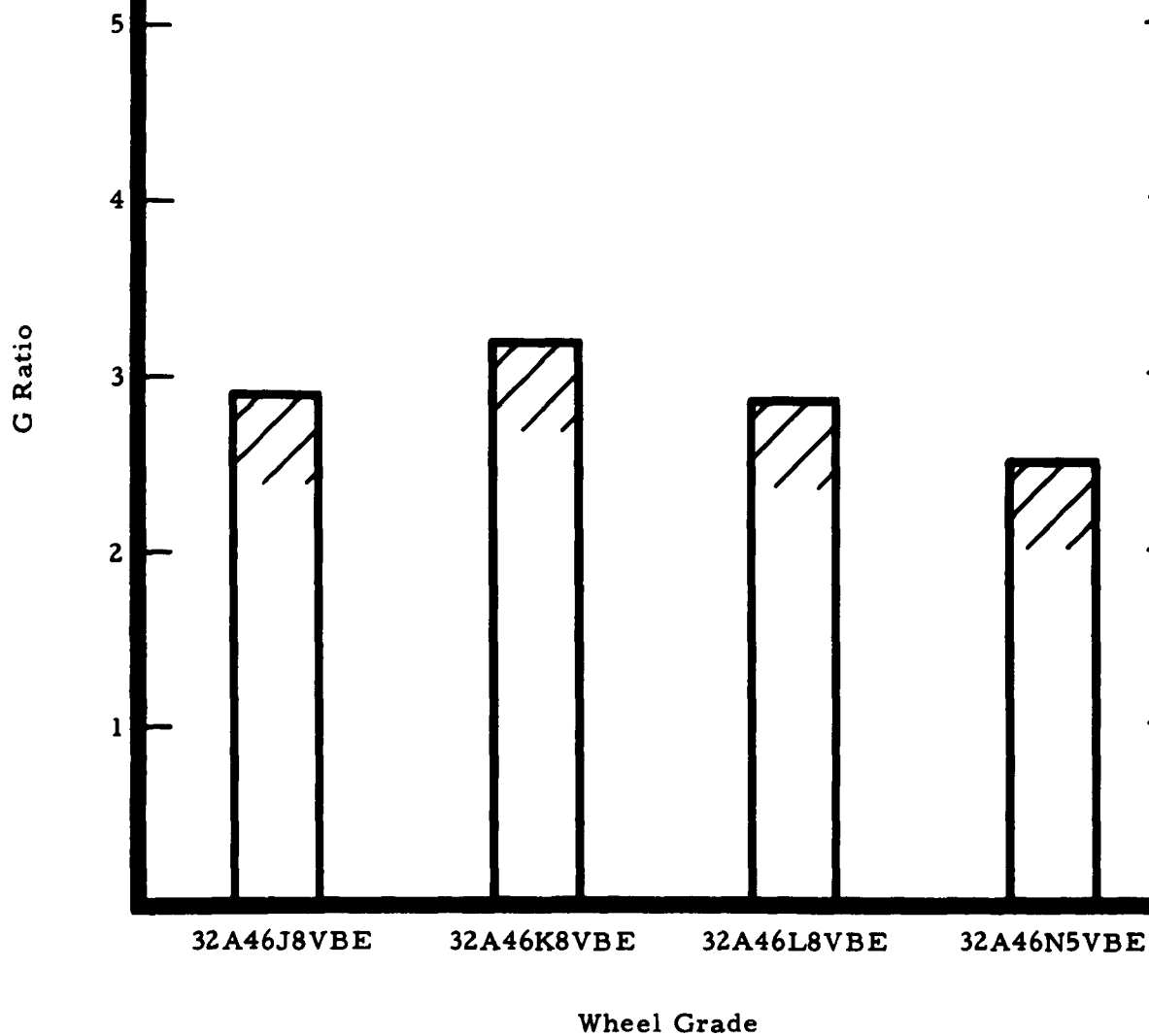


See Text page 25

Figure 89

Grinding Unalloyed Columbium, 112 BHN  
Effect of Wheel Grade

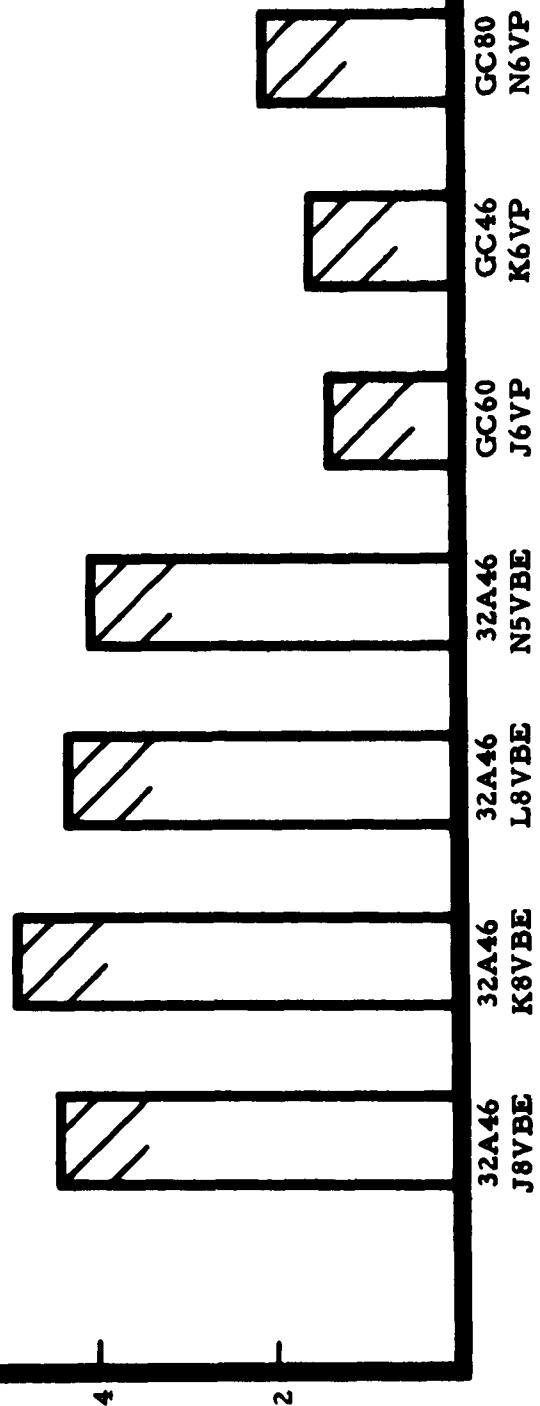
Wheel Speed: 4000 feet/minute  
Cross Feed: .050 inches/pass  
Down Feed: .001 inches/pass  
Table Speed: 40 feet/minute  
Grinding Fluid: Highly Chlorinated Oil



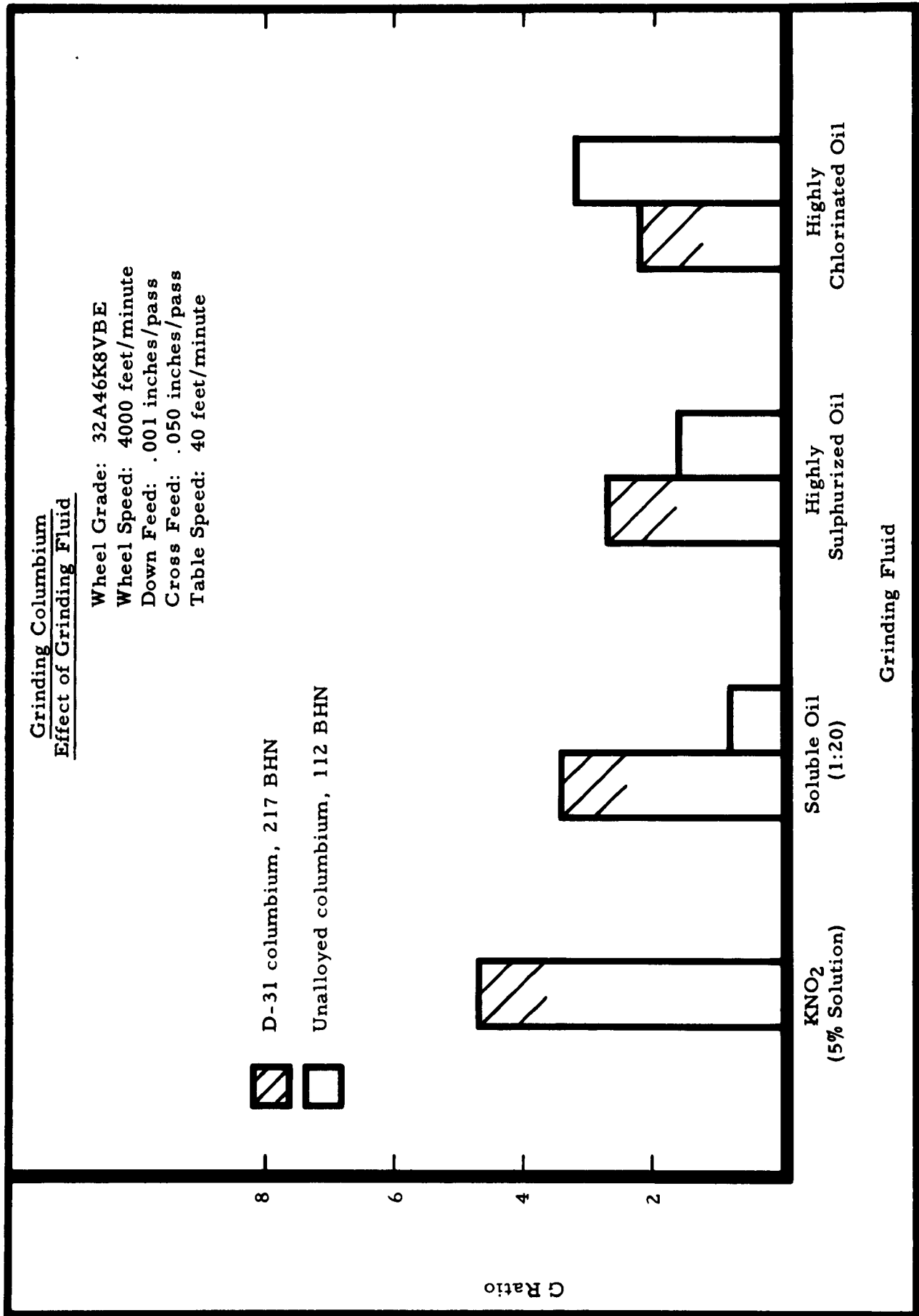
**Surface Grinding D-31 Columbium Alloy, 217 BHN**  
**Effect of Wheel Grade**

Wheel Speed: 2000 feet/minute  
 Down Feed: .001 inches/pass  
 Cross Feed: .050 inches/pass  
 Table Speed: 40 feet/minute  
 Grinding Fluid: KNO<sub>2</sub>, 5% solution

G Ratio

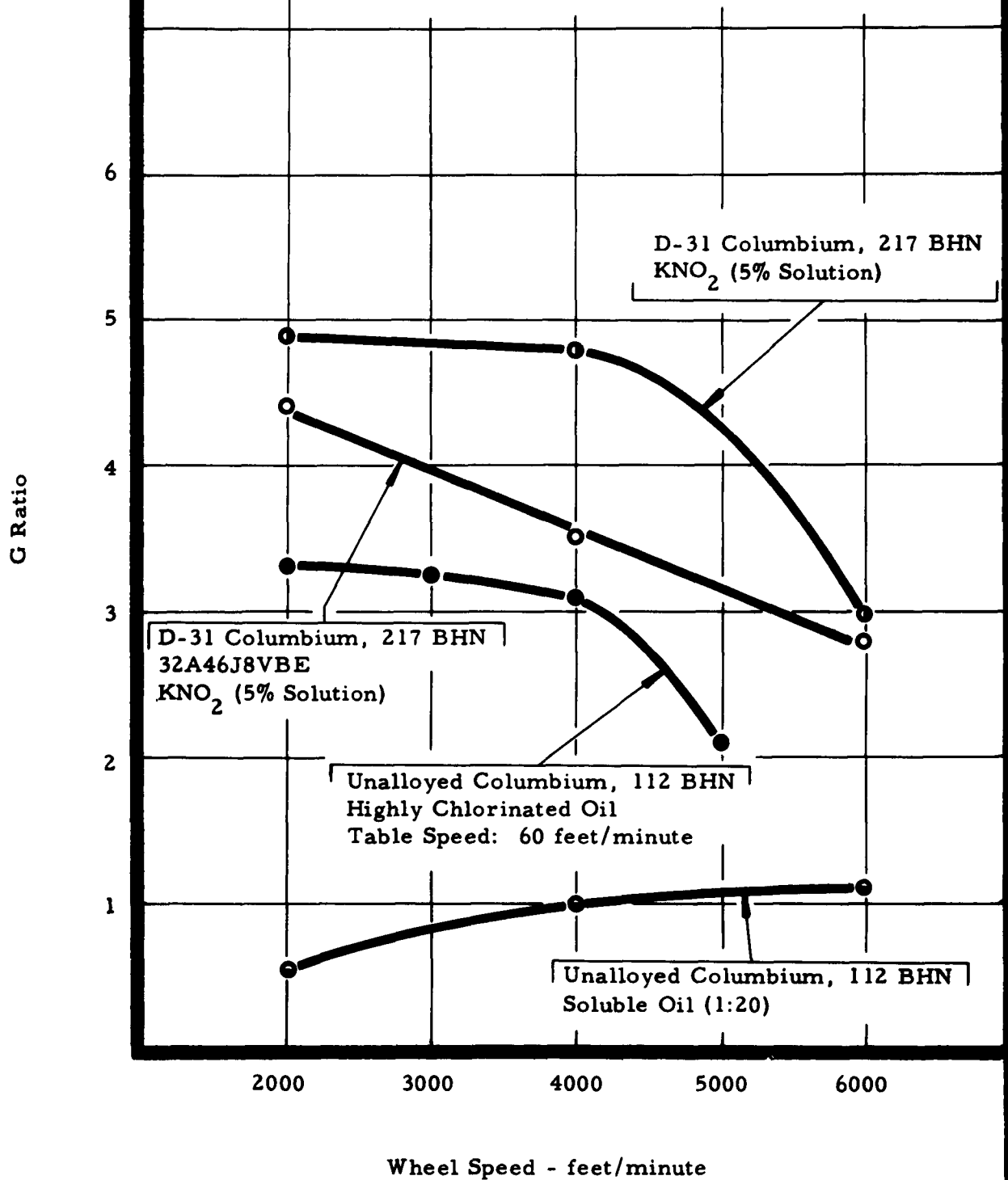


Wheel Grade



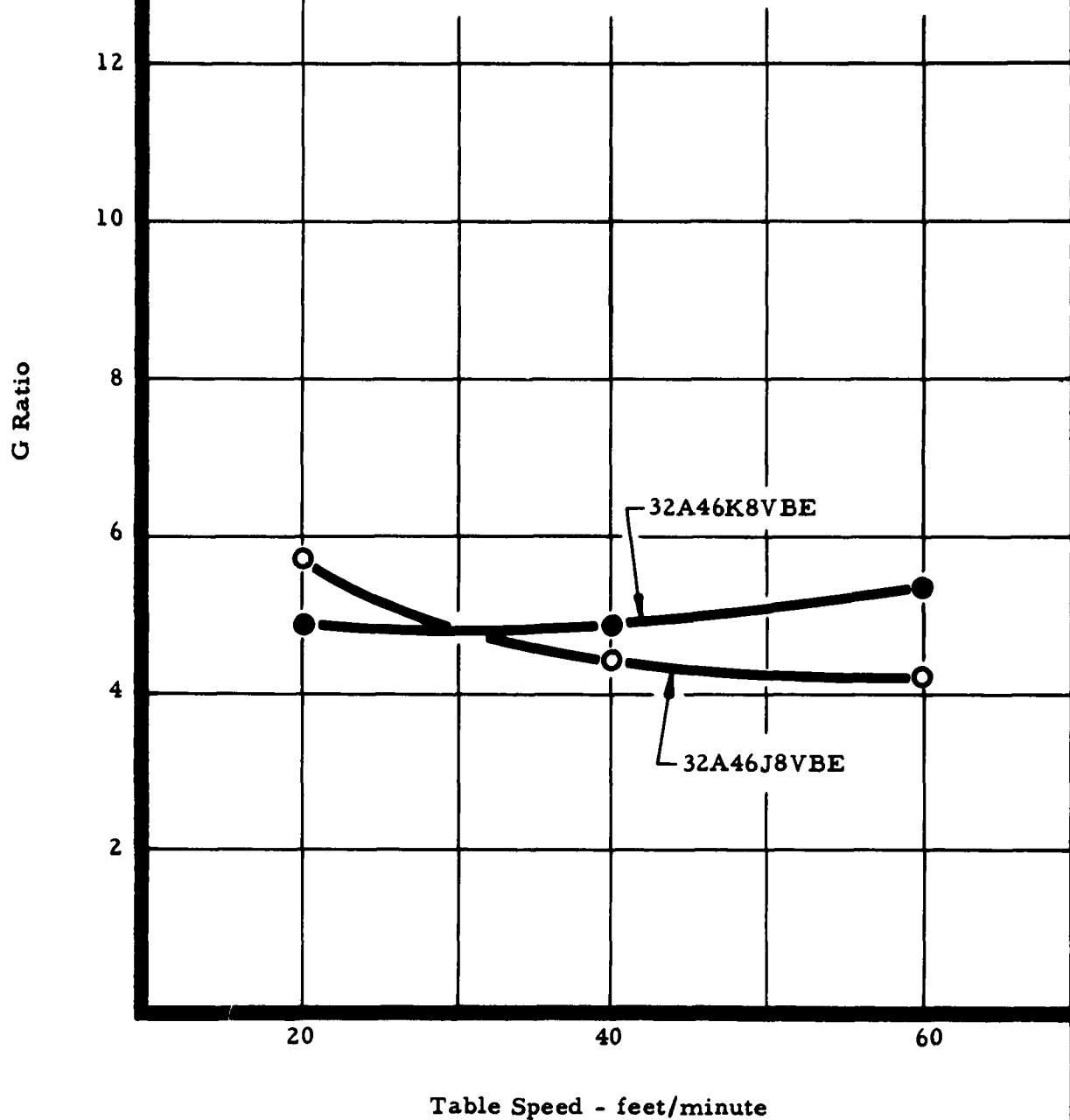
Grinding Columbium  
Effect of Wheel Speed

Wheel Grade: 32A46K8VBE (unless noted)  
Down Feed: .001 inches/pass  
Cross Feed: .050 inches/pass  
Table Speed: 40 feet/minute (unless noted)  
Grinding Fluid: See Below



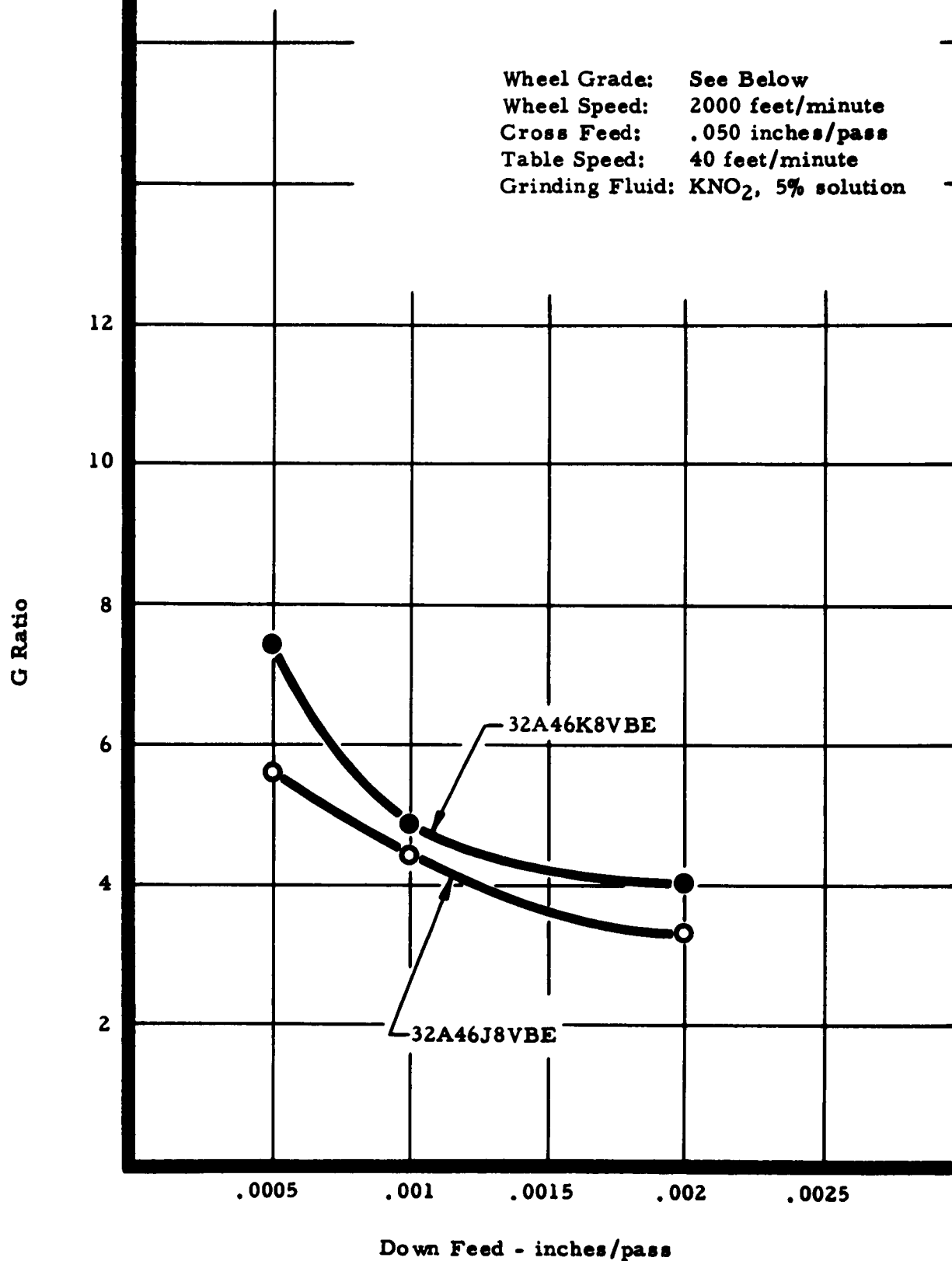
Surface Grinding D-31 Columbium Alloy, 217 BHN  
Effect of Table Speed

Wheel Grade: See below  
Wheel Speed: 2000 feet/minute  
Down Feed: .001 inches/pass  
Cross Feed: .050 inches/pass  
Grinding Fluid:  $\text{KNO}_2$ , 5% solution



Surface Grinding D-31 Columbium Alloy, 217 BHN  
Effect of Down Feed

Wheel Grade: See Below  
Wheel Speed: 2000 feet/minute  
Cross Feed: .050 inches/pass  
Table Speed: 40 feet/minute  
Grinding Fluid: KNO<sub>2</sub>, 5% solution



Surface Grinding D-31 Columbium Alloy, 217 BHN  
Effect of Cross Feed

Wheel Grade: See Below  
Wheel Speed: 2000 feet/minute  
Down Feed: .001 inches/pass  
Table Speed: 40 feet/minute  
Grinding Fluid:  $\text{KNO}_2$ , 5% solution

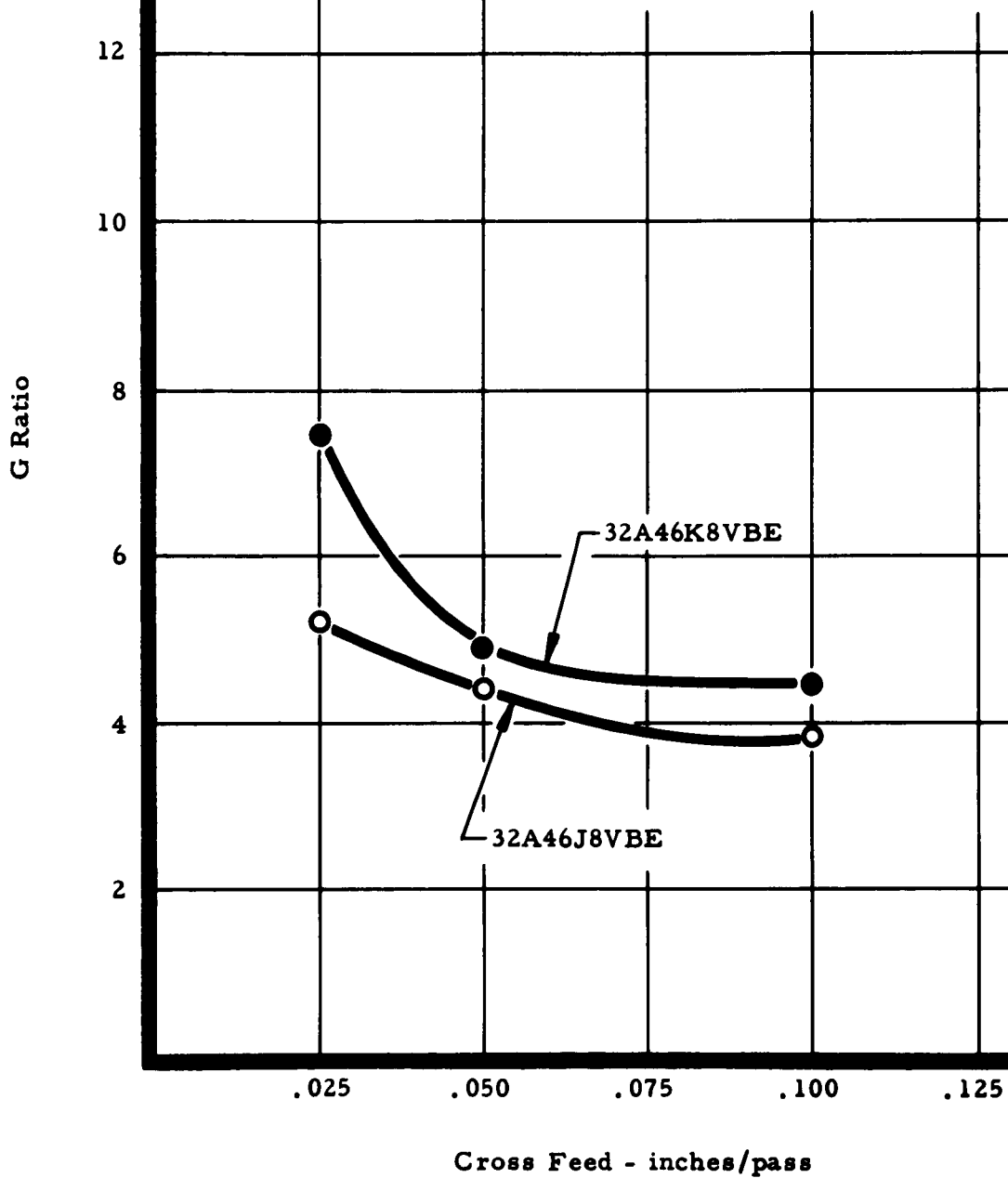


**TABLE I**  
**RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING**  
**TZM MOLYBDENUM - 217 BHN**

| Operation               | Tool Material | Tool Geometry                                                    | Tool Used for Tests                | Depth of Cut inches | Width of Cut inches | Feed in/rev   | Cutting Speed ft./min. | Tool Life    | Wear-land inches | Cutting Fluid      |
|-------------------------|---------------|------------------------------------------------------------------|------------------------------------|---------------------|---------------------|---------------|------------------------|--------------|------------------|--------------------|
| Turning                 | C-2 Carbide   | BR: 0° SCEA: 15°<br>SR: 20° ECEA: 15°<br>Relief: 5°<br>NR: 1/32" | 5/8" square brazed tool bit        | .030                | -                   | .009 in/rev   | 450                    | 25 min.      | .010             | Soluble Oil (1:20) |
| Turning                 | C-2 Carbide   | BR: 0° SCEA: 15°<br>SR: 20° ECEA: 15°<br>Relief: 5°<br>NR: 1/32" | 5/8" square brazed tool bit        | .060                | -                   | .009 in/rev   | 350                    | 20 min.      | .010             | Soluble Oil (1:20) |
| Face Milling            | T-15 HSS      | AR: 0° ECEA: 10°<br>RR: 20°<br>CA: 45°<br>Clearance: 15°         | 4" diameter single tooth face mill | .060                | 2                   | .010 in/tooth | 100                    | 70 in/tooth  | .015             | Soluble Oil (1:20) |
| Face Milling            | C-2 Carbide   | AR: 0° ECEA: 5°<br>RR: 0°<br>CA: 45°<br>Clearance: 10°           | 4" diameter single tooth face mill | .060                | 2                   | .005 in/tooth | 350                    | 100 in/tooth | .015             | Soluble Oil (1:20) |
| End Mill Slotting       | T-15 HSS      | Helix Angle: 30°<br>RR: 10°<br>Clearance: 10°<br>CA: 45°         | 3/4" diameter 4 tooth HSS end mill | .125                | .750                | .004 in/tooth | 190                    | 78 inches    | .012             | Soluble Oil (1:20) |
| End Mill Peripheral Cut | M-3 HSS       | Helix Angle: 30°<br>RR: 10°<br>Clearance: 10°<br>CA: 45°         | 3/4" diameter 4 tooth HSS end mill | .125                | .750                | .004 in/tooth | 190                    | 142 inches   | .012             | Soluble Oil (1:20) |

TABLE I (continued)  
RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING  
TZM MOLYBDENUM - 217 BHN

| Operation | Tool Material | Tool Geometry                                | Tool Used for Tests                          | Depth of Cut inches | Width of Cut inches        | Feed in/rev | Cutting Speed ft./min. | Tool Life holes        | Wear-land inches | Cutting Fluid          |
|-----------|---------------|----------------------------------------------|----------------------------------------------|---------------------|----------------------------|-------------|------------------------|------------------------|------------------|------------------------|
| Drilling  | M-33 HSS      | 118° plain point<br>7° clearance angle       | .250" diameter drill<br>2-1/2" long          | 1/2" thru hole      | -                          | .005 in/rev | 150                    | 68 holes               | .015             | Highly Chlorinated Oil |
| Reaming   | M-2 HSS       | Helix Angle: 0°<br>CA: 45°<br>Clearance: 10° | .272" diameter<br>6 flute<br>chucking reamer | 1/2" thru hole      | .010" depth on hole radius | .015 in/rev | 60                     | 51 holes               | .012             | Highly Chlorinated Oil |
| Tapping   | M-10 HSS      | 4 flute plug<br>75% thread                   | 5/16-24 NF tap                               | 1/2" thru hole      | -                          | -           | 70                     | 100 <sup>+</sup> holes | -                | Highly Chlorinated Oil |
|           |               |                                              |                                              |                     |                            |             |                        |                        |                  |                        |

#### SURFACE GRINDING

| Wheel Grade | Grinding Fluid               | Wheel Speed feet/minute | Table Speed feet/minute | Down Feed inches/pass | Cross Feed inches/pass | G Ratio |
|-------------|------------------------------|-------------------------|-------------------------|-----------------------|------------------------|---------|
| 32A46N5VBE  | 5% KNO <sub>2</sub> Solution | 2000 <sup>*</sup>       | 40                      | .001                  | .050                   | 25      |
| 32A46L8VBE  | 5% KNO <sub>2</sub> Solution | 4000                    | 40                      | .001                  | .050                   | 13      |

\* If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

**TABLE II**  
**RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING**  
**D-31 COLUMBIUM ALLOY, 207 BHN**

| Operation         | Tool Material | Tool Geometry                                                  | Tool Used for Tests                 | Depth of Cut inches | Width of Cut inches | Feed in/rev   | Cutting Speed ft./min. | Tool Life                | Wear-land inches | Cutting Fluid          |
|-------------------|---------------|----------------------------------------------------------------|-------------------------------------|---------------------|---------------------|---------------|------------------------|--------------------------|------------------|------------------------|
| Turning           | M-2 HSS       | BR: 0° SCEA: 0°<br>SR: 20° ECEA: 5°<br>Relief: 5°<br>NR: 1/64" | 5/8" square solid HSS               | .030                | -                   | .005 in/rev   | 60                     | 40 <sup>+</sup> min.     | .030             | Soluble Oil (1:20)     |
| Turning           | C-2 Carbide   | BR: 0° SCEA: 0°<br>SR: 20° ECEA: 5°<br>Relief: 5°<br>NR: 1/64" | 5/8" square brazed tool bit         | .030                | -                   | .005 in/rev   | 300                    | 40 <sup>+</sup> min.     | .010             | Soluble Oil (1:20)     |
| Face Milling      | Super HSS     | AR: 0° ECEA: 5°<br>RR: 20°<br>CA: 45°<br>Clearance: 10°        | 4" diameter single tooth face mill  | .030                | 1-1/2               | .010 in/tooth | 135                    | 50 <sup>+</sup> in/tooth | .016             | Highly Chlorinated Oil |
| Face Milling      | C-2 Carbide   | AR: 0° ECEA: 10°<br>RR: 10°<br>CA: 45°<br>Clearance: 10°       | 4" diameter single tooth face mill  | .030                | 2                   | .010 in/tooth | 150                    | 90 in/tooth              | .016             | Highly Chlorinated Oil |
| End Mill Slotting | T-15 HSS      | Helix Angle: 30°<br>RR: 10°<br>Clearance: 10°<br>CA: 45°       | 1/2" diameter 4 tooth HSS end mill  | .060                | .500                | .003 in/tooth | 100                    | 200 <sup>+</sup> inches  | .008             | Highly Chlorinated Oil |
| Drilling          | M-1 HSS       | 118° plain point<br>7° clearance angle                         | .125" diameter drill<br>1-7/8" long | 1/8" thru hole      | -                   | .005 in/rev   | 75                     | 175 <sup>+</sup> holes   | .008             | Highly Chlorinated Oil |

**TABLE II (continued)**  
**RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING**  
**D-31 COLUMBIUM ALLOY, 207 BHN**

| Operation | Tool Material | Tool Geometry                             | Tool Used for Tests                          | Depth of Cut inches | Width of Cut inches        | Feed in/rev | Cutting Speed ft./min. | Tool Life | Wear-land inches | Cutting Fluid          |
|-----------|---------------|-------------------------------------------|----------------------------------------------|---------------------|----------------------------|-------------|------------------------|-----------|------------------|------------------------|
| Reaming   | M-2 HSS       | 10° RH Helix<br>CA: 45°<br>Clearance: 10° | .213" diameter<br>6 flute chucking<br>reamer | 1/2" thru hole      | .010" depth on hole radius | .005        | 125                    | 105       | .012             | Highly Sulphurized Oil |
| Tapping   | M-10 HSS      | 2 flute chip driver tap<br>75% thread     | 1/4-28 NF tap                                | 1/2" thru hole      | -                          | -           | 12                     | 50 holes  | -                | Highly Chlorinated Oil |
|           |               |                                           |                                              |                     |                            |             |                        |           |                  |                        |
|           |               |                                           |                                              |                     |                            |             |                        |           |                  |                        |

**SURFACE GRINDING**

| Wheel Grade | Grinding Fluid               | Wheel Speed feet/minute | Table Speed feet/minute | Down Feed inches/pass | Cross Feed inches/pass | G Ratio |
|-------------|------------------------------|-------------------------|-------------------------|-----------------------|------------------------|---------|
| 32A46K8VBE  | 5% KNO <sub>2</sub> Solution | 2000*                   | 40                      | .0005                 | .025                   | 7.5     |
| 32A46K8VBE  | 5% KNO <sub>2</sub> Solution | 4000                    | 40                      | .001                  | .050                   | 4.5     |

\*If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

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| <p>AD</p> <p>a better than average potential for success in edge trimming 6Al-4V titanium sheet and 15-7 Mo sheet in the 500 to 2500 ft./min. cutting speed range. Drilling tests have been made using the Tornetic drilling unit and a constant speed drill press on D6AC steel in the 54-58 R<sub>C</sub> hardness range. Tapping test results on B-120VCA titanium at 400 BHN are presented comparing the Tornetic tapping data with conventional tapping. Machining test data is also presented on B-120 titanium, TZM molybdenum, and D-31 columbium alloy.</p> | <p>UNCLASSIFIED</p> |
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