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#### MACHINING

#### TECHNIQUES AND PROCEDURES FOR

URANIUM, GRAPHITE, TITANIUM, ZIRCONIUM, THORIUM,  
TANTALUM, BERYLLIUM, BISMUTH, LITHIUM, AND STELLITE

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### INTRODUCTION

This report is an attempt to compile various techniques that have been developed by many investigations in the machining of several materials. It should be pointed out that because of many variables involved, tests were not run under exactly equivalent conditions and results may not necessarily coincide. Several different combinations of feeds, speeds, cutting angles, coolants, etc. have been reported as being satisfactory in the process of machining similar items.

Factors which should be considered in judging machinability are: speed with which a metal may be removed, length of life of the cutting tool, amount of heat developed by the cutting operation and surface finish required on the machined parts.

The machine itself has a very definite effect on machinability. When machines are solid, rigid, and in good condition, rapid machining is more easily accomplished than on old machines with loose bearings and guides. Lack of rigidity in machines tends to make the tools chatter, decreasing machinability and shortening tool life. Vibration of the machines should be minimized as this can, and frequently does, cause chatter at particular speeds. The tool life is considerably reduced. Power requirements of the machine is an important consideration. Many machines are underpowered, which decreases the possibility of using increased feeds and speeds which may be necessary for optimum machining conditions.

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As the cutting tool is forced into the metal, heat is developed at the point of cutting. Excessive temperature may tend to warp the machined parts and also have a detrimental effect upon the tools. Coolants and lubricants, therefore, are necessary to dissipate the heat. The proper coolant and lubricant permits increased machining speed, increases tool life and improves the finish of the machines surfaces.

Cutting tools must be shaped with accuracy and skill because only a few degrees difference in cutting edge angles will make a marked change in the ease with which metal can be removed, and minimize friction and abrasion as far as possible. The tool surface finish can be an important factor from the standpoint of friction of chip and work piece against tool faces.

Although uranium metal can be handled with a minimum danger insofar as external radiation is concerned, the hazards of contamination are always present. It is important, therefore, that employees working in areas that might become contaminated are afforded maximum protection against this hazard.

A frequent survey should be made of all equipment of the operator (clothing, protective glasses, gloves, etc.), the machines, and surrounding area in order to determine the extent of radioactive contamination collected. This survey should be conducted by a competently trained inspector who is suitably equipped for the purpose.

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## I. MACHINING OF URANIUM

### 1. Characteristics of Uranium

Uranium is a comparatively soft metal with a hardness of approximately 85-95 Rockwell "B" but it is very tough and abrasive. Consequently, tool life is much shorter when machining uranium than when machining carbon steels. A large amount of heat is generated by the cutting tools which further decreases tool life.

Uranium machines somewhat like austenitic stainless steel, work hardening under a tool and becoming difficult to cut unless the depth of cut is fairly heavy. Tool failure comes from wear at the tool point instead of cratering and fracture behind the cutting edge. Machinability of uranium varies from lot to lot; even different sections show hard and soft sections. This has been attributed largely to the presence of iron.

Rates of feeds and speeds are determined by depth of cut and it appears characteristic of uranium that a cutting tool will have a longer life under a heavy cut and fast feed than under a light cut and slow feed. Less surface abrasion and generation of heat is developed in removing the heavy cut than several light cuts. However, uranium distorts readily upon machining. Light finishing cuts and an ample supply of coolant are desirable to reduce the distortion to a minimum. It can be seen, therefore,

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that a compromise between the two effects is necessary in order to obtain the most effective feed and speed rate.

When machining uranium, the chip will burn rapidly due to the heat generated by the cutting tool. To prevent this, a generous amount of coolant should be used on the cutting tool and the work. However, there are some instances when it is not desirable to use a coolant. Uranium can be machined with a smooth but not a slick finish. Great care must be taken to prevent burning of the finished surfaces and to adjust cutting speed to reduce the oxidation rate and to eliminate sparking. It should be possible to operate a lathe with no or very infrequent sparking. The air contamination rate with proper operation should be low if fires are to be avoided and chips should fall into the coolant at the bottom of the lathe to prevent burning. Turnings should not be allowed to accumulate under the lathe but should be raked away frequently and deposited in a drum.

## 2. Rod Straightening

A Medart straightening machine has been employed for the purpose of producing straight uranium bars. Each bar was passed through the roller several times (up to four) depending on its condition. A coating of L. S. Cutting Base Gulf "A" oil was applied to the rotating bar with a brush to prevent escape

of the uranium oxide dust into the atmosphere. Approximately 36 bars could be processed in three hours. The recovery of slugs was materially increased by first straightening the rods and it was possible to obtain a roughing cut much closer to the final diameter of the slug than that called for in the specification. (6)

### 3. Turning of Uranium

The cutting speed is governed principally by the kind of tools used, the feed and depth of cut, the cooling medium used and the size and condition of machine.

Tungsten carbide tipped tools have been used successfully.

Recommendations for tool grinding have been given as follows:

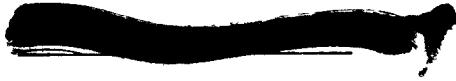
0°	back rake
0°	side rake
10°	side relief
15°	secondary relief
1"	to 1/16" nose radius
<u>32</u>	

The cutting speed was reported as approximately 130 ft/min and the feed was .010" - .012" per rev., which prevented the cutting tool from riding on the surface as uranium work hardens rapidly. (5)

For finish turning the cutting speed was increased slightly (130-150 ft/min) and the feed reduced to .003" - .004" per rev.

The same type tool used for roughing was used and ground identical with the exception of the nose radius which was increased slightly (1" to  $3/32"$ ). (5)

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Roughing slugs consisted of rough turning and cutting off the slugs in a 2 5/8" six spindle automatic screw machine made by Cone Automatic Machine Company, Windsor, Vermont. Collets of bronze were provided to prevent sparking. Cutting tools were carbide-tipped as the high speed steel cutters would not stand up to excessive abrasive action of uranium and the high heat developed. The particular grade used was Kennametal #6 - 3T40. Other machining conditions reported were:

78 surface ft/min  
238 r.p.m.  
0.019" feed per rev. tool slide  
0.005" feed per rev. cross slide

Tools were reground every 2000 pieces.(6)

Slugs have been produced using a #1 Acme turret lathe with Kennametal tools which were ground with a 7° cutting angle, a 5° rake with the tool set on center. The tip had sharp-stoned edges and it was claimed that any radius will give a tapered or out-of-round slug. (3)

Heavy rough cuts have been made effectively on a Medart Rough Turner, a machine used in roughing down stainless steel bars. The uranium bars were 9 feet long. The machine works on the principle of a firmly held, fixed bar being fed slowly through a revolving cutter head. This is armed with one or two sets of tools, four tools to a set, 90° apart and takes a deep, rough

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cut as the bar slowly passes through the machine. Tool wear was very high when it was used on uranium bars. Much of the operator's time was spent in changing and setting tools. A deep, continuous cut was taken on the length of the bar. (3)

Tantung has been recommended for rough turning and tungsten carbide tool bits for finishing.

American Machine & Foundry reported machining uranium on a Warner Swasey #3 Turret Lathe using Kennametal K3H grade carbide tools with a surface speed of 280 ft/min. The spindle speeds and feeds were given as:

	<u>Spindle Speed</u>	<u>Feed</u>
Turning	740 rpm	0.018 in/rev.
Facing	"	0.004 in/rev.
Radius	"	hand fed
Cutting off	"	0.0025 in/rev.
Cycle time -	4 min/piece	(1)

At Iowa State College, experiments on machining resulted in machining uranium in two steps: a heavy roughing cut and a light finishing cut. For the heavy cut the depth of cut was about 0.080", rate of feed 0.0065"/rev and the speed 300 rev/min or 118 ft/min. Everything was the same for the light cut except the depth of cut which was about .020". Carboloy tipped tools were used for both cuts. Various grades of Carboloy tips were used and good results were obtained with No. 883. No. 78B fractured badly; No. 44A was fair; and No. 831 was fair, but had

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a tendency to crater. Tools made from high speed steel gave good results for the roughing cut but were unsatisfactory for the finishing cut. The finishing cuts were often made at 600 rpm instead of 300 rpm. Good results and unoxidized turnings were obtained at both speeds. Heavy feeds during the roughing cuts tended to reduce the chattering. (4)

Machined slugs were also prepared using No. 883 Carboloy. The diameter was reduced in one cut from 1 1/16" to .997". The tool was ground in the following manner:

8°	side rake
5°	top rake
0.015" - 0.025"	radius of nose
480	rpm
0.010"	feed
135	ft/min surface speed

X slugs were machined in one cut using a spindle speed of 540-600 rpm, tool feed of 0.010"/rev. Spindle speed of cut-off operation is the same but with a tool feed of 0.005"/rev. A production rate of 17-20 slugs/hr. was the best record obtained in that set-up.

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4. Parting

For accurate cutting, the lathe tool has been used in production and found to be satisfactory. A speed of 60-100 ft/min for .050" cut has been successfully used. Advantages listed for the operation were: excellent scrap recovery was obtained as the turnings were clear; no sparking or fire occurred; a close tolerance was obtained; operation was performed at high speed with very low air contamination. The disadvantages were: a comparatively long set up time was necessary except for repetitive operations; large quantities of coolant were used but this was easily applied and controlled. (2)

5. Power Sawing and Cut-Off

The high tension to which common hacksaw blades must be tightened for sawing uranium causes them to break very readily. Many types of high speed blades were tested and only one was found to be satisfactory - the Marvel High Speed Blade #1404 and #1406. Blades having four or six teeth to the inch were found to be most satisfactory. The Marvel Blade is constructed of two kinds of metal. The body of the blade is a special tough alloy which is quite flexible and has a very high tensile strength. To this body a hard, brittle, tungsten alloy cutting edge is welded having the same coefficient of expansion. The average blade will cut through about 150 sq. in. of uranium metal before failure. When it was mounted in a Peerless High-Speed Hacksaw, a rod 4.25" D was cut through in about four minutes. An

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emulsion-type water-soluble cutting oil called Superla was used. The most rapid and satisfactory cutting was obtained by using high pressures on the force feed of the hacksaw at high speed. It is necessary to cut the metal in this manner since the material work hardens rapidly and slower rates cause a hard, tough surface. Hydromite, a true water-soluble fluid was found superior to Superla, an emulsion type water soluble oil. Later studies have shown that lard or mineral-oil-type cutting fluids are superior to the aqueous types. In addition to giving better results, the fire hazard from moist saw chips was eliminated. (4)

The power hacksaw is used extensively for rough cutting of rectangular as well as round shapes. These have been cut successfully as follows: 48 strokes/min; stroke - 6" to 8"; cutting speed - 1/2 to 1 sq in/min depending on the sharpness of the saw. Relatively infrequent sparking developed in the cutting. Results showed a fair chip recovery and very low air contamination. A fairly clean cut and no burning of the piece occurred. (2)

It was found that Gulf Lard Sulfur Base "B" cutting oil has proved to be the best hacksaw coolant for uranium. A three tooth per inch hacksaw blade has proven to be the best after many tests. There has been an average of at least 150 square inches of uranium cut per blade using this set-up.

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Cutting of uranium bars have also been made in a circular saw. Material up to 5" diam. has been cut with a 2 ft. diam. blade as follows: 15 surface ft/min; blade - 1/4" thick; and 0.030" side clearance. This method was rapid; no sparking was obtained; very low air contamination resulted; moderately close tolerance was obtained on any size stock with a low setup time. Coolant was easily applied and no local ventilation was required. A disadvantage of this method is the high initial cost of equipment. Results have also indicated a high percentage scrap. (2)

Abrasive cut off wheels (including "Cutamatic") have been used in trimming uranium stock. Diameter of wheels have been 12" to 18" with a speed of 1800 to 3600 rpm. Advantage of this was the rapid speed of cut obtainable. Disadvantages were: the cut has a tendency to draw; wheels have broken slowing operation and introducing a safety hazard. Large volumes of coolant of soluble oil and water were necessary. Fumes and excessive atmospheric dust contamination developed which required carefully designed exhaust hoods and large quantities of air. Burning of the piece occurred and there was very poor chip recovery. The work had to be securely clamped. (2)

## 6. Shaping

A standard shaper was used following regular shop procedures in shaping uranium. Guts of 1/8" were made without any noticeable sparking and with low air contamination. The cutting speed for shaping varied from 40-50 ft/min depending on: the tools used, the feed, the depth of cut, and the rigidity of the machine.

  
Roughing - feed 0.020" to 0.030"  
Finishing - " 0.005" to 0.010"

Tungsten carbide tipped tools were used. Recommendations for grinding of the tools were:

0° back rake  
0° - 10° side rake  
10° side relief  
10° front relief  
15° secondary relief  
1/16" nose radius

The tool was well supported on the work to reduce chattering and tool breakage. Cutting oil was used in the work to increase tool life and to obtain a better surface finish. (5)

#### 7. Milling

Good results have been obtained for both rough and finish milling with cutters up to 12" diameter. (2)

Speed and cutting rate are very important factors governing the quantity of chip burning and rate of air contamination. At tool speeds representing a peripheral velocity of 150 FPM (96 RPM using a 6" cutter) and a 1" feed, enough burning of chips occurred to require the constant attendance of the machinist to daub out the fires and to keep the chips under the coolant. (2)

At velocities of 100 RPM or less, sparking was very occasional with coolant quantities in the neighborhood of 10 gpm. Any increase in peripheral tool speed above 150 RPM resulted in almost continual burning of chips and a high air contamination.

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It appeared that from the standpoint of machinability, scrap recovery, and air contamination, a deeper cut at a slower speed was advantageous. This gave a more massive chip, which burned less easily, and also undercut the hard case formed by the previous cut. (2)

Carbide tipped milling cutters were used for milling uranium as abrasion dulls high speed cutters rapidly. (5)

High speed steel cutters have been used, with a cutting speed of 30-50 ft/min. With carbide tipped milling cutters, a cutting speed of 100-175 ft/min was used successfully. The rate of feed depended very much upon the rigidity of the machine, the depth of cut, and the surface finish desired. Recommended feeds reported were from 0.003" to 0.008" per tooth per rev. A sufficient supply of coolant composed of soluble oil and water was directed upon the milling cutter and the work. (5)

A full length slot was machined in the uranium slug on a Van Norman milling machine #118 with hydraulic feed. The machine was equipped with a special jig holding two slugs. The spindle speed used was 137 rpm using 3" diameter slitting saws with a feed of 6"/min. The width of the slot was  $0.0625 \pm 0.002"$  and the depth was  $0.073 \pm 0.002"$  until this was changed to  $0.015 \pm 0.002"$ . The coolant used was L. S. Gulf cutting oil "A". The cutters were 3" O. D. by 1/16" x 1" bore Union M103 high

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speed steel. Cutters were designed for cutting both on the front and sides of the teeth, but, because of abrasion, they were only satisfactory after treatment by deep freezing at - 120°F. for a period of two hours. With this treatment, the cutters were good for approximately 400 slugs/treatment. There was no burning or oxidation of chips. The chips were considered to be too fine for safe storage and therefore were burned in a special incinerator. Considerable difficulty had been experienced in attempting to find Carboloy cutters as thin as required, and it was feared that brittleness would render them impracticable. Carboloy tools for this operation were also considered very costly. (6)

#### 8. Drilling

Composition and hardness of material, depth of hole, lubricant used, type of machine used, condition of machine, grinding of the drill, and quality of the finish desired have a distinct influence on the speed at which a drill should be run. For high speed steel, recommendations have been to use a peripheral speed of 50-70 ft min and a feed as follows:

0.001" - 0.002"/rev. for drills smaller than 1/8"  
0.002" - 0.004"/rev. for drills 1/8" - 1/4"  
0.004" - 0.007"/rev. for drills 1/4" - 1/2"  
0.007" - 0.015"/rev. for drills 1/2" - 1"  
0.015" - 0.025"/rev. for drills larger than 1"

Constant feed once the drilling has started has given the best results. High speed drills to as low as #60 have been used for drilling 2"-deep holes. (5)

Tantung tipped flat drills have been used fairly successfully. It has been shown that the cutting ability of the drill is controlled more by the thickness of its web than by the material from which it is made. Results indicated that it was desirable to have the web of the drill ground as thin as possible with an included angle of about  $135^{\circ}$  at the point. The web thickness varied with the diameter of the drill and, for best results, was tried at various thicknesses.

In drilling small holes, it was found to be helpful to heat the metal to  $150^{\circ}\text{C}$ . and to use a drill speed of 100 rpm on a sensitive-touch drill press with no lubrication. With larger drills, just enough coolant was used to keep the drill from burning, but the work was not flooded with the coolant. A mixture of soluble oil and water was found to be a satisfactory cooling medium and lubricant when drilling uranium. (5)

High speed drills have been used since carbide-tipped drills chipped readily. This was especially true when the operation consisted of enlarging holes with a drill. The hole was drilled to the correct diameter with one drill instead of using a small drill first and then progressively larger drills to attain the required size. This reduced chattering and consequently increased the life of the drill between grinding. (5 )

The drill was ground with a lip clearance of  $12^{\circ}$ . The point angle was  $59^{\circ}$  with the axis of the drill. The rake angle, the angle

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of the flute in relation to the work, was increased to 90°. Because of the enlarged rake angle, the chip did not curl in the conventional manner.

The same procedure was followed for deep hole drilling with the exception of feed and speed. The cutting speed was decreased slightly and the feed was increased slightly. (5)

It has been found that, using an air blast instead of oil in drilling small holes, the cutting speed increased up to 50 percent. Additional precautions found necessary were to hood and exhaust the area properly. (28)

Drilling operations have some inherent technical difficulties which required careful handling. There was apt to be some distortion of the hole; this was overcome by good technique. It was necessary to keep the hole free of cuttings. The coolant used was of such a viscosity as to allow penetration to the bottom of the hole. Holes up to 1" in diameter have been drilled in this manner at speeds of about 700 rpm. (2)

#### 9. Boring

The cutting speed used for boring uranium was approximately 100-120 ft/min depending on the rigidity of the boring tool, feed, depth of cut, and surface finish required.

Tungsten carbide tools were used and supported as rigidly as possible. A feed of 0.002" to 0.006" per rev. was found to be satisfactory. (5)

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Recommended grinding of the tools have been given as:

0° back rake  
0° side rake  
10°-15° side relief  
10°-15° front relief  
20° secondary relief  
1/32" nose radius

An ample supply of coolant was directed upon the tool to prevent the temperature from becoming excessively high and to prevent burning. A mixture of soluble oil and water was found to be a satisfactory coolant. (5)

#### 10. Reaming

A comparatively slow cutting speed was used for reaming uranium. A surface speed of 20-30 ft/min was found to be satisfactory. The feed varied with the size of the reamer from approximately 0.002"/rev. for a 1/8" reamer to 0.015"/rev. for a 1" reamer. A tungsten-carbide tipped reamer withstood the abrasive action of the metal for a much longer period of time than a high speed steel reamer.

A mixture of soluble oil and water was used freely upon the reamer and the work. (5)

#### 11. Threading and Tapping

Uranium was threaded quite readily with a single point tool, but it was very difficult to tap. For a single point threading tool, the cutting speed was about 1/2 the cutting speed for turning. The feed was sufficient to allow the tool to cut, for if the

tool was allowed to travel in the groove without cutting, it burnished and hardened the sides of the threads so that on the next cut the tool dug in and tore the thread or broke the tool. No coolant was used on the work or on the tool.

Deburring was accomplished manually by means of files or other hand tools.

Tapping was found to be very difficult and was done slowly by hand. A paste of acetylsalicylic acid and water was used as a lubricant. Heating the uranium made tapping easier to perform. (5)

Small holes, small slots, odd shapes (including tapping) are best achieved by using the Method "X" process which is a patented process owned by Firth Sterling Steel Company. Elox Corporation of Michigan has a process called Arc Machining which is essentially the same as Method "X". (29 to 36)

## 12. Grinding

Centerless grinding, the grinding of rods and slugs which are not held between fixed centers have been used on uranium since the first rods were extruded. By using a grinding wheel, stock was removed evenly from a bar, out-of-round bars were rounded, and taper was removed from semi-finished slugs. Grinding has been done on No. 3 Cincinnati Centerless Grinders. (For description and pictures of process, see Colvin and Stanley - "Grinding Practice") (3)

A heavy flow of coolant (same as used in machining) was maintained over the wheel surface during grinding to prevent burning of the bar surface. At the end of each shift, the coolant tank was emptied, grindings were removed and stored in an open metal container which was kept outside of buildings. If grindings and contaminated solutions were not removed every eight hours, there was a danger of fire and hydrogen explosions in the machine during operation.

Wheels used successfully for grinding were 46/60 grit SiC bonded Corex wheels from Safety Grinding Co., Springfield, Ohio, for rough cutting, and 80 grit SiC bonded wheels from Carborundum Co. for finishing. (3) Vitrified carborundum wheels with a 6" face were found unsatisfactory. A #2 Cincinnati Centerless Grinder has been reported to operate successfully. (6)

Slugs were ground under a continuous flow of coolant using an 8" feed-through mechanism. Attempts were made to use oil as a coolant to avoid water and generation of hydrogen by the fine uranium particles. The use of both high and low flash-point oils, however, proved successful; the fog of oil resulting from the centrifugal effect of the wheel was invariably and quickly converted to a wreath of flame by the abraded uranium particles. The use of water-soluble coolants became necessary. (6)

The original water-soluble oil tried was "Cimcool", which did not produce a good finish. The next oil tried was "Silver Chip" (Machinery Lubricant, Inc., Boston) which proved satisfactory. Texas Co. Soluble Oil D was tried and used thereafter with good results. The original mixture was 50% soluble oil and 50% water,

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but this proved to be too rich a mixture. It was later reduced to seven gallons of soluble oil per 100 gallons of water, to which 1/2 gallon of kerosene was added.

The presence of water with uranium grindings rendered the operation hazardous with respect to fire, which necessitated cleaning the grinding immediately at the end of each day's run. The grindings, well covered with water in the coolant settling tank, were cleaned and burned twice weekly. It is extremely important that damp grindings be burned as soon as possible. One fire occurred when such grindings consumed the water content of the bucket in which they were stored (for two days) and ignited by spontaneous combustion. Fortunately, the fire did little damage, but probably did deposit some oxide throughout the work area. With this exception, all grindings were quickly burned to oxide in an incinerator. (6)

For cylindrical grinding, the peripheral speed of the wheel used was between 5500 and 6500 ft/min and, for surface grinding, from 4000-6000 ft/min. There are a number of factors, such as finish desired, amount of material being removed, rigidity of machine, type of wheel, etc. which determined the proper wheel speed; hence, the speed was varied to suit the conditions. A surface speed of 25 ft/min was found to be suitable for rough grinding, and for finish grinding the speed was decreased to 15 ft/min. (5)

For rough grinding large work with a heavy machine, use of feed of 1/2 to 3/4 the width of the wheel to each rev of the work was found to be satisfactory. A cut 0.001"-0.004" deep was used for roughing and 0.00025"-0.0005" was used for finishing.(5)

For roughing, a Norton #3824-J wheel or its equivalent was used. This is of the aluminum oxide or alundum type having a porous nature, and it is more friable than regular alundum. As a result, it had a cool cutting and almost self-dressing action. It is made with a vitrified bond, and the grain size is coarse. The wheel is soft, which reduces the "loading or clogging" of the wheel. For finishing, the same type wheel was used, with the exception of grain size. A finer grain size, #46, was found to be satisfactory. An ample supply of coolant of soluble oil and water was used.(5) This system of grinding performed by H.K.Ferguson Co.

for B.N.L. proved satisfactory and time saving. When the abrasive wheel was only 6" wide, the system initially was not satisfactory. This width was not sufficient to attain the desired uniformity of diameter between different slugs or between the two ends of the same slugs. In this case it was necessary to place the slugs in the grinder individually.

The initial rest bars upon which the slugs rotated were of mild steel, hardened steel, and chilled cast iron. These surfaces proved unsatisfactory. They, together with the rather hard abrasive wheel first used, set up a high frequency vibration of the

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of the slugs, evidenced by "squealing". These factors contributed to the production of oval-shaped slugs, multiple-sided slugs with burned surface areas caused by excessive localized friction, and a complete lack of uniformity in results. The harder vitrified-bond abrasive wheel first used also loaded itself with the rather ductile or malleable uranium, causing the wheel to lose its cutting qualities and causing its grinding face to lose its contour. This necessitated frequent and almost prohibitive redressing to maintain a fresh cutting surface.

To offset the above faults, softer wheels which were able to shed thin grit and continually to present fresh cutting surfaces were bought. The Norton Co. supplied 6" face resin-bonded Alundum A4615B5. This material proved to be quite an improvement, but was slightly harder than desired. The Norton Co. also supplied 6" face Crystolon 37C46J5B5. The wheel was satisfactory in every way. It was fast cutting, did not load with uranium, and maintained its contour with little dressing. This type wheel wore rather rapidly, which was, of course, expected. Feed wheel were Norton Co. Alundum A60R0R30.

Having established the desirability of the softer wheel, the grinding operation was again set up for continuous or "through feed" with new wheels having 8" face Norton Co. No. 37C46K5B5 and No. 37C46L5B5 material. The former wheel gave a better finish to the slugs than the latter type of wheel. It was stated previously that Norton Crystolon 37C46J5B5 proved satisfactory in

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every way as the type grinding wheel eventually used. The surface speed of the wheel was 5000-6000 ft/min. The speed of the work was varied from 6" to 3.3 ft/min, depending on depth of grind.

A supply of rest bars, upon which the slugs rotated, made of soft cast iron were substituted for the hard ones previously used, and worked fairly satisfactorily. (6)

### 13. Lubricants and Coolants

A heavy flow of coolant was used in machining to prevent fires from developing from turnings. Fires were controlled by removing the turnings from the region where a glowing turning might fall and, in the case of a small fire, by quickly extinguishing it with a gallon or two of the coolant. An open top can containing the coolant was within reach of the operator at all times. The amount of sparks and, therefore, the likelihood of a turnings fire increased with the speed of machining. During cutoff operations, there was a tendency for more sparking to occur with light feeds than with a heavy feed.

No definite conclusion can be drawn about the flash points and fire points of the cutting oils other than that oils with flash points below 300°F and fire points below 350°F are undesirable and produce unnecessary fire risks.

[REDACTED]

The viscosity data do not substantiate the idea that there is a relationship between viscosity and ability of an oil to extinguish a fire. However, sticky, viscous cutting oils which adhere in thick layers are better in eliminating and cooling hot turnings. It is very likely that cutting oils with a viscosity of less than 75 SUV at 100°F are unsatisfactory. The difference in the cost of the cutting **oils** used is not very significant in comparison to the value of the material being machined.

At Iowa State College various coolants have been tested to obtain information regarding performance with uranium.

- (1) Gulf Lasupar Cutting Oil A
- (2) Gulf Lasupar Cutting Oil B
- (3) Gulf Lasupar Cutting Oil C
- (4) Gulf Electro Cutting Oil A
- (5) Gulf Electro Cutting Oil B
- (6) Gulf Electro Cutting Oil C
- (7) Gulf ML Cutting Oil A
- (8) Gulf ML Cutting Oil B
- (9) Gulf Cut-Aid
- (10) Solnus
- (11) Lard Oil
- (12) 10% Hydromite

The first nine oils were sulphurized lard oil and were recommended by the manufacturer to give a fine finish at high speeds for all kinds of machining. Grades A, B, and C differed only in viscosity.

The Electro-Cutting Oils were sulphurized mineral oil and are recommended by the manufacturer for all types of machining.

Again A, B, and C differed only in viscosity.

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The ML cutting oils represented a mineral oil-lard oil type.

Grade A and B differed in lard oil content. Cut-Aid was a light cutting oil and was recommended for Mg, Al, and other non-ferrous alloys. It was mixed with any of the first eight cutting fluids to reduce the viscosity.

Solnus was a vacuum pump oil purchased from Sun-Oil Company.

Lard Oil was purchased from Globe Machinery Co. of Des Moines, Iowa.

Hydromite was a triethanolamine salt of a chlorinated fatty acid, manufactured by Filmite Oil Corporation of Milwaukee, Wisconsin. A 10% solution in water was recommended by the manufacturer.

#### Rating of Cutting Oils at Various Speeds and Feeds

Speed, ft/min	151	209	301	415	151	204	301	415
Feed-in.	0.0036	0.0036	0.0036	0.0036	0.0056	0.0056	0.0056	0.0056
Rank								
1	LA(1)	LA(2)	LA(2)	MA(2)	EA(1)	EA(1)	LB(1)	MA(3)
2	LB(1)	LB(2)	LB(2)	LC(3)	EB(1)	EC(1)	EA(2)	LC(3)
3	EA(1)	LC(2)	LC(2)	MB(4)	LA(2)	LA(2)	EC(2)	Lard(6)
4	EB(1)	EA(2)	L(3)	L(6)	LB(2)	LB(2)	MA(3)	MB(6)
5	LC(2)	EB(2)	MA(3)	LA(6)	LC(2)	EB(2)	LA(3)	
6	EC(2)	MA(3)	EA(3)		EC(2)	MA(3)	LC(3)	
7	S(3)	EC(3)	EB(3)		MA(3)	LC(3)	EB(3)	

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8	MA(3)	L(4)	MB(4)	MB(3)	L(4)	L(4)
9	C(4)	C(4)	EC(4)	L(4)	MB(4)	MB(4)
10	MB(4)	MB(4)		C(4)	S(5)	
11	L(5)	S(5)		S(5)	C(6)	
12	H(7)			H(7)		

Ratings indicated relative brightness of turnings from machined parts.

LA - Lasupar A      EA - Electro A      MA - (ML-A)  
LB - Lasupar B      EB - Electro B      MB - (ML-B)  
LC - Lasupar C      EC - Electro C      S - Solnus  
C - Cut-Aid      H - (Hydromite 10% aqueous solution)  
L - Lard Oil (4)

Water soluble coolants have been used, including "Cimcool", for machining uranium. <sup>(24)</sup> These were used with water in varying proportions. There was some overheating and consequent burning of uranium turnings. The water in contact with uranium caused it to oxidize, and the liberation of hydrogen gas was a fire hazard. The storage of uranium turnings dampened with water was an additional hazard. Water soluble coolants were abandoned in favor of a high flash point oil coolant of high viscosity, L.S. cutting Base Gulf A. The oil met the following specification:

Gravity API	26.7
Viscosity SUV - 70°F	488
Viscosity SUV - 100°	201
Viscosity SUV - 130°	109
Viscosity SUV - 210°	50
Flash; open cup, °F	345

Fire, open cup, °F 390  
Pour, open, °F 325  
Carbon residue, % 0.56  
Sulphur B, % 2.49  
Sulphurized lard oil, % 22.00

In order to prevent firing of the turnings, the oil was circulated on all tools at the rate of 50 GPM, and the base of the machine was kept filled with 150 gallons so that the turnings were kept covered at all times. The life of tools was prolonged with the oil coolant, and a smoother cut was possible than that realized with water-soluble oil. Oil from all equipment was used over and over again after being put through settling tanks, sterilizer and centrifuge processing in order to purify it. (24)

Fire can be brought under control by smothering it with powdered graphite or dry sand. Never fight a uranium fire with water! Water will cause the fire to burn more furiously and tend to spread it over a larger area. Any radioactive contamination in the area of the fire will be spread with the water.

#### 14. Safety Precautions

It appears that machining of uranium is best done in a building designed for the job. Such a building should have a smooth-faced interior (e.g. tile) to enable washing down of contamination caused by any means. Physical obstructions such as piping etc. should be minimized. Such a building should have the necessary filter, blower, and incinerator systems.(6)

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Machines employed on such work should be assigned permanently to the task. It has been demonstrated that such machines can never be completely decontaminated, even though they (in special instances) can be cleaned to the point that the health hazard can be said to be nil and that the probability for future metal contamination is at a minimum.

Before machining uranium, certain precautions must be taken. It is imperative that the worker have eye or face protection because the chips fly about readily. The chips usually burn rapidly upon exposure in the air and can cause painful burns.

The room in which uranium is machined must be well ventilated to remove the fumes coming from the metal as it is machined. An individual suction pipe should be used to draw off these fumes directly from the work if at all possible.

The chips and scraps of uranium should be disposed of at frequent intervals. If they are allowed to accumulate in large quantities and a burning chip falls upon them, they will burn quite readily.

The following are rules and regulations formulated for uranium machining areas by the Atomic Energy Commission, Oak Ridge National Laboratory, and Brookhaven National Laboratory. (6)

Health Physics Rules and Regulations

1. GENERAL

A. Application of Regulations

- (1) Installations performing operations involving

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radioactive material shall establish procedures and practices that will insure maximum safety for all employees. The provisions of this part (Part 14 of AEC Standard Safety Requirements No. 3) are based on established safe practices, and any rules adopted shall be consistent therewith.

B. Enforcement

- (1) It shall be the duty of management and supervision to enforce meticulous compliance with established rules and procedures.

2. TOLERANCES (Maximum permissible exposure)

A. Personal Monitoring

- (1) All persons entering areas of potential radioactivity, or handling, or transporting radioactive material, shall wear personal monitoring instruments, e.g., film badge meters. This applies to visitors as well as working personnel.
- (2) Film badge meters shall not be tampered with in any way, nor used for any purpose other than personnel monitoring.

3. PROTECTIVE CLOTHING AND DEVICES

A. Clothing

- (1) It shall be the responsibility of the individual and his immediate supervisor to see that suitable

[REDACTED]

protective clothing and shoes are worn wherever clothing contamination is probable.

- (2) Protective clothing used in the process area is to be worn for a maximum of one day (unless determined otherwise).
- (3) Cloth hats are to be worn over the hair when in the process area.
- (4) Operating personnel are to wear overalls or coveralls in the process area.
- (5) Operating personnel are to remove their overalls or coveralls and replace these with clean coats before entering the lunch room.
- (6) Visitors may not be required to remove clothing to enter or leave the process area but must wear a coat in the process area in addition to hats and shoe covers mentioned elsewhere.
- (7) Plant shoes or shoe covers are to be worn by personnel and visitors in the process area.
- (8) A shower must be taken by personnel before leaving the plant at the end of the shift.
- (9) Leather gloves shall be worn as much as possible to reduce exposure to the hands.

B. Laundry

- (1) Laundry equipment is to be operated only by designated personnel.

- [REDACTED]
- (2) Articles having particles of metal or heavy greases or oil must not be placed in the laundry equipment.
- (3) Laundry equipment operators must take extreme care that no radioactive material is passed into the drains.

#### 4. EATING AND SMOKING

##### A. Process Area

- (1) No eating, smoking, chewing or drinking is to be permitted in this area at any time.
- (2) Cigarettes, cigars, chewing tobacco, pipes, food or drinks should be left in the uncontaminated rooms and kept out of the process area - even though not used there.

##### B. Wash Room (Laundry, Shower & Toilet Room)

- (1) Smoking may be permitted in this room on the conditions as stated below and on the condition that the door between this room and the process area is kept closed by a spring door closer (not locked or latched).
- (2) Personnel and visitors entering this room from the process area may smoke or chew after washing hands and face.
- (3) Personnel and visitors may smoke or chew in this room when entered from the lunch room.

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(4) No food is to be prepared or eaten in this room.

Drinking water from a fountain is permitted.

C. Lunch Room

- (1) Visitors and personnel must wash their hands before entering the lunch room from the process area.
- (2) Eating is to be permitted only within the lunch room.
- (3) The preparation of coffee, drinks or food and the storage of same in the area is to be allowed only on approval of A.E.C. inspectors.
- (4) No protective clothing or equipment used in the process area shall be allowed in the lunch room.
- (5) Plant shoes for use in the process area may not be worn in the lunch room unless covered with clean shoe covers.

D. Street Clothes - Locker Room

- (1) Smoking is to be permitted in this room.
- (2) No food or drinks are to be used in this room.

E. Guard Room

- (1) Smoking is to be permitted in this room.
- (2) No food or drinks are to be used in this room.

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5. OPERATING REGULATIONS

A. Service Departments

(1) Work by servicing departments in the area shall be done under the rules incorporated in this bulletin and only after the approval by authorized individuals.

B. Operating Personnel

(1) Gloves used in the area are not to be removed from the area.

(2) Gloves showing excessive radiation (as determined by meter readings) shall be discarded.

(3) Tools and equipment must not be removed from the process area until it is determined (by instrumental test) that their level of contamination will permit their safe removal. This applies to stationary and portable tools. Privately owned tools or instruments are not to be exempted from this rule. Individuals should not take private tools into the area.

6. HYGIENE

A. Personal

(1) All persons working with or exposed to radioactive material shall observe the following precautions:

(a) keep fingernails cut short

(b) wash hands thoroughly before eating, smoking or leaving the area for any purpose.

- (c) when rubber gloves are worn, they shall be washed before removing from the hands.
- (d) hands or absorbent gloves must be kept out of contaminated machine cutting coolants as much as possible.

B. General

- (1) Lockers must be kept clean. Contaminated clothes must be kept in "contaminated lockers". Clean clothes must be kept in "clean lockers".
- (2) Urinals, lavatories, showers, and all facilities shall be kept in such sanitary conditions as to encourage the requisite hygiene.
- (3) Floors in all areas shall be kept clean.
- (4) Cleaning devices used in the process area and the wash room shall not be permitted in the lunch room, street clothes locker room or the guard room.
- (5) Good ventilation shall be maintained at all times with air intakes directly from the outside of the building.
- (6) Ventilation intakes shall be located well away from the contaminated exhausts.
- (7) All solid wastes are to be collected and stored or burned as directed.

(8) There shall be no direct access between the guard room and process area in either direction. The door is to be used for emergency exit only.

## 7. MEDICAL

### A. Injuries

(1) All injuries of whatever nature or cause must be immediately reported to the supervisor in charge and the plant physician. It shall be the duty of the plant physician to keep a record of all injuries. All wounds must be dressed so as to exclude all possible entry of radioactive particles into the blood stream.

(2) All instances wherein radioactive chips or particles (of whatever size or quantity) are taken into the mouth or lodged under the skin, or in a wound, must be immediately reported to the supervisor and plant physician.

## 15. Disposal of Uranium Scrap

At Brookhaven National Lab., turnings from the automatic screw machine and the two lathes were accumulated in a metal tray, 6' square by 10" deep, and allowed to drain. A centrifuge was installed, but it was decided that the heavier film of oil left on the turnings under gravity draining gave added protection against the danger of fire,

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and the centrifuge was therefore not used regularly on the turnings. The turnings were placed in ten gallon, 16 gauge metal cans and packed tightly by means of a ram in a home made press. A metal cover with a 1/2" overlap was placed on the can. A rather loose fit was intentionally provided, and the cover was attached to the can by means of a metal strap. The purpose of this type cover and method of holding it in place was to provide for the escape of any gases which might be generated within the can, without providing a hole in the cover of the can through which water could enter during transportation or storage. The cans were 13 1/8" diameter, 18" high, and weighed 17 pounds apiece. Each can held about 125 pounds of turnings initially, but, with the aid of the vertical ram in compressing the turnings, the contents were brought up to about 160 pounds.

All crop ends, rejected slugs, and turnings heavy enough for direct reconversion into ingot without pressing through the chemical processes were segregated for shipment in their material or metallic state. Scrap in all other forms were converted into oxide. These included floor sweepings of large and fine uranium turnings, chips from the milling machine considered to be too fine for safe permanent storage, grindings from the centerless grinder in their damp or wet condition, and all trash and refuse. These were burned and converted to oxide in an incinerator. (6)

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II. MACHINING OF GRAPHITE

At Oak Ridge in machining graphite, woodworking tools were used in the roughing operations, but carbide tipped tools were employed for precision finishing. A woodworking band saw was used for slitting bulk stock into rough slabs. Before cutting, the piece was inspected to find a flat surface that could be placed against the cutting guide, which was twice as long as the piece being cut. A 3 to 6 pitch DoAll saw blade was used at a speed of 200 - 690 fpm depending upon the type and size of the piece being cut. (8)

A woodworking planer was used occasionally for removing excess stock prior to grinding, but in the majority of cases, sawing alone produced accurate blocks. In using the planer, certain modifications were necessary; for example, the bedplate and power rollers were removed and replaced by a continuous steel bedplate. This change helped to keep the material level as it passed under the cutter. Also, the metal upper rollers were covered with rubber washers to prevent chipping the surface of the material.

Even with these modifications, the woodworking planer could not be used for removing any twists and bows in raw blocks. Since pressure is applied in this machine only as the piece passes under the cutting blades, a long bow or twist would be repeated rather than removed. Therefore, the material was usually taken directly from the sawing operation to a primary sizing operation, performed on either standard surface grinding or milling machines. A Delta - Crescent wood planer

was used for shaping graphite blocks to size within a tolerance of 0.002" on cuts as deep as 7/8".

Since graphite is non-magnetic, the usual magnetic chucking method would be cumbersome because it would necessitate blocking of the graphite slabs with steel parallels. On the large surface grinder used in the sizing operation, the magnetic chuck was replaced by a fixed vacuum chuck. This chuck consisted of a hollow stub block with holes through the top plate. Suction is applied by a vacuum system which can be used by several machines at one time. The vacuum chuck is particularly valuable for grinding thin slabs upon which it is difficult to place steel parallels.

The vacuum chuck is, of course, limited to applications where the work pieces have a flat uninterrupted surface that can be acted upon by the vacuum; for parts in which holes have been machined, the magnetic chuck was often needed. It was, therefore, inadvisable to attach the vacuum chuck permanently on all surface grinding machines. Consequently, several vacuum chucks have been constructed to be held in place by the magnetic chuck so that either chucking method could be conveniently used.

As the graphite blocks came from the sawing operation, grinding of large surfaces was done on a vertical surface grinder equipped with a vacuum chuck and automatic table feed. A segmental abrasive wheel was used. Careful control of the table feed and the wheel

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speed was maintained to insure a smooth surface. In grinding to a fine finish on graphite, about 0.010" of stock was removed at a pass, using a feeding rate of 0.005"-0.020" per rev and maintaining a tolerance of plus or minus 0.001".

The grinding wheel was dressed in a manner peculiar to the Oak Ridge shop. The wheel used originally had a cutting surface 2" wide. At speeds and feeds selected for a good surface finishes, enough heat was generated in the graphite to distort the chuck. To stop the excessive heating and continue operating at efficient speeds, the cutting surface of the wheel was reduced to a width of 1/4" after dressing the wheel square. A 45° cut is taken on the entire inside circumference of the rim, leaving 1/4" cutting surface on the outside of the wheel.

Two sides of the graphite block were ground parallel to each other, and one of the other sides was then squared. As in most squaring operations, a 90° angle plate was used. The plate was clamped to a vacuum chuck or placed on a magnetic chuck, depending upon the machine used for grinding. The graphite block was then clamped to the angle plate in such a way that a small amount of stock extends above the plate. The required amount of stock was ground off by using regular grinding techniques. Squaring completes the primary operation. At this stage, the stock had been cut to the outside dimensions of the work and was ready to be machined to final form.

The final forming was accomplished on milling machines when the part to be made was not cylindrical. Many of the parts were basically boxes, with various contours, slits, or holes machined in them, or flat parts intricately designed. In milling such parts, tolerances range from plus or minus 0.001" to plus or minus 0.005".

Duplicating or tracing was done on milling machines equipped with moving tables which follow a template. If a large amount of stock is to be removed, the piece was rough-cut on a band saw and finished on a milling machine. When large faces having a width of 3 inches or more were to be machined, an extra long end mill was used. Light cuts ranging from 0.002" to 0.030" were taken at a spindle speed of about 1400 rpm. This procedure resulted in a good finish and in high accuracy.

Slits and holes were cut on a vertical milling machine. Spindle speeds and table feeds were selected according to the size of the tool and the depth of the cut. A slit 1/4" long x 1/2" wide was cut satisfactorily with a spindle speed of 1000 rpm and a table feed of 16 in/min. On deeper, wider cuts, the table feed and spindle speeds were considerably reduced. For example, a slit 1 $\frac{1}{2}$ " deep by 1 $\frac{1}{2}$ " wide was cut at a spindle speed of 300 rpm and a table feed of 3 $\frac{1}{2}$ "/min. It was necessary to take deep narrow cuts even more slowly to prevent breaking the tool. A Bridgeport turret milling machine was used for cutting semicircular grooves in graphite parts with a special fly cutter.

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In machining graphite, the usual high speed steel drills and cutters were used. However, because of the presence of abrasive ash (approx. 0.25%), cutter wear was high. It was found that a dull cutter caused chipping and shearing, so that if tolerances were to be maintained, a close check had to be kept on cutter wear, and it was necessary to regrind tools frequently.

Cutter wear was probably one of the most serious problems in machining graphite. Even carbide-tipped cutters have a comparatively short life. An economical solution was found in the development of fly cutters made from used high speed steel saw blades. Cutter of this type was made in the toolrooms of the shop, and since they are constructed from used blades, the costs involved in their fabrication and maintenance were minimized. The cutters were easily constructed in various sizes and shapes and were readily ground.

In addition to having the advantages of low cost and easy grinding, the fly cutter is especially adaptable to graphite work. One of the limiting factors to the speed at which graphite was machined was the temperature of the tool. External coolants could not be used on graphite, since the coolant formed an abrasive paste with the graphite dust. The fly cutter was adequately cooled by the air surrounding it and thus was used at higher speeds than, for example, a drill.

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Fly cutters were regularly made for machining holes from 1/2" to 10" in diameter. In special cases, holes of even larger diameter have been machined with cutters of this type. Where it was desirable to cut compound curves on the external surfaces of parts; the fly cutter was also found to be suitable.

The grinding of tools for graphite work, as for metal work, was of prime importance. Since graphite had little cutting resistance, it was possible to grind more clearance on cutters used for machining graphite than on those employed for cutting steel. In fact, it was advantageous to grind enough clearance to allow maximum space for chips on cutters that were to be used in graphite. This practice not only increased the life of the cutter, but also speeded up operations. In drilling, for example, it reduced the number of times that it was necessary to remove dust from the holes being drilled.

The machines in the Oak Ridge shop were equipped with a 4" flexible hose which was attached to an exhaust dust collector having a capacity of 5000 cu. ft./min. The exhaust hose was placed close to the work, so that most of the dust is withdrawn from the operation. In cutting holes, the fly cutter did not block the entrance to the hole; this reduced the possibility of binding of the tool. More important, however, the operator was able to drill a fairly deep hole without contending with the normal problems of dust removal.

The Oak Ridge carbon shop is an experimental as well as a production shop. Mills, drying boxes, heater parts, containers, threaded pipes, spiral powder feeders, springs, nuts, washers, and standard parts for the calutron isotope separation equipment, as well as entire graphite assemblies for nuclear reactors, have been fabricated. (8)

At Brookhaven, graphite has also been machined on wood working machinery. Lathe and milling machine operations were performed similarly to other materials, with the exception that much higher cutting feeds and speeds were employed.

One particular problem encountered at B.N.L. involved the machining of blocks approximately 4" x 4" x 60" and 4" x 12" x 60". Dimensions of  $\pm 0.001"$  were maintained both in squareness and taper in the 4" x 60" dimensions. The blocks were squared on a wood jointer and finished to size on a planer. Cutter speeds were high, approximately 6400 sfm, with feeds up to 25' a minute, removing material up to 7/8" at a pass across the 12" x 60" surface. On the 4" x 4" x 60" block, feeds up to 48 ft/min. were attained. Cutter blades were made of Vascaloy. Bars were cut to length on a DeWalt Saw, maintaining a plus 0.000" and minus 0.005" tolerance. The 4" thickness of 4" x 12" slabs have been split through on a Fay and Egan Saw and finished on jointers and shapers. Other operations have been performed on milling machines and lathes using the highest possible speeds and feeds. (38)

Experience indicated that:

1. Steel cutting tools are better for graphite than wood working tools.
2. A three tooth per inch skip tooth band saw blade gives twice as great a tool life as any other blade tested.
3. High speed tools are generally better than carbide tools for turning graphite.
4. Good surface finish (63 RMS) was obtained in milling using high-speed steel at 125 rev/min and a table feed of 3 inches per minute.
5. Slitting has been done using a 1 inch deep cut at 125 rev/min and a table feed of 32 in/min with high-speed steel.

### III. MACHINING OF TITANIUM

Titanium alloy machining is difficult because of three basic characteristics of the material: Extreme abrasiveness of the titanium carbide in the alloy; smearing, or galling; and work hardenability.

The abrasive problem has been nearly eliminated with the development of melting practices that hold the carbon content down to about 0.2%. The use of abrasion resistant carbide, cobalt high speed steels, and vanadium-cobalt steels together with  $\text{CO}_2$  as a coolant, have greatly alleviated abrasion problems. (37) With even lower carbon alloys, machining is approaching favorable comparison with stainless steel. (16, 17)

Smearing is characteristic of titanium. When wet, titanium will mark glass. Titanium alloy will adhere to tool steel, high speed steel and even carbide to a high degree. This buildup on the cutting edge or smearing on the clearance faces leads to tool breakdown. It can be most effectively combated by using  $\text{CO}_2$  gas coolant in conjunction with tools of optimum clearance. Smearing increases if the point of contact becomes hot from friction. Therefore a cold stream of  $\text{CO}_2$  gas is directed at the tool-work-piece interface. (37) Keeping the tool dry also reduces smearing.

Water soluble coolants, oils and waxes will also reduce the smearing tendency, but  $\text{CO}_2$  has an advantage from the standpoint of recovery of turnings. For example, a finished disc may weigh 40-50# while the forging from which it is machined weighs 200#. A large percentage of this removed metal can be recovered and sold for melting stock at premium prices if kept clean and free from oil.(15)

Hardness analysis of the chip and work piece show that titanium is work hardenable only if the tool is dull or if the machine tool or part is not rigid. When a sharply stoned carbide tool bit is used the cut surface evidences a 5-10 point increase, DPH scale. But when the tool is dull or the work not rigidly supported, the hardness will increase up to 25 points over the base material.

A typical chip is continuous and curly, but with buildup edges. Hardness measurements of such a chip show an increase of 52 points over the base metal, 321-373 DPH when  $\text{CO}_2$  is used as the coolant. Chip hardness will average 395 DPH with an oil coolant, an increase of 74 points. Obviously work hardenability will increase if the tool becomes dulled by abrasion, or if excessive smearing occurs, so the factors are closely related.

Data compiled in evaluating carbides and coolants in turning 1 3/4" bar stock have been applied with success to production items such as jet engine compressor discs. This stock was Titanium 150A, both high and low carbon. The hard

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cast iron grade and super hard grades of carbide have been found to produce longest tool life in both continuous and interrupted cutting of titanium. Carbides in the above classes from manufacturers have all proven satisfactory.

Data is given on turning tool design. The use of a chipbreaker is advisable whenever possible. For increased tool life, the cutting edge of the tool must be stoned.

On high carbon titanium alloy it is necessary to take depth of cuts as heavy as the part and machine tool will allow. In general, the depth of cut will vary from  $1/8"$  to  $1/2"$ . On roughing operations, feed is maintained between .015 to .023 ipr with an average of .018. Satisfactory tool life has been obtained at speeds of 90-110 sfpm on the high carbon alloy. This is about 200 cu.in. removal to  $0.030"$  of land wear.

On the low carbon alloy, the speed can be increased to 150-170 sfpm for equivalent tool wear. These data are based on the use of water soluble oil coolants. On finish turning .006-.008 ipr with 100-120 sfpm and .030 to .060 in depth of cut will produce a 50-60 microinch finish. Good tool life is also obtained using .0035 ipr with 150-200 sfpm and  $.015"$  depth of cut on the low carbon titanium alloy.

Some experimental work has been completed with  $\text{CO}_2$  gas as a coolant. Initial results are highly encouraging and warrant additional attention. For example, approximately 250 cu. in. of metal were removed from a large diameter disc of high carbon titanium alloy at

160 sfpm, .023 ipr feed, 1/4" depth of cut, using CO<sub>2</sub> coolant.

Examination of the tool tip revealed only approximately .010" land wear and no burning or build-up.

In all turning operations, the work should be held rigidly and the tool should have minimum overhang and be supported firmly.

In broaching, present information indicates that each tooth should be loaded about .003-.005". Shave cuts should be avoided from the standpoint of work hardening. Design of the broach naturally depends upon the work being performed. Staggered tooth loadings with a shear type of cut reduces friction. With this design, the teeth should be well supported.

The use of CO<sub>2</sub> gas here has given excellent results and tests are still being conducted. The broach should be designed so that a maximum amount of gas can be carried into the work by the broach. Broach bar speed is maintained at 6-8 fpm, but considerably higher speeds will undoubtedly be feasible as the full capabilities of the CO<sub>2</sub> coolants are utilized.

Carbide tipped broaches have performed satisfactorily. High speed 18-4-1 steel does not have sufficient abrasion resistance to give adequate tool life with high carbon material. Modifying 18-4-1 with addition of Co has given increased life, and it is expected that Co-V high speed steel will give still better results.

In broaching, as in turning, the workpiece should be rigidly supported. One-pass broaches should be used whenever possible.

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Through-hole drilling of holes of 1/2" maximum depth has been done on a production basis. Best tool life is obtained from Co high speed steel although standard HSS drills give fair results.

Drills should be ground with a notch to act as a chip breaker. A satisfactory tool grind has a 118° point angle with 12-15° clearance on a 28° spiral. Stub lengths should be used if possible. Highly sulfurized oils give good results, as do some special wax-mineral oil mixtures.

Using 12-15 sfpm with .008-.020 ipr feed on drills up to .250 in diameter produces good results. As an example, using .013 ipr feed, 13 sfpm, a total of 29.6" was drilled. Hole depth was .400".

A standard HSS drill drilled only 10 1/2" using a speed of 20 sfpm and .003 ipr feed. Hole depth was 0.125".

Machine-operated carbide tipped reamers have given good service. Best surface speeds are 100-200 sfpm with feeds of .005-.008 ipr. Four flute reamers are used. Depth is .012", minimum, to .030" on diameter. Back taper is .0002" per in. of flute length. Primary clearance angle is 10-15° on carbide. Chamfer angle is 45°. Highly sulfurized oils make satisfactory coolants.

The type of tap recommended for titanium is an interrupted three flute, spiral point tap using an operating speed of 12-15 sfpm. Sulfurized oil and some waxes have produced good tap life.

Some external threading experience has been gained in making laboratory specimens and some developmental parts. In this work HSS threading inserts were used in a tangentially collapsing geometric die head with good results.

Milling of the high carbon alloy cannot be accomplished with facility and tool life is very short. Lower carbon alloys show a considerable improvement, but considerable work remains to be done.

At present, practice in milling can be briefly summarized as:

Table feed	1/2 - 3/4"
Speed	32-45 sfpm
Rake	10°
Cutter Width	3/16"
Tool Material	18-4-1 high speed steel

Whatever the type of machining, machine tools must be rigid with minimum bearing play. Tools should be finished on a 150 grit or finer wheel and should be designed so that the cutting edges have adequate clearances to avoid side drag. Titanium should never be cut with a dull tool. Tools should be rigidly clamped. High pressure directional cooling on the cutting edge is important so that maximum tool life is obtained. Use of  $\text{CO}_2$  is recommended whenever practicable. (15)

Tools for Machining Titanium:

Turning

Material - carbide, cast iron or super hard grades  
Side rake- 3 - 7°  
Back rake- 0°  
Side cutting edge angle - 0°  
End cutting edge angle - 6°  
Relief - 6°  
Radius - .030"

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### Drilling

Material - cobalt high speed steel  
Point angle - 118°  
Clearance - 12-15° on 28° spiral

### Reaming

Material - carbide tips  
Flutes - 4  
Back taper - .0002"/ in flute length  
Primary clearance angle - 10-15°  
Chamfer angle - 45°

### Tapping

Type - Interrupted three flute, spiral point tap

### Milling

Material - 18-4-1 high speed steel  
Rake - 10°

Machinability of titanium is similar to that of austenitic stainless steels. In general, the same tool angles, cutting speeds and feeds required for 18-8 stainless steel are recommended.

Titanium in the "as forged condition" may have a hard surface scale which will require carbide tools to remove.

Chips from the drilling of titanium are tough and stringy and it is frequently necessary to clean the drill by removing it from the work. (15)

### Surface Grinding

The following information on grinding titanium is a purely interim and tentative report. (18,19) The results (showing the beneficial effects of low wheel speed) were obtained solely with vitrified

bonded wheels on a small surface grinder. It is possible that similar results will be obtained with vitrified bonded wheels in other precision operations such as cylindrical and internal grinding, but experiments have not yet been run to determine when this assumption is justified.

Titanium is an unusual and difficult metal to grind because it wears the grinding wheel at an extremely high rate. The high rate of wheel wear can be overcome by using slow wheel speeds. This report outlines the technique used. (18,19)

#### Grinding Ratio

Each variable in precision grinding was studied for its effect on the grinding ratio, which is defined as the ratio of cubic inches removed to cu. in. of wheel wear. The higher the value of G, the lower is the wheel wear and hence it is easier to maintain dimensional tolerances on parts.

With G known, it is possible to calculate approximately the wheel wear on the diameter for a given size wheel and a given work surface area. Experience will indicate the tolerances that can be maintained for a certain amount of wheel wear. The G values for titanium and its alloys are roughly between two and three. This is the range for high carbon, high Cr die steels ground with a 32A 46-H8VBE wheel which is frequently used to grind this material. Therefore, the tolerances obtainable in grinding titanium alloys should be about the same as can be obtained in grinding similar size surfaces of parts made of this type of die material. (18,19)

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Typical grinding results obtained on commercially pure titanium and three of its alloys are presented in Table I. The conditions that were used are listed in Table II. Relative values of G in Table I are those obtained under this particular set of grinding operations which are not necessarily the best for each of the materials investigated.

Table I - Results of Grinding Titanium and its Alloys

Material	Rockwell Hardness	G Value Mat.Rem/Wheel Wear cu.in/cu.in	Profilometer Reading microinches	
			Roughing	Finishing
Ti 75A	B82	3.0	85	25
Ti 150A	C37	2.3	40	15
RC 130B	C37	2.0	40	15
RC 130B	C42	2.0	40	15
Ferrochrome				
Ti(experimental)	C29	1.7	50	20

Grinding Variables

- (a) Abrasive - 32 aluminum oxide abrasive is superior to all others, 38  $\text{Al}_2\text{O}_3$  is next but it wears about 20% more. (20% lower value of G).
- (b) Grit size - 60 grit is best for surface grinding. Finer grit size result in higher wear.
- (c) Grade of grinding wheel - K or L
- (d) Structure Number - 8 is better than 12P or 5.
- (e) Bond - Vitrified is probably best. Resinoid bonds have not been studied adequately.
- (f) Treatment in wheel - sulfur in the wheel as a treatment does not improve the grinding action.

- [REDACTED]
- (g) Grinding Fluids - Various soluble-oil compounds acted about the same in the preliminary experiment. More work needs to be done under improved grinding conditions.
  - (h) Wheel speed - 2000 sfpm appears to give the lowest wheel wear, 3000 sfpm is almost as good. (Change the pulley or motor to obtain the desired speed.)
  - (i) Table speed - Wheel wear is least between 400-500 ipm and increases at both lower and higher table speeds.
  - (j) Unit downfeed - .001" maximum. Heavier downfeeds will cause burn and increase the wheel wear.
  - (k) Unit crossfeed - Maximum of .050" for a .001" downfeed or .100" for .0005" downfeed, otherwise wheel wear increases.
  - (l) Width of Wheel - Use widest wheel possible, even a recessed wheel to permit mounting.
  - (m) Diameter of Wheel - should be as large as possible to minimize radial wheel wear. Use full size wheel at low rpm. Most of the benefit of low wheel speed is lost if the low wheel speed is obtained by the use of a smaller diameter wheel.

Table II - Grinding Conditions Used to Obtain Data

Wheel - 8 x 1/2 x 1 1/4, 32A60-L8VBE aluminum oxide vitrified  
Machine - 6 x 18 in surface grinder

Wheel speed - 2200 sfpm

Table speed - 450 sfpm

Unit downfeed - .001" for roughing; .00025" for finishing

Unit crossfeed - .050" for roughing; .010" for finishing

Total downfeed - .020"

Soluble oil - 1-40

Area ground - 7 1/2 - 9 sq. in; av. 8 sq. in.

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Summary of Research

Use aluminum oxide abrasive wheel 32A60-L8VBE or 32A60-K8VBE.

Grinding should be done wet whenever possible to minimize the fire hazard. Titanium in finely divided form is highly explosive in nature and in this respect is like magnesium. Avoid fluids which may contribute to the fire hazard. Although the experiments concerned surface grinding, the use of low wheel speed appears to be applicable to vitrified wheels used in other precision operations like cylindrical or internal grinding on difficult work. (18, 19)

Titanium 150 Titanium (using standard wheel speed)

1. Cylindrical Grinding

Wet, light grinding - 32A60-J8VBE

Wet, heavy grinding - 32A60-K8VBE

2. Surface Grinding

Wet - 32A46-18VBE or 32A46-H12VBEP wet low wheel speed.

3. Cutting-off

Wet - 16 x 3/32 x 1 in wheels: Bar stock 1 1/2" and smaller - 37C60-POR-30; Over 1 1/2" diameter - 37C46-MOR-30.

A marked increase in wheel wear of rubber bonded wheels as wheel speed is lowered. Slower cutting action and burning of the work occurred with aluminum - oxide specifications.

4. Cutting off

Dry - A54 - L8B (tentative)

5. Snagging

a. Swing frame.

Ingots for forgings: wheel speed 7500 sfpm - A14-Q4B7

Billets: wheel speed 7500 sfpm - A14-Q4B7  
9500 sfpm - A123-Q4B5

b. Portable.

Forgings: wheel speeds 9000 sfpm - A16-Q4B7

c. Bench stand: dry - Wheel speed 5500 sfpm - A36-K8VBE

6. Offhand polishing - A801-G20BLIO (cork resinoid wheel)

RC 70 Titanium sheet

1. Removing discoloration - set up wheel with A240-ElB grain bonded to canvas wheel with polishing cement after sizing. Some wheel loading occurs with set up wheels.

2. Buffing - cloth buff - A240 ElB grain mixed with stearic acid.

Buffing can follow the setup wheel if final polishing is desired.(18,19)

Drilling

Drilling and tapping are major problems in machining titanium.

The difficulty arises from the tendency of the material to work harden and chip-weld, plus a tough, non-curling chip and poor thermal conductivity.

Drilling must be continuous to prevent work hardening and pilot holes are inadvisable for the same reason. The initial recommendations were: a drill with point off center, to drill an eccentric hole (thus minimizing rubbing, pickup and heating) and notched lips to break chips. High cobalt drills seemed best. However, an eccentric drill produces a hole of varying diameter and holes will vary one from the other as well.(20)

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Avey Drilling Machine used 12% Co HSS drill with a 29° helix angle and 140° included point angle. Drills were as stubby as possible and the setup rigid. With highly sulfurized oil, cutting speed of 9-12 fpm and feed of about .004 ipr on a .096 in diameter drill, Avey drilled 20 to 25 holes .420" deep.

Greenfield Tap and Die Corporation has since made a number of additional experiments which clarify the problem. Drilling was done with a 17/64" drill to produce 65% depth of thread for a 5/16-18 tap. A fast-spiral drill worked best, with included point angle of 135-143°, 135° being preferable. For coolant, standard sulfur base oils proved inferior to some water soluble oils and particularly to Thread-Kut 99 as well as to CO<sub>2</sub>. At 450 rpm (31 sfpm) and .006 ipr 20-90" could be drilled between grinds. This is three times the surface speed of the Avey tests and twice to nine times the work between grinds.

Greenfield tests also indicate that with CO<sub>2</sub> as the coolant there is no cold working of the material as long as the drill stays sharp but immediate cold working when it dulls. Dulling can be detected quickly from the squealing just as in drilling other materials susceptible to work hardening. If work hardening occurs, tapping becomes impossible.

Another company, making extensive tests on both forged and on machined Titanium 150A, reports results almost identical with those at Greenfield except that CO<sub>2</sub> was not tried. (20)

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CONT.

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Chance Vought reports Titanium drills somewhat like quarter-hard stainless steel but requires a lower drilling speed and constant feed to reduce or avoid cold working and wear of the cutting edge. Engineers there emphasize, as Avey does, that drills should be as short as possible; a long flexible drill drills an out-of-round hole. They also point out that feed should be reduced as the drill breaks through to avoid heavy burrs. Tests there gave 100-150 holes/grind.

Whitman and Barnes found that  $176^\circ$  included angle resulted in least burr, but that  $90^\circ$  included angle resulted in best roundness. Tests there were run in a drill press with water soluble oil as the coolant. Speeds up to 75 fpm were satisfactory.

Titanium could be reamed successfully, under general conditions, with either straight or spiral-flute reamers. Holes reamed in a drill press were suitable for size, roundness and finish. With a hand drill, at normal speeds (1750 rpm) reamers with conventional chamfer angles cause excessive chatter. A taper reamer, or a regular reamer with a longer lead angle, avoids this chatter.

Only reports on tapping come from Lockheed. Interrupted tooth taps worked best. Speeds of 12-15 fpm proved satisfactory for a 60% thread. (20)

#### Grinding

Wheel loading, poor surface finish and very high wheel loss have made titanium an extremely poor material to grind. Some recent

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research by Lockheed Aircraft Corporation concludes:

- 1) Satisfactory surface finish can be obtained.
- 2) Material removal must be kept to a minimum.
- 3) Thread grinding is practical.

As all tests were run on 5% Cr, 3% Aluminum, Mallory Titanium alloy, caution should be used in applying the following results to other alloys.

Centerless Grinding on a Cincinnati No. 2 machine showed the best wheel grade to be a Carborundum C54-04-VGC. A mixed coolant was used which contained: 25% Codol from L. A. Oil and Grease Co., 25% Solcut from E. F. Houghton and Co., and 50% water. Stock removal should never be more than .002"/cut. By following this method a ten microinch finish was readily obtained. (20)

Cylindrical Grinding on a Norton 6 x 30 machine was found most suitable with a Carborundum C60-P wheel and a coolant composed of one part Antisep soluble oil (E. F. Houghton & Co.) to 70 parts of water. At very slow feed and light depth of grind a ten microinch finish was obtained. Grinding action was similar to that when grinding Carboloy.

Surface Grinding on a No. 3M abrasive machine using a Norton 3760 L wheel, and the same coolant as for cylindrical grinding, produced a 12 microinch at approximately .0005 in per cut using a slow table feed. Wheel wear is rapid.

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Thread Grinding on a No. 636 Jones and Lamson machine showed the best wheel to be a Macklin 100 W2B7 dressed to 12 tpi. Stuart Super Kool 81X Grinding Oil was used. Satisfactory threads were produced with a stock removal of 0.010 in. per cut. Material acted like high-carbon, high chrome steel hardened to Rc 65.

Titanium can be ground satisfactorily but these tests indicate that wheel surface speeds must be reduced to 3000 or 3500 sfpm rather than the standard 5000-7000 sfpm. When these lower speeds are used grinding action will be similar to that when grinding hard chrome plate. Stock removal, rather than good surface finish, causes the greatest difficulty. The lower surface speeds seem to improve the rate of stock removal. (20)

#### Power Sawing

Extremely difficult since work hardening sets in, often knocks the set from saw blades and causes the blade to seize in the work. Band saw cutting does not seem to be practical at present. Tool breakdowns make it slow speed, thus inadequate for production work. Abrasive cutting is too expensive. No real machine shop solution has yet been worked out for sawing titanium either alloyed or commercially pure. (21)

#### Drilling

Proper lubricants should provide success here. In all cases of drilling and milling, the problem centers about work hardening. Machinists in North America are now working out feed and speed

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ratios having accepted the formula: less speed, more feed. This is necessary so that tools are continually biting into "virgin" stock keeping ahead of work hardened portions. (21)

#### Turning

High speed steel tools having the following angles:

0° back rake  
15° side rake  
0° side cutting edge angle  
5° end cutting edge angle  
5° relief

afford 9 cu. in. tool life at 40 fpm cutting speed at .009" feed and .062" depth of cut. A water soluble cutting fluid was used. Carbide tools provide 10 cu. in. tool life at 200 fpm cutting speed. Early laboratory tests indicate that feed should be about .012". Cast iron grades of carbide appear to give the best results. (22)

One of the most important processing operations on titanium is the lathe cleanup of billets prior to all forging and rolling operations. The surface condition of these billets is poor because of casting pits, slag inclusions, hard particles and contaminated alloy. These surface defects must be removed before billets are processed to avoid distributing the contamination throughout the finished product and to prevent damage to forging and rolling tools.

Some improvement to the surface can be effected by sand or shot blasting and by etching as much as .008" - .012" if necessary. Some of the worst defects are removed by scarfing or snagging. (22)

Milling of Titanium

Comparative test findings on milling, drilling, and all others immediately introduce an array of additional variables. Factors such as cutter diameter, number of teeth or flutes and helix angle to mention a few, make the analysis more difficult. Comparative information may be misleading, therefore, unless tests are conducted under identical conditions. (22)

The presently available data on milling and drilling are of a preliminary nature to uncover the best course to follow in more detailed test work. In general it can be said that titanium alloys can be machined fairly satisfactorily at speeds in the vicinity of 70 fpm.

18-4-2 High speed steel has been found to be about the best of the steel tool materials and cast alloy cobalt-chromium superior to carbides. One trouble in carbide milling is that the carbide sections tend to flake off due to combined effects of intermittent cutting and the "welding" of chip to toolface. Axial flow compressor blades are being made from Titanium 150A as a possible substitute for AISI 410 stainless steel. Data on this operation follows: With Tantung side and end mills operating at about 90 fpm (4" diameter, 75 rpm) tool life is about 150 pieces per cutter grind. With Vasco Supreme (18-4-1) high speed steel end mills, the ends of 1 1/4" x 1 1/2" bars are milled square to length at about 50 fpm (2 1/4" cutter diameter, 92 rpm) with a 1/8" depth of cut and a 1" per minute table feed. Tool life is about 120 pieces between grinds (about 25 cubic inches metal removal). (22)

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Cut-Off Operations

Reports on sawing vary from "difficult" to "almost impossible". Band sawing seems to be out; the Motch and Merryweather saw seems to work with fair success; and certain types of hacksaws give promise. Abrasive sawing is the best bet, however, provided proper equipment is used.(22)

In abrasive sawing Titanium, it is impossible to plunge straight through a large piece. The wheel must cut successive overlapping shallow scallops, keeping the area of wheel contact as small as possible at all times and giving the coolant the maximum access. If possible, the work should be slowly rotated or indexed so that the wheel can cut toward the center and never have to cut more than halfway through. Machines having a wheelhead capable of oscillating as well as plunging motion are ideal. Titanium's poor heat conductivity requires the maximum flow of coolant if heat cracking is to be avoided. The tendency to clog wheels also accentuates the importance of minimizing the wheel-work contact area.

A soluble oil type coolant is available that kills the objectionable rubber wheel odor. 7" diameter Ti bars have been cut, rotating and oscillating the wheel in ten minutes (about 14.2 sec/sq.in.). A 1" bar is cut in four sections. Considerable promise is shown in abrasive cutting of titanium at lower wheel speeds. 3000-4000 fpm speeds (instead of the usual 5000-6000) have been tried with good results. At these speeds wheel wear is reduced appreciably.

With hacksawing, constructive recommendation indicate an extremely coarse saw (2-4 teeth per inch), slow speeds, and heavy feeds. Ordinary fine toothed saws and conventional feeds result in extremely small feeds per tooth. With titanium this results in rapid work hardening which makes further cutting extremely difficult. (22)

#### Drilling and Tapping Titanium

All machining operations on Titanium alloys require the observance of this rule: because of the rapid and extreme work-hardening tendency, do not disengage feed while tool is in moving contact with work. This is particularly true in drilling. For the same reason pilot holes are "out" and the enlarging of holes is to be avoided. Poor thermal conductivity and a strong "pick-up" or "welding" tendency are two more properties of titanium which require special techniques, and the tough, non-curling type of chip further complicates the picture in drilling and tapping because of the space restrictions.

Eccentric drilling, using high cobalt drills with notched lips and slow speeds about double the feed common with steel offer promise of improved results. (Next smaller size drill, point ground off center, run outs, drilling a larger hole). This minimizes rubbing and reduces pick up and heating. (21)

The notched lip idea in drilling carried over to tapping results in use of staggered-tooth taps, which also tend to break up chips.

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Use of a 60% thread and a tapping speed of 12-15 fpm are also recommended. (21)

Titanium Alloys - Lockheed

Extensive preliminary tests on 5% Cr, 3% Al alloy have been made. Selected data on the development of turning and milling techniques are included here: (21)

Turning tests were run with carbides of several makes, cast-alloy materials and high speed steel. Of the carbide tool tests, the information on Kennametal is the most complete but its inclusion is not intended to imply any exclusive preference.

Styles AR 10, BR 10 and D 10 and modified versions of these tools were used, all having the following tool angles: 0° back rake, 6° side rake, 0° side cutting edge angle, 6° end cutting edge angle, 6° relief. Lockheed's tool-life technique is to cut a predetermined quantity of metal (measured in sq. in. of machined surface) with each tool under identical conditions, then study the wear and/or extent of breakdown. The four initial tests were made using a feed of .010" ipr, a depth of cut of .030", and 35 fpm cutting speed. Oil was used as a cutting fluid and 55 sq. in. was machined. (This is equivalent to 5.5 cu. in. at .100" depth of cut).

K3H, a steel cutting grade; K6, a hard cast iron grade; K2S, a cast steel grade; and KM, a general purpose grade were tried. Both the K6 and K2S tool performed successfully, exhibiting practically no wear for the 55 sq. in. cut. K3H showed medium tool wear, considered as excessive; the KM tool wore about the same.

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On the strength of these findings, K6 was again tried, this time at .020" ipr feed, .060" in depth of cut and 100 fpm cutting speed. The tool was permitted to cut 95 sq. in. of surface in which time the tool had cratered badly. (With double the feed and almost three times the speed of the finishing test, the machining rate here was six times that of the earlier run in terms of sq. in. and 12 times in terms of cubic in. as the depth of cut was also doubled. The number of sq. in. machined increased from 55-95; therefore the cutting time for the second test was approximately 1/3 that of the first test.

A finishing cut was then made again, again using K6 carbide. Feed was set back at .010" ipr and depth of cut very shallow, only .0025 in. Speed however, was increased slightly to 120 fpm and 140 sq. in. of surface was machined. Wear was very slight and results were considered satisfactory. Finish in all tests but the heavy feed run was good; about 100 microinches. (21)

Milling tests were performed on a Kearney and Tucker No. 2 horizontal milling machine, using both carbide and high speed steel cutters. Cutting speeds from 20-720 fpm and feeds from .004" - .016"/tooth were tried. (21)

With a 4" diameter, four tooth KM carbide-tipped endmill having 6° negative axial rake and approximately 6° positive radial rake and a 6 1/2° clearance angle, tests were run under various conditions. At 21 fpm, cuts were taken at .006" and .008" feed per tooth using

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lard oil. In both cases, the tool dulled rather quickly. A later test was run with the same cutter on titanium, using no cutter fluid at 46 fpm and .008" feed per tooth. In this case, the tool cut well for a short time, followed by extreme heating and rapid breakdown.

High speed steel side milling cutters plain and chromium plated were also tried, at speeds from 27-31 fpm and feeds of .004" - .005" per tooth with poor results. The Cr plated tool broke down very quickly while the plain cutter having a slightly lower radial rake and less axial rake lasted for 2 sq. in. before losing its edge. Tests were then performed with a 6" diameter, six tooth Carboloy-tipped side milling cutter having a  $2\frac{1}{2}^{\circ}$  negative radial rake and a  $6^{\circ}$  negative axial rake. The titanium test piece was submerged in a bath of dry ice and a tri-ethyl-phosphate resulting in a temperature of  $100^{\circ}\text{F}$ . With this set up, speeds from 31-69 fpm at feeds of .005" - .008" per tooth produced no tool wear. At 30 fpm and .016" per tooth, wear was slight. At 89 fpm and .013" per tooth wear was also slight. (In both cases, the finish was coarse.) Tests were also run at 118, 151 and 195 fpm and feeds of .0045", .0015", and .008" per tooth respectively and the results were successively poorer. A test was made at 720 fpm in which the tool was badly damaged. (21)

#### IV. MACHINING OF ZIRCONIUM

The machining characteristics of Zr resemble those of Al quite closely. Zr is soft and very ductile and galls readily with materials rubbed against it.

Machining practices such as are used for Al appear to work quite satisfactorily with Zr except that cutting speeds must be very low. When Zr is cut without a coolant, the desirable maximum cutting speed is 50-100 surface feet/min. At higher speeds, a poor surface finish is obtained. When cutting fluids are used, the allowable speed may be as high as 150-200 surface ft/min. Tool wear, even with high speed tools does not appear to be a serious problem.

Tool angles should be those desirable for cutting Al, namely, conventional clearance angles and high positive rake angles. A rake angle of 30° has been found to work well with all kinds of cutting which have been investigated.

Zr appears to be subject to one kind of machining difficulty which is not ordinarily found, namely, "end damage". In a shaping or milling operation, when the tool leaves the work abruptly it has been found that a small fragment of Zr may be torn away below the angle of cutting. This kind of damage is pronounced when cuts are deep, but unimportant when depth of cut is .005" or less, or when high rake angles are used. In other respects, the depth of cut can be that of conventional finishing operations, that is, of the order

of .020" - .030". Heavier cuts are not ordinarily needed for such processing operations.

One other characteristic of cutting Zr is that chips often become rewelded to the surface being cut giving localized areas where corrosion may occur. This has been more bothersome with very light cuts (.001" - .003" depth) than with heavier ones.

Unique conditions are required in the chipping of ingots of uranium-zirconium alloy preparatory to smelting. In this operation, it is absolutely essential that contamination of the chip surfaces be avoided - otherwise the remelted ingot will be excessively hard and brittle and not corrosion resistant. To accomplish this objective, the procedure which has been used in the past consists of machining to chips with a feed of .010", a depth of cut of .10" and a cutting speed of 40"/min. Obviously, this operation is extremely slow and laborious. It would be desirable to machine this material at a very much more rapid rate and experiments are in progress to determine how the chips may be protected from contamination when the cutting speed is much higher.

Zr grinds very unsatisfactorily. With conventional grinding practices, it is found that wheel wear is extremely large, in some cases exceeding the amount of metal removed by the grinding operation. This observation has been made in experiments performed at Battelle as well as in work carried on for Battelle at three outside companies who are specialists in grinding. (23)

Experience at Eindhoven in the Phillips Laboratories, in Philadelphia, at the Foote Mineral Company and at various AEC installations indicates that the ductile Zr can be easily machined. Experience at ORNL has shown that it machines with as little difficulty as a low grade carbon steel. (26)

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V. MACHINING OF THORIUM

Thorium can be readily machined, cutting somewhat like mild steel. It can be machined without a coolant, although the turnings may ignite. However, they are least likely to ignite with a heavy cut at slow speed. High speed steel makes a satisfactory cutting tool although Carboloy is better. The wear on cutting tools is high. It can be machined at lathe speeds of 150-175 ft/min once the surface of the casting has been removed. The scale resulting from hot working is hard and dulls the cutting edge of the metal more rapidly than the clean metal. The thin outer layer formed by reaction with the crucible is pyrophoric and must be machined slowly in order to avoid combustion of the chips.

Surface grinding of thorium is easily performed as there is no surface working or warping under heating by cutting or grinding as in the case of uranium. A highly reflecting surface is obtained which darkens on standing in air.

The metal drills easily but is very abrasive on the drills due, doubtless, to the oxide inclusions and it is likely very pure metal would cut easily and with little wear of tools. However, it might offer more difficulty due to "hogging" in drilling and loading of the stone on grinding. Cast thorium can be sawed with "Marvel" tool steel edged blades with or without a coolant. (9, 10, 11)

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VI. MACHINING OF TANTALUM

1. Safety Precautions:

When tantalum is being machined, there are no particular safety precautions to be observed other than those employed in good machine shop practice.

2. Recommended Coolant:

Although tantalum may be machined dry, a coolant mixture of carbon tetrachloride and lard oil is recommended. (12,13, 14)

3. Machining:

Machines should be provided with oil splash guards and equipped with a dust collecting system that will collect the oil-mist and assure thorough filtering before being exhausted out-of-doors.

4. Tools:

All cutting tools should be ground to the same angles as those used for cold rolled steel. There should be no difficulty encountered when machining pure tantalum metal since it has a machining similarity to low carbon steel. (27)

**VII. MACHINING OF BERYLLIUM**

**1. Safety Precautions**

Although some people working with beryllium do not appear to be susceptible to its dust, there are some who are allergic to it and develop symptoms somewhat akin to silicosis. Therefore, every possible protection should be extended to guard against dust inhalation both in the plant and the surrounding area. Machines should be hooded to assure that the proper amount of coolant reaches the work and, at the same time, exhausts the dust and oil-mist from within the hooded area. All air exhausted from the direct machining area (as close to the cutting operation as possible) must be properly filtered and exhausted out-of-doors. Respirators equipped with Ultra filters should be worn at all times.

All cuts, scratches and/or abrasions should be treated immediately by a physician who has knowledge of the hazards involved in order to prevent granulosis of the wound from beryllium dust.

No smoking nor eating should be permitted in the area where beryllium is being machined. Hands and face should be thoroughly washed before smoking, handling and/or eating food or before touching any part of the body.

**2. Recommended Coolant**

Beryllium may be machined dry with a minimum of difficulty but a coolant is recommended since it helps to control the dust hazard.

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A powdered oil solution has been found to be the best coolant for most machining operations. Any of the conventional soluble oils that mix with water or any of the commercial lard oils are also satisfactory. Experienced operators favor a water soluble powdered oil manufactured by Henry E. Sanson & Son, Inc., of Manhasset, L. I., N. Y., which is mixed in recommended proportions for general use.

### 3. Machining

Little difficulty is encountered in machining this metal. It can be machined as readily as any of the common materials by employing similar machines and cutting tools. Its hardness and brittleness makes it peculiar to other metals. It has a tendency to chip wherever the tool leaves the work piece. This can be overcome by taking light cuts when approaching the finished size or area. Therefore, a depth of .015" is recommended.

### 4. Tools

The machining of beryllium offers no particular difficulty insofar as cutting tools are concerned. Cutting tool angles employed for machining brittle grades of brass and copper alloys work very well.

#### a. Turning

Turning operations present no particular problem. The metal does have a tendency to chip when the cutting tool leaves the work piece. Tool bits of high-speed steel are excellent; carbon-steel tools also work well.

b. Milling

Milling operations present no problems. Cutters generally used in milling operations are very satisfactory. The metal will chip whenever the cutter leaves the work piece.

c. Drilling

Drilling is not difficult. Drills ground similarly to those used on brass are recommended.

d. Tapping

Beryllium is difficult to tap. The metal pulverizes in front of the cutting edge of the tap and has a tendency to roll between the tap and the tapped hole. This condition can result in breakage of the tap or the threads which are (in themselves) weak.

e. Grinding

Beryllium may be ground as easily as any of the more common materials. It may be ground dry with excellent results. However, the finish will be improved and the dust hazard controlled if a powdered oil and water solution is used. A Norton Grinding Wheel #38A60 E12 VBEP (white) or its equivalent will give good results.

f. General Machining Notes

1. Beryllium may be machined to any shape desired.

Because of its brittleness, it has a tendency to chip

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and break on the edges.

2. Clamp a piece of cold-rolled steel on the back side of a piece of beryllium before drilling a hole through it. This will offset the tendency to break the edge of the hole. The same technique should be employed when milling beryllium. (27)

It has been pointed out (39) that microcracks are produced quite readily in a machined beryllium object. This, apparently, is especially true if a beryllium rod is first cut off with a cut-off wheel. If a deep enough machinery cut is not taken subsequent to this operation, the material may still be full of microcracks.

VIII. MACHINING OF BISMUTH

1. Safety Precautions

There are no particular safety precautions necessary when bismuth is being machined other than those observed in good machine shop practice.

2. Recommended Coolant

Bismuth may be machined dry. If a coolant is desired, a solution of powdered oil and water in recommended proportions (Henry Sanson & Sons, Inc., Manhasset, L.I., N.Y., manufacturer) is satisfactory. However, plain tap-water is equally effective.

3. Machining

Bismuth is not difficult to machine. The conventional machines and tools used for cast iron are satisfactory. The metal in its natural form is hard, crystalline and extremely granular in structure. Bismuth, as cast, has a resemblance to lead but is harder and extremely brittle.

4. Tools

All cutting tool angles should be similar to those employed on cast iron. Tools with a more positive rake - as those used for mild steel - also work with good results. Any of the conventional materials used for tool bits, cutters, etc., can be used satisfactorily.

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a. Turning

Bismuth turns very easily but has a tendency to chip and uproot the crystals. Ordinary high-speed tool bits are satisfactory. Tools may be ground with rake angles similar to those used for cast iron or mild steel (1-1/2° to 5° positive).

b. Milling

All milling operations are simple. The only difficulty that will be encountered is the crystalline and granular structure of the metal. Sharp edges are difficult to maintain since the metal will chip and flake off wherever the tool leaves the work. The metal is so brittle and weak that it barely holds together during the cutting operation.

c. Drilling

Drilling bismuth is not difficult if care is exercised when starting the drill. The drill has a tendency to go off center and follow the crystals. The "creeping" is very noticeable whenever small holes are being drilled.

d. Tapping

Tapping bismuth is difficult. The metal crumbles ahead of the tap and crushes and uproots the thread. The crystalline and granular nature of this metal makes it almost impossible to tap or thread, i.e., tapping, threading with dies, turning on a lathe (either external or internal).

e. Grinding

Bismuth can be ground easily with no particular problem. Any of the conventional methods of grinding, i.e., cylindrical (internal or external), surface, thread and centerless are simple. If bismuth must be threaded and the size of the thread will permit, thread grinding is recommended. However, threading should be avoided if possible because the thread will usually be too weak to be of any normally practical use. Norton or equivalent wheels of a 38A60 E-12 VBEP or 32A60 E-12 VBEP grade do excellent finishing operations if a soluble powdered oil and water solution as recommended by the manufacturer (Henry E. Sanson & Sons, Inc., of Manhasset. L. I., N. Y.) is used.

f. General Machining Notes

1. Bismuth may be machined to any shape or form desired by using regular cutting tools.
2. Bismuth is not adaptable to threading. It is too brittle and granular to withstand any shear action and has a tendency to separate the crystals and crumble. If it must be threaded, a coarse thread is preferable. (27)

IX. MACHINING OF LITHIUM

1. Safety Precautions

Lithium should be kept in an airtight container or submerged in kerosene. It becomes a definite fire hazard in the presence of moisture or when subjected to elevated temperatures (200° C). The danger of an unpredictable explosion dissuades the use of carbon tetrachloride or water soluble oils around lithium. Lithium should, therefore, be handled with extreme caution. It should be kept from actual contact with the skin and its fumes should not be inhaled. A trained safety engineer should be consulted before lithium is handled - especially, whenever it is to be machined.

2. Recommended Coolant

The only recommended coolant is kerosene. Care should be taken to assure that the cutting tools are sharp and that the surface of the lithium metal is covered with the coolant.

3. Machining

Lithium metal works similar to lead and has all of its machining characteristics. It is ductile and can be easily rolled and drawn into wire. It can be machined to any desired shape.

4. Tools

Insofar as cutting tools are concerned, the machining of lithium presents no particular difficulty.

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Turning, Milling, Drilling & Tapping

There are no particular problems to be encountered in these machining operations. All "stringy" chips should be removed and the work should be kept covered or submerged in kerosene. The latter is necessary in order to prevent oxidation.

Grinding

The grinding of lithium is not recommended. There is a definite danger of having it burst into flame or explode in the kerosene vapor.

General Machining Notes

The reaction of lithium with hydrogen and nitrogen (as released in damp air and moisture) renders the metal impracticable to machine into machine elements unless the lithium part can be submerged in kerosene. (27)

X. MACHINING OF STELLITE

1. Safety Precautions

When working with Stellite\*, there are no particular safety precautions to be observed other than those employed in good machine shop practice.

\*Stellite is a trade name of Haynes Stellite Company. It is an alloy of cobalt, chromium, tungsten, carbon (about 2%) and small amounts of molybdenum. Some grades contain a small amount of boron to increase the hardness. It is normally used as a cutting tool material and is cast to the desired shape and then ground for finishing. Recently, it has become most useful as vane buckets in superchargers and turbo-jet engines. The same alloy - with slight variations in its composition - is sold by manufacturers under a multitude of trade names.

Any experience gained in machining Stellite is applicable also to the following trade-named alloys which are practically the same as Stellite: Delloy #6 - Penn Rivet Company; "T" and "W" Alloys - Jessop Steel Company; Speed Alloy - Tungsten Alloy Company; Rexalloy - Crucible Steel Company; Vitallium - Austinal Laboratories. The boron grades of Stellite equivalents are: Kutkost - General Tool & Die Company; Crobalt - Michigan Tool Co.

There is a slight difference in the composition of each of the trade-named alloys. Greater proportions of chromium and tungsten make the material more difficult to machine. However, Stellite can be machined to any desired shape.

  
2. Recommended Coolant

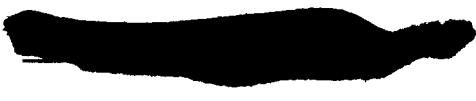
Stellite machines best dry. A soluble powdered-oil solution will work satisfactorily when sustained machine operations are necessary. Some operations require kerosene as a coolant and as a dielectric in the ionization process of material reduction.

3. Machining

Most grades of Stellite can be turned and threaded in a lathe. They can be milled but this operation presents its own problems. Any machining operation that tends to crush the material being removed, e.g., in milling and drilling, is difficult. All efforts to tap and die-cut threads on Stellite have proven futile. It is believed that a special high-speed steel gun tap (properly designed) could thread holes from 1/4" up to any size that is practicable to tap. Large threaded diameters can be lathe-cut with little difficulty. Small fine-threaded holes can be threaded by employing the Method "X" process. This method can be used in innumerable ways to shape Stellite. However, this method is very slow and costly and should be avoided whenever possible.

4. Tools

Tungsten and boron carbide tipped tools are satisfactory. Experiments with high-speed tool bits (steel) have indicated that they are too soft and will not penetrate the Stellite. However, Pratt & Whitney has just developed a process for surface hardening high-speed steel which would be satisfactory for cutting this material.



a. Turning

Turning operations can be done easily with tungsten and boron carbide tipped tools. However, the tool must be plunged without any hesitation into the work. If the operator should allow the tool to "dwell" on the work, the work will work-harden and chip the cutting edge of the tool bit.

b. Milling

Knowledge obtained in turning and threading the Stellite has shown that it can be milled with a tungsten or boron carbide-tipped cutter. Interrupted cutting is recommended in order to avoid "dwelling". A fly cutter is satisfactory for milling operations. This gives the interrupted cutting action desired.

c. Drilling

Drilling is not difficult if a tungsten or boron carbide-tipped drill is used. This drill - running dry - can be used to drill 1/8" diameter holes. The drill must be fed slowly. If it "dwells", it will work-harden the piece and add to the drilling difficulties. For this particular operation, a thin web drill - ground in the conventional manner - should be used.

d. Tapping

Knowledge obtained in tapping Stellite was gained through experience employing the Method "X" process. (29 to 36) This process will thread holes quite successfully but, pending further improvements, is very slow and costly. Rapid progress is being made to improve

machining conditions and to overcome these obstacles. Stellite probably can be threaded in the conventional manner. A special high-speed steel gun tap with a spiral cut tip as employed by Pratt & Whitney on their spiral tip gun taps is recommended. The use of a Jones & Lamson tangent die head for chasing and die-cutting threads is also recommended. This type of die would be very adaptable for tipping with carbide.

### e. Grinding

• Stellite can be ground to any shape desired by employing the conventional methods.

f. General Machining Notes

Pertinent notes and recommendations have been added under the various machining operations. (27)

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