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EVALUATION OF THE HAZARD ASSOCIATED WITH FABRICATING BERYLLIUM COPPER ALLOYS

Thomas J. Senn

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Introduction

HISTORY OF HAZARDS ASSOCIATED WITH FABRICATING BE-CU ALLOYS

Beryllium metal is mainly used as a minor alloying agent with copper, nickel, or other metals. Although the hazards of working with pure beryllium have long been recognized, there is some confusion as to whether or not these same hazards exist when the metal is handled in the alloy form.

More than ten different beryllium compounds have caused some type of beryllium disease. The beryllium ore, beryl, is the only beryllium compound to which there has been considerable exposure, and yet there have been no reportable cases of beryllium disease.[1]

As the number of cases of beryllium disease increased through the 1930's and 40's, the need to document the cases became evident. The Beryllium Case Registry was instituted in 1951 at Massachusetts General Hospital. This central source of beryllium disease cases provided the medical community with (1) criteria selection for diagnosis of beryllium poisoning, (2) judgment of effectiveness of controls, and (3) evaluation of the clinical course of beryllium disease and response to therapy.[2]

Of the over 800 cases in the Registry, only about 20 to 30 had their initial exposure subsequent to 1949. This date is generally considered the time when the beryllium hazard became widely recognized, and the industry instituted workplace control measures. In fact, the fluorescent light industry dropped the use of beryllium completely. The 20 to 30 recent cases mentioned above include not only workers in smelting and extraction operations but also workers in alloy and ceramics operations where contaminant control was previously thought to be quite successful.[2]

The majority of those persons whose only exposure to beryllium came from beryllium alloy manufacturing worked in the casting areas. Here the men worked with the master alloy which is a molten metal solution containing 5-10% beryllium with 90-95% base metal and trace elements. The exposure to beryllium fumes in this operation may have been considerable.

-1-

There are a few cases in the Registry and several other nonregistered, less definite cases where the worker's only exposure was from fabricating the alloy in the solid state. The hazard associated with these types of fabrication is the topic of this thesis.

In spite of the many forms beryllium may take, it enters the body almost entirely by inhalation. Very little beryllium is absorbed through the intestinal wall, while none penetrates the unbroken skin. Once in the lung, beryllium combines with a protein and is transported to liver, spleen and bone, with varying amounts remaining in the lung.[2]

The effects of beryllium poisoning can be divided into two categories: acute and chronic. The acute effects may involve either the upper or lower respiratory tracts, and may result in chemical pneumonitis and pulmonary edema. These acute reactions may be serious, and at least 18 such cases have resulted in death.[3] Signs and symptoms may include a nonproductive cough, dyspnea, bilateral widespread chest x-ray changes, and some weight loss in most cases. All abnormal signs and symptoms reverse within weeks to 6 months.[1]

The chronic form of beryllium disease most often affects the respiratory tract. The first signs are often weakness, easy fatigability and

weight loss without cough or dyspnea. A great number of cases have developed evidence of disease 5, 10 or 20 years and more after the last beryllium exposure.[2]

The clinical form of chronic beryllium disease has many variations which have been dealt with completely elsewhere.[3] There have been some clinical problems in positively identifying chronic beryllium disease cases. The disease may be asymptomatic, productive only of chest x-ray changes. When x-ray changes do exist, they are not specific to the disease and often correlate poorly with the patient's clinical status. The detection of beryllium in tissue or urine is evidence of exposure to beryllium, but does not necessarily mean that beryllium disease is also present.[3]

There are at least 45 individuals who were exposed to toxic beryllium compounds by proximity (neighborhood cases) and/or by handling contaminated clothing of workers and subsequently became ill.[3] Only estimates of exposures can be made in these and the majority of other cases of beryllium disease.

In 1961, the AEC presented data that showed a substantial fraction of more than 100,000 in-plant air samples with concentrations in excess of $0.1 \, mg/m^3$ for short periods and a significant number exceeding 0.5

mg/m^3 without the development of acute beryllium disease.[4]

Cholak et al.[5] have presented air sampling data from a beryllium copper alloy plant where the majority of area samples greatly exceeded the threshold limit value (TLV). The authors feel that these high concentrations have probably existed during the last 13 years in this plant, and, yet no cases of chronic beryllium disease have been reported among workmen who are under close medical surveillance. The Threshold limits Committee of the American Conference of Governmental Industrial Hygienists chose to let the original AEC limit of $2\mu g/m^3$ stand when they adopted their TLV on beryllium.[6] This limit was originally established in 1949, and was based on data presented at the Saranac Symposium in 1947.[7] The Occupational Safety and Health Administration (OSHA) has also adopted this limit in their standard, but has recently proposed a new TLV limit of $1 \mu g/m^3$.[8]

On October 17, 1975, OSHA proposed a new standard for beryllium which would lower the TLV from $2 \mu g/m^3$ to $1 \mu g/m^3$. OSHA's regulatory decision, based largely on animal data, was "to treat beryllium as a substance that poses a carcinogenic risk to man."[9] In justifying their decision, OSHA cited a few inhalation animal studies including work performed with rats by Reeves et al.,[10] and with monkeys by Vorwald et al.[11] Other references on bone cancer in experimental animals include Barnes et al.,[12] Dutra et al.,[13] and Gardner and Heslington[14] who worked with rabbits. Another study in bone cancer, not cited by OSHA, was performed by Higgins et al.[15] All of these animal studies resulted in some degree of positive correlation between exposure to beryllium compounds and the development of some form of cancer in animals.

Studies involving workers occupationally exposed to beryllium have not been as conclusive. Stoeckle et al.,[16] reported on 60 selected cases of chronic beryllium disease while Mancuso and El-Attar[17] studied the incidence of cancer in two separate beryllium companies. Neither study could correlate the incidence of cancer in a particular organ with the worker's exposure to beryllium. Later work by Mancuso[18] and a report by Hardy et al.[19] in 1967 present evidence which suggests some association of cancer with exposure to beryllium.

This thesis is concerned with the topic of beryllium-copper alloy, and the remainder of this historical review will be devoted to this subject. The interested reader can

find a thorough review of all aspects concerning the topic of beryllium elsewhere.[20]

The literature specifically concerned with the Be-Cu alloy is very limited, and the views expressed are much more conflicting. The majority of the literature that does exist on Be-Cu alloys covers the initial production process rather than other types of fabrication such as machining, welding, and grinding. The initial alloy production process is concerned with the casting of master alloys containing about 5% beryllium metal. These casts are then distributed to foundries where they are diluted to the final beryllium content and cast into various shapes, depending on their final use. About 22 cases of beryllium disease reported in the Beryllium Case Registry[21] up to 1948 could be attributed to alloy manufacturing. Of the 41 cases of beryllium disease reported to the Beryllium Case Registry from 1969 to 1972, 9 of the workers had worked exclusively with beryllium alloys.[22] Most of these cases were found in workers exposed to dust and fumes from the casting operation. However, several of these cases were individuals who did not work in the casting department.

Jackson[23] in 1950 described six cases of chronic beryllium disease where none of the six were engaged

in casting the alloy. However, all of the six worked with the alloy at different points in the fabrication process.

Sneddon[24] described a case in 1955 of a woman in England who developed chronic respiratory disease from employment in an alloy plant where her only job was trimming 2% beryllium alloy strips on a rotary shearing machine.

Another case reported by the Occupational Hygiene Service[25] in England describes a person who had machined Be-Cu alloy.

Dickey[26] reported a patient with berylliosis who had been employed as a tumbling barrel operator for 12 months. The alloy used in the process contained less than 3% beryllium.

Tepper et al.[3] reported two patients with berylliosis whose only exposure was to beryllium copper alloy.

Israel and Cooper[27] reported two additional cases of beryllium disease from a Pennsylvania plant which fabricated beryllium copper alloy.

In 1964, Lieben et al.[28] reported three additional cases of probable berylliosis in persons working with beryllium-copper. The only occupational exposure to beryllium in one of these cases was the machining of Be-Cu alloys.

Several articles on the hazard of machining Be-Cu alloys take an

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opposite view of the occupational hazard.

In 1956, the American Industrial Hygiene Association published their Hygienic Guide on Beryllium and its Compounds.[29] In it they state that "machining of beryllium-copper alloys has never produced illness."

Recent information printed by the manufacturer states that "health experiences among the fabricators indicate that any hazard that may exist is of a low order. The absence of accredited toxicity cases may be related to the small percentages of beryllium in the wrought materials, the fact that the beryllium is to a great extent in solid solution, and the fact that the major fabricating operations are nonhazardous."

In opposition to the no-hazard concept for Be-Cu alloys, the Department of Labor has eliminated the distinction between beryllium and Be-Cu alloys. In their proposed occupational safety and health standard on beryllium, they define beryllium as "elemental beryllium and compounds and alloys of beryllium (as elemental beryllium) that may be released into the place of employment as particulate matter or that may be present in the place of employment in bulk forms."

Some animal studies with Be-Cu and Be-Cu-Co (cobalt is a common additive to the alloy) have been performed.

One study[1] found no frank beryllium lung disease occurring in several types of experimental animals exposed to varying concentrations of Be-Cu. Be-Cu-Co exhibited a rather high toxic potential for producing chronic pulmonary granulomatosis. Be-Al alloys were shown to produce not only this chronic pulmonary disease, b'.t pulmonary tumors as well.

These references contain a wide range of views concerning the possibility of disease from handling beryllium copper alloys, and suggest attitudes ranging from hazard to as hazardous as pure beryllium.

In industry, the alloy is handled with the same confusion as is found in the literature. Frequently the alloy is machined, ground, or otherwise fabricated without any workplace controls. Other times the alloy is treated with the same care given to pure beryllium.

Copper is generally considered as being a low-toxicity substance. Patty[30] lists some references describing discomfort and distress among workers exposed to copper fumes and dust.

Gleason[31] described three cases with similar symptoms resulting from exposure to fine copper dust in the order of one-tenth the TLV.

When compared with the TLV for copper dust (1 mg/m^3) or copper fume (0.2 mg/m^3), the TLV for beryllium

is 500 and 100 times lower, respectively. This simply means that even though there is 50 to 200 times more copper than beryllium in the alloy, the beryllium TLV will often be exceeded before the copper TLV in a given operation. In any case, both the beryllium and copper exposures must be measured to determine the worker's exposure.

The lack of information on the respirable dust hazard generated by the fabrication of Be-Cu alloys has created a problem anywhere these materials are handled. For this reason, the workroom practices may or may not treat the Be-Cu alloys as toxic materials.

PROPOSED STUDY

This study is concerned with those types of fabrication which take place after the alloy has been diluted to its final beryllium concentration and cast to some desired shape. These types of fabrication include machining, welding, drilling, grinding, brazing, sawing, and many others which modify the alloy's shape and appearance for some specific application. In any of these fabrication steps, there is the possibility that metal dust or fumes are generated and emitted into the workplace environment.

In this study, four methods of fabrication are investigated: milling, sawing, welding, and brazing. Each of these operations is performed on the alloy to determine the following:

- Are aerosols generated which contain beryllium and copper and if so, in what concentrations do they exist?
- What are the characteristics of these aerosols?
- What effect do variations within each operation have on the amount of aerosol generated?
- Are dust and fume controls required and if so, what types are effective?

Hopefully, some conclusion can be made on the possibility of a hazard existing in the many other fabrication methods not evaluated in this study.

GENERAL INFORMATION

For many years, the value of Be-Cu alloy has been well known to engineers for achieving high reliability and performance in instrument electrical components. More recently, the application of these alloys has expanded greatly. The broadening use of these alloys is a result of the need for higher reliability, longer life, and higher current

ratings without increasing component size. A typical automobile today may have as many as 20 beryllium-copper parts in it. These parts include electrical connections, diaphragms, and springs, many of which are not readily accessible for replacement and so must be highly reliable.

The current major use of beryllium metal is as the minor alloying agent in copper and other metals. The Be-Cu alloys may consist of 0.5 to 4% beryllium, although the most common alloy has about 2% beryllium. In general, the Be-Cu alloy family has a number of advantageous characteristics. It has about 25 to 50% the electrical conductivity of pure copper. It has the highest hardness rating of any copper-base alloys; in fact, hardness approaches the hardness of some forms of steel. Its tensile strength is high, making it the ideal alloy for springs used with electrical contacts. It has high fatigue strength, unusual wear resistance, good corrosion resistance, and it is also nonmagnetic and nonsparking. Because of these diversified characteristics, the alloys have found many applications including spark-proof tools, electrical circuits, aircraft bushings, springs for circuit breakers, and brushes, gears, and diaphragms.

Beryllium-copper generally comes from the manufacturer in one of two forms, either wrought products such as strip, rod, bar and wire for machining and forming, or as casting ingot for foundry use. The wrought forms go through a solution heat treatment at the mill which softens the metal. Then by varying age-hardening times and temperatures, different combinations of properties such as strength, ductility, conductivity, impact resistance, and elasticity can be obtained. This final heat-treatment step is generally performed by the fabricator after the alloy has been fabricated into its approximate size and shape so a minimum of milling and grinding on the hardened metal is required to acquire final dimensions.

MILLING AND SAWING

"Beryllium-copper alloys machine much like steel, but significant improvements can be achieved by modifying a few machining parameters." An article by two employees of Kawecki Berylco Industries, Inc.[32] contains the previous statement and recommends several machining parameters for properly turning, drilling, reaming, tapping, milling, sawing, and grinding different forms of the alloy. The article points out a few

special characteristics of the alloy that are worth mentioning here.

Beryllium is a strong solid-solution hardener, and its presence causes Be-Cu alloys to work-harden rapidly. This is a condition where the heat generated by the operation causes the surface of the metal to form a hard "glaze." This hardened layer is almost impossible to work with, and a cut of at least 0.007 in. is needed to get under this layer. Hardening can take place while the alloy is being machined if enough heat is generated. This hardening occurs when the metal is exposed to 550°F for long periods of time, and almost immediately at 700°F. This hardening results in ineffective machining and excessive tool wear.

Figure 1 shows a closeup of a milling operation. The number of metal chips in this photo could have been generated in about 10 minutes of milling. The particular milling tool shown is a shell mill, although three other types of tools were tested (see Fig. 2).

The shell mill consists of 8 to 10 cutting edges, and makes a corresponding number of cuts per tool revolution. This tool removes metal from the top of the metal bar as the bar passes back and forth under the

Fig. 1. Close-up of a milling operation.

-8-

End
mill

Shell
mill

Fly
cutter

Tool
holder

Carbide
cutting
edge
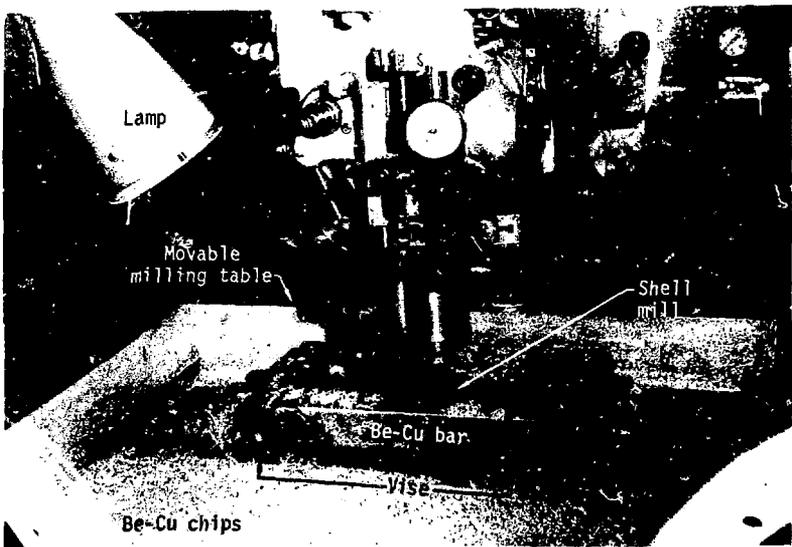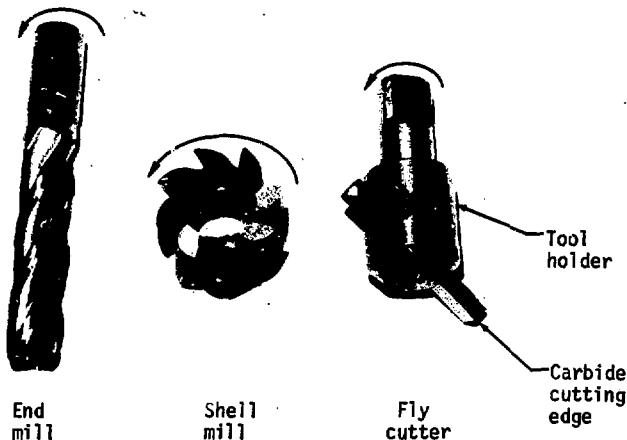
Fig. 2. The three milling tools tested (arrows show rotation of tool).

tool. The rate at which the metal bar passes is called the feed rate, and is measured in mm (in.)/min.

The fly cutter is similar to the shell mill in that it removes metal from the top of the metal bar, but has only one cutting edge made of carbide steel.

The end mill differs from the first two tools in that it removes metal from the side of the metal bar instead of the top. This tool has four cutting edges, and like the shell mill is made from high-speed steel.

The distributors of Be-Cu alloys often recommend various milling parameters such as cutting speeds and feed rate.[33] But depending on the type of surface needed and the time allotted for the job, a whole range of feed rates and cutting speeds may be used. Invididual machinists often cut Be-Cu alloy according to the way they think is best. One LLL machinist told me that the best cutting edge speed is when "the tool is revolving at a speed where you can barely see the individual flutes (cutting edges) as

they pass."[34] Others knew only that the alloy cut about the same as steel.

In any milling operation, the cutting tool is in a stationary position while it revolves at a given speed. The metal piece is secured to the milling table by a vise (Fig. 1). The entire table can be adjusted in any of three axes in order to make the desired cut. This movement determines the depth and width of the cut.

In general, machining operations can either be done wet or dry; that is, with or without a cutting or cooling liquid. The purpose of the liquid is to cool the metal piece and tool as cutting takes place; thus the piece does not become work hardened from excessive temperatures. The advantages of using a coolant also include a longer tool life due to less dulling, a better surface finish, and some control of the dust and chips generated while cutting. For these reasons a coolant is generally used when milling, sawing, or otherwise machining Be-Cu alloy especially because Be-Cu alloy can work-harden at normal dry milling temperatures. Cutting liquids are generally emulsions of soluble oil in water. The type of oil and the oil/water ratio depend on the lubrication and heat removal needed.

Beryllium-copper has different machinability ratings, depending on the type of alloy. The greater the percentage of beryllium, the harder the alloy becomes. The amount and type of heat treatment also affects the alloy hardness and therefore its machinability.

In some parts of this study, two types of Be-Cu were tested. However, most of the milling experiments were performed using the higher percentage beryllium alloy. This alloy contains 1.80% beryllium while the other alloy contains 0.50%. Although the amounts of beryllium in both alloys may appear quite similar, each has very different properties. The 1.80% beryllium alloy is considered a high-strength alloy and has 25% the electrical conductivity of pure copper. The lower percent alloy is the better conductor (50% that of copper), but has only half the tensile strength of the 1.80% beryllium alloy. Even with only 0.50% beryllium, the tensile strength is more than twice that of pure copper. Cobalt is also present in both of the alloys and may consist of up to 2% by weight, depending on the characteristics needed.

The sawing of Be-Cu alloy is the other mechanical type of fabrication studied. There are a number of different types of sawing, e.g., hacksawing, bandsawing, or circular sawing. A Do-All bandsaw was used in this part of the study. This mechanical method of cutting the

alloy is preferred over cutting with a torch since the latter does not result in a "clean" cut.

The method of metal removal in sawing is similar to that in milling. A tooth or blade is dragged across the metal, exerting a certain amount of pressure to mechanically remove the metal. Sawing is not recommended on age-hardened material. Generally it is performed to cut a piece of metal to approximate size so that it can be milled. Heat treatment generally takes place after milling and before grinding so that the shrinkage due to heat treatment can be allotted for, and any over-allotments can be removed in the final grinding.

WELDING AND BRAZING

According to Wesmantel et al.,[35] "beryllium copper alloys can be welded using the gas-tungsten-arc, gas-metal-arc and electron-beam processes. Except for the factors discussed, the basic welding practices follow those used for pure copper."[35]

The only type of welding performed in this study is inert-gas-tungsten-arc (TIG). In this type of arc welding, there is a flow of electric current from the tungsten electrode in the welder's hand, across the air gap to the piece of metal which is grounded. The flow of electricity causes a tremendous build-up of heat on the grounded metal. How quickly the heat dissipates depends on the thermal conductivity of the metal and atmosphere surrounding the point of contact. When the temperature at this point exceeds the melting point of the metal, a pool of molten metal forms. The welder works with this molten pool to form a weld between two pieces of metal. Depending on the temperature, a certain percentage of the molten metal vaporizes and then condenses in the air to form a metal fume. Typically, welding fumes of this type consist of very small particles that are not visible to the naked eye except in high concentrations.

Figure 3 shows the welding set-up used in one of the experiments. In the welder's right hand is the Linde HW-18 welding torch which serves a number of purposes. The welding torch securely holds the tungsten electrode for the welder. The welding torch, electrode and welder's hand are cooled by a closed-loop water cooling system within the welding torch. The torch also supplies a blanket of inert gas to the weld site. The inert gas used in this work was a 4-to-3 ratio of helium and argon. By adjusting this ratio, the welder can control the amount of heat at the weld site. The primary purpose

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Fixed sampler

Personal sampler

TIG welding torch

Flanged local exhaust opening
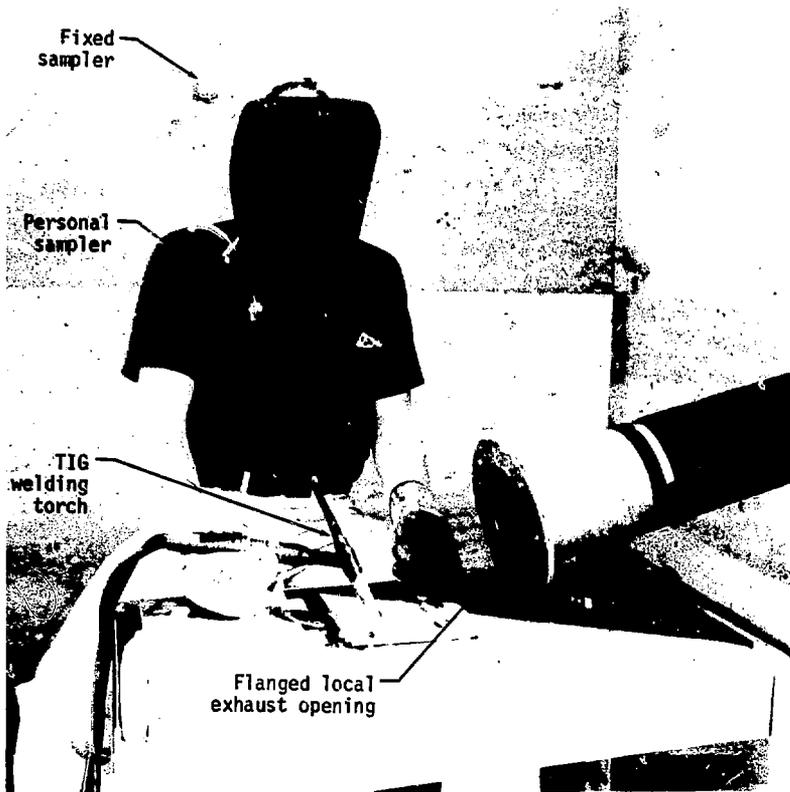
Fig. 3. Close-up of welding set-up used in evaluation of local exhaust control.

of the inert gas mixture is to shield the immediate welding area to prevent oxidation of the metal weld.

The brazing operation uses an oxygen-acetylene torch instead of TIG. First the metal pieces are generously covered with a flux which consists mostly of fluorides, to prevent oxidation of the surface of the metal during heating. Next, the area to be soldered or brazed is heated slowly, using the "feather" or far end of the oxy-acetylene flame. When the metal becomes almost a cherry red and the flux has become clear, the metal pieces are ready to be brazed. The brazing material is touched to the metal where it melts

-12-

and flows into the interface of the two metal pieces. This brazing material consists of 45% silver, 15% copper, 16% zinc, and 24% cadmium. For this experiment, a piece of brass and Be-Cu were brazed together.

Experimental Procedures

MILLING SAMPLING PROCEDURES

The Milling Matching Enclosure

To perform this phase of the study, an enclosure for the milling machine was required. The base of the enclosure shown in Fig. 4 is 1.8 × 1.8 m (6 × 6 ft) and stands 2.4 m (8 ft) high. The two side walls and the back wall were 1.9 cm (3/4 in.) plywood while the roof was composed of transparent plastic film. The front wall was also equipped with a door and a PF-105 filter section to clean the make-up air. Leaks in the enclosure were kept to a minimum by taping any visible cracks or seams. During sampling periods, the door and glove ports were kept sealed any time the operator did not need access to the controls inside.

The enclosure was necessary for a number of reasons. First, it provided a control for any beryllium dust which may have been generated during milling. The present Laboratory policy on Be-Cu alloy requires work practices equivalent to those used for beryllium metal. This enclosure was a suitable substitute for the normally used close-capture ventilation system. Secondly, the enclosure eliminated the natural air currents in the room, and allowed for an adjustable rate of general ventilation within the enclosure. Third, the enclosure isolated the sampling from any airborne beryllium dust that may be in the general room air as a result of work in the area with beryllium or its compounds.

To find whether any beryllium dust was escaping or entering the enclosure, a "giraffe" sampling unit was placed immediately outside the enclosure to sample for any airborne beryllium that may have been present. This unit was kept running any time sampling was going on inside the enclosure.

The flexible duct of the close-capture system can be seen on both machines shown in Fig. 4. The flexible duct inside the enclosure was positioned in the upper corner, opposite the make-up air inlet. The resulting air currents provided good mixing within the enclosure, as determined by smoke tube tests. With

-13-
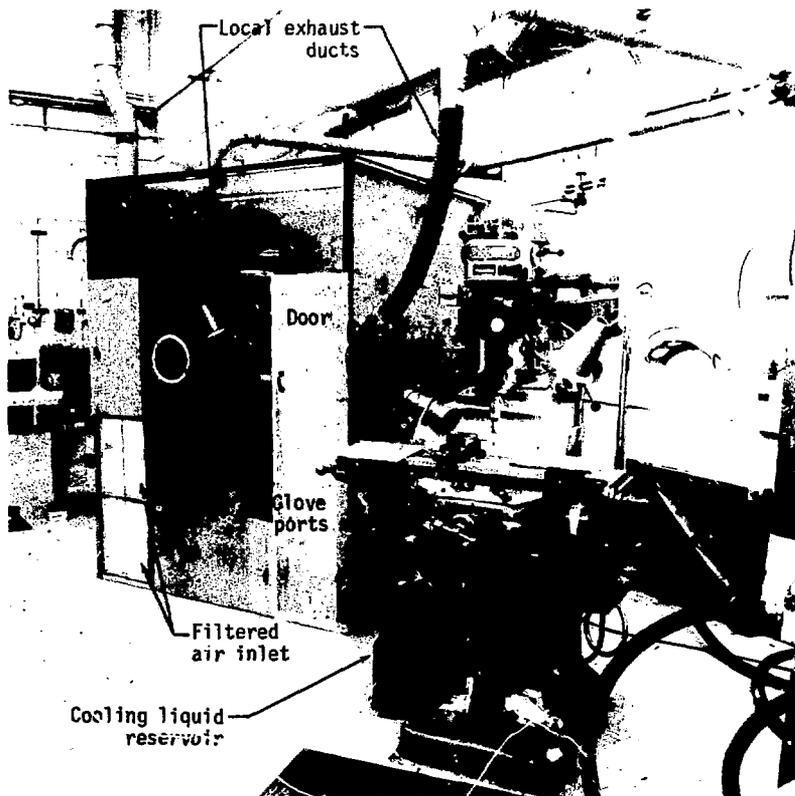
Fig. 4. A Bridgeport milling machine in an enclosure and a similar milling machine nearby.

this arrangement, the local exhaust rate was altered to provide the desired general ventilation rate within the enclosure. Since the volume of air in the enclosure was about 7.1 m^3 (250 ft^3), a local exhaust rate of 0.02 m^3/s (50 cfm) resulted in about 10-12 air changes per hours. If we assume good mixing in the enclosure, a doubling of the local exhaust rate would result in a doubling of the general ventilation rate.

The Air Sampling Train

Figure 5 is an illustration of the air sampling equipment used in this part of the study which includes four

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Plastic tubing - 7 ft

Orifice

37 mm filter
cassettes

Limited flow
orifices

10 mm nylon
cyclone

Pressure drop
indicators

Air sampling pump
("giraffe")

Diaphragm
valve
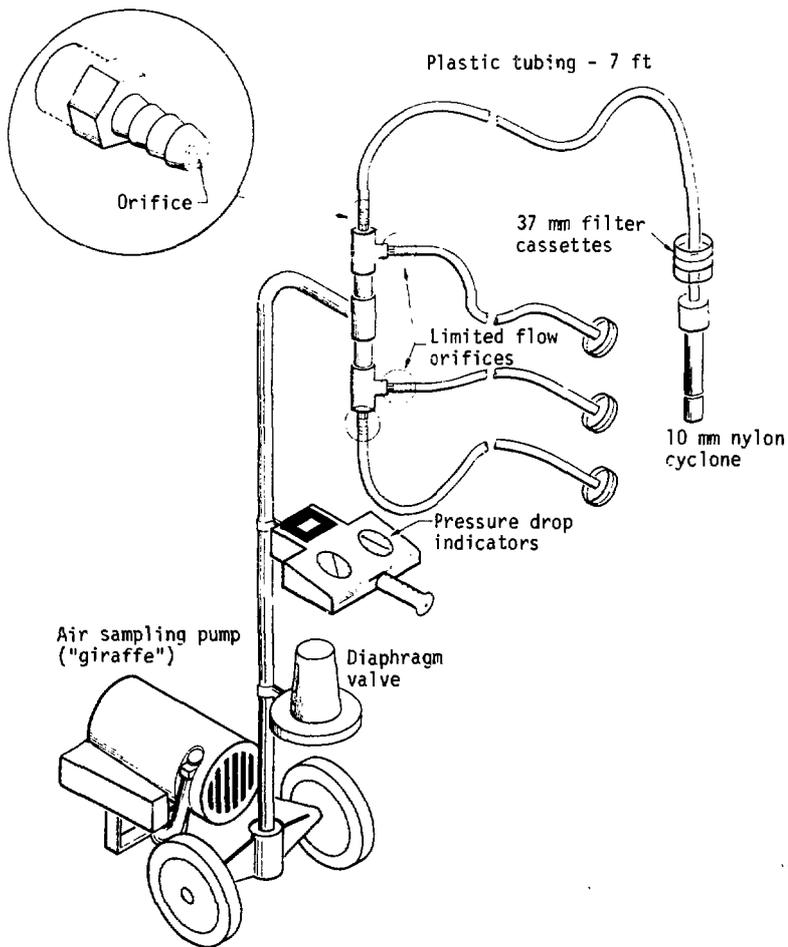
Fig. 5. Sampling train for milling experiment.

37-mm filter cassettes with either a 0.8 or 0.45-µ pore size Mf-Millipore filter. The flow rate in each of the four sampling heads was controlled through limited flow orifices. A close-up of the four-orifice set-up is shown in Fig. 6. The orifice consists of a brass hose fitting with a brass plug soldered over one end and a small hole drilled into this plug. A #78 drill provides the hole size necessary for the desired flow rate (2.8 ℓ/min). Each orifice was calibrated, and the individual results were within 2% of each other.

The critical or limited flow orifice requires a high differential pressure drop across the orifice to function properly. The "giraffe" high-volume air sampler provides approximately 0.51 m of mercury pressure drop across the orifice.
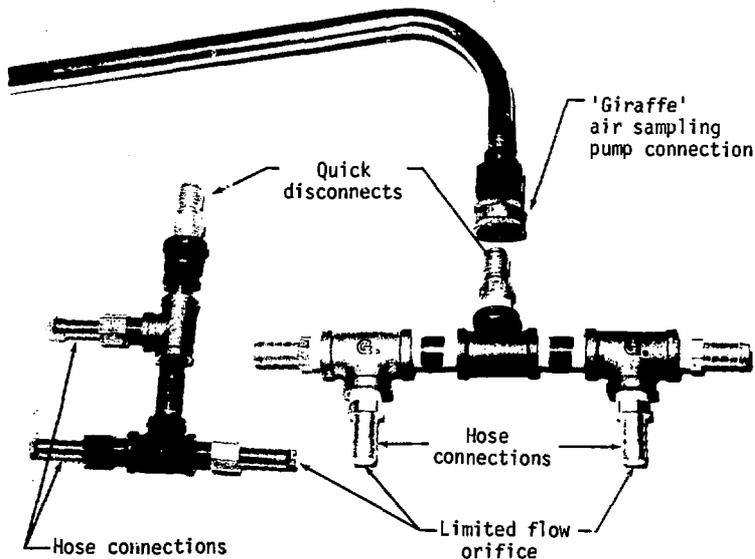
Fig. 6. Limited orifice set-ups for sawing (left) and milling (right) operations.

This air sampling pump was originally developed by the Lawrence Livermore Laboratory, and is now commerically available. The Radco Company in Oakland, California markets the pump as model HD-28. The pump's flow rate is adjustable from 14 to 85 ℓ/m through most filters.

In this experiment, the pump was used to provide a high-pressure drop across the limited or critical flow orifices. This differential pressure across the orifice keeps the flow rate through the orifice fairly constant, even with a build-up of particulate on the filter.

Using the set-up described, the air flow rate through a $0.8-\mu$ pore size filter averaged about 2.8 ℓ/min and about 2.7 ℓ/min through the $0.45-\mu$ pore size filter. The advantage of keeping the flow rate around this value was that any of the four sampling heads could be fitted with a 10-mm nylon cyclone for sampling respirable dust. The $2.8-ℓ/min$ flow rate for the 10-mm cyclone is recommended by Lippmann and Harris[36] to separate the nonrespirable dust portion in the first stage.

The four sampling cassettes were equally spaced around the cutting area during each run in order to obtain an average breathing area sample. Each cassette was from 0.3 to 0.6 m (1 to 2 ft) from the cutting area and approximately 1.5 m

(5 ft) above ground level which can be considered a conservative estimate of a machinist's normal breathing zone. The open face cassettes were partially shielded to prevent large particles or metal chips from being flung onto the filter face. These breathing area samples differ from breathing zone samples in that the latter are always personal samples, that is, the sampling cassette is attached to the worker and positioned near his nose while work is being performed. The breathing area samples were not attached to the worker, but were positioned as described above to estimate a milling machine operator's exposure. This method allowed three or four breathing area samples to be taken each run without exposing a worker to any hazardous particulate which may be generated. Generally, milling machine operators are required to remain at the mill while it is operating so that they are constantly exposed to any contaminants present.

Sixteen sampling runs were made using the milling machine. Each run lasted at least a couple of hours during which time the cassettes were sampling at a flow rate of 2.8 ℓ/min. Runs were made with and without coolant, under a number of varying tool conditions, and at various general ventilation rates within the enclosure to determine the effect

of these parameters on the dust concentration.

SAWING SAMPLING PROCEDURE

Another enclosure is shown in Fig. 7 which contains a Do-All band saw. This saw is used for cutting radioactive or toxic metals, and the enclosure controls any aerosols which may be generated. Generally, the plexiglass enclosure was exhausted at about 0.24 m^3/s (500 cfm) to maintain an inward draft through any openings in the enclosure and thus
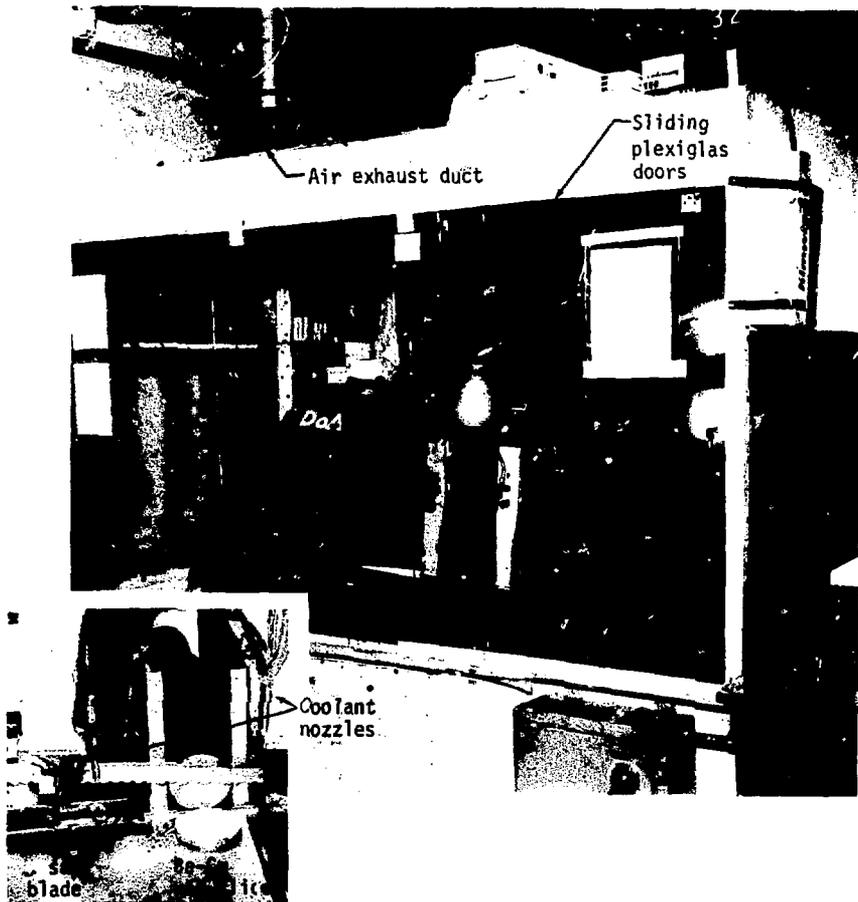

Fig. 7. Band-saw enclosure and close-up of the cutting area.

control the toxic dusts. During this sampling the exhaust was cut down to less than $0.01 \text{ m}^3/\text{s}$ (25 cfm) to estimate the concentrations of beryllium-copper dust that exists when no controls are maintained.

Figure 7 includes a view inside the enclosure with a 6.3-cm (2 1/2-in.) diameter Be-Cu rod securely in place and the band saw blade returning to its original position above the bar after having cut a 6-mm (0.25 in.) thick slice. Note the coolant nozzles both before and after the cutting area.

The band saw consists of a 3.6-m (12 ft) continuous blade made of steel which travels at a speed of about 37.5 m (125 ft)/min. Since cutting can be done either with or without a cooling liquid, both conditions were tested.

The sampling train used in evaluating the sawing operation was similar to the milling sampling train (see Fig. 5). Again the limited-flow orifice was used to control the flow rate and the "giraffe" air-sampling pump was used to supply the high differential pressure needed. Figure 6 shows the three orifice connections. Each orifice was calibrated at a flow rate of 2.7 ℓ/min through a 37-mm filter cassette with a 0.45-μ pore size Millipore Mf filter. The three cassettes were kept a short distance apart from each other and each was

positioned about 0.6 m (2 ft) from the cutting area. Since the bandsaw operator is again required to stay with a running machine, this sampling scheme was considered a good estimate of the operator's exposure.

Four runs were made on the band saw described above. Two of the runs were with coolant and two were without coolant. Sampling times averaged about one hour during which time as many as twelve individual cuts were made. At the end of each cut, it was necessary to open the enclosure door and change the position of the Be-Cu rod before another cut was made.

Both the 0.5% and 1.8% beryllium alloys were tested in this experiment. Other specifics of each individual run are presented in Appendix A.

WELDING AND BRAZING EXPERIMENTS
Welding Fume Generation Rate

An experiment was designed for estimating the amount of beryllium and copper fumes evolved while welding Be-Cu plate. The gloved box shown in Fig. 8 is the usual control used by the Laboratory for this type of operation. Generally the gloved box is exhausted, and serves as a total enclosure around the welding operation. In this particular experiment there was no air exhausted from the gloved box other than that pulled through the air sampler
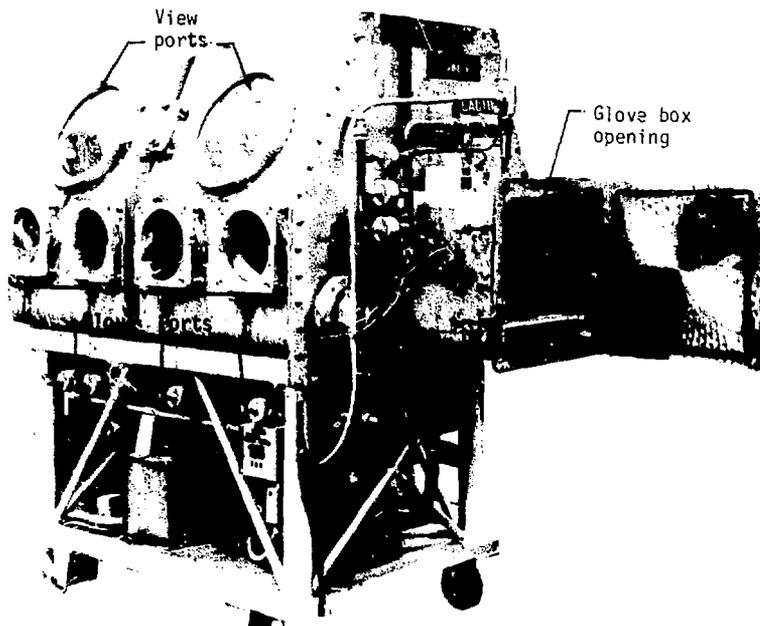
Fig. 8. Gloved box for welding experiments.

(Anderson impactor) at a rate of 28.4 ℓ/m (1 cfm). Table 1 gives the specific welding data for the two types of Be-Cu alloy plate which were welded.

Two sampling instruments were used in this experiment: (1) a Bendix electrostatic precipitator, Model No. 957, Serial No. 107 (see Fig. 9), and (2) an Anderson seven-stage impactor. According to the manufacturer of the electrostatic precipitator,[37] the instrument is about 95% efficient for particles less than 0.3 μ in diameter; however, it loses efficiency quickly above 1 μ, and is ineffective in capturing particles above 10 μ. The Anderson impactor, on the other hand, is very efficient for larger particles. In this experiment, a 47-mm Millipore filter with a 0.65-μ pore size was used as the back-up filter. The Anderson impactor sampled at a flow rate of 28.4 ℓ/m (1 cfm) while the precipitator sampled at a flow of 190 ℓ/m (6.7 cfm).

Five welds were made in this phase of the experiment, each 5 minutes long. Three welds were made on the 1.8% beryllium plate and two

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Table 1. TiG (tungsten inert gas) welding data sheet for two types of Be-Cu alloy.

	Be 1.8%	Be 0.5%
Base metal		
Thickness	Plate 0.95 cm (3/8 in.)	Plate 1.27 cm (1/2 in.)
Surface condition	Clean; acid etched	Clean; acid etched
Fitting	Same as base metal	Same as base metal
Thickness	0.31 cm (1/8 in.)	0.63 cm (1/4 in.)
Circumference	17.8 cm (7 in.)	17.8 (7 in.)
Flux or filler	None	None
Shielding gases & flow rate	Helium @ 8.5 ℓ/m (0.3 cfm) Argon @ 7.1 ℓ/m (0.25 cfm)	(Same)
Joint type	Lap	Lap
Welding current	200 amps alternating current	200 amps alternating current
Welding speed	~2 in./min	~2 in./min
Electrode	Tungsten	Tungsten
Diameter	0.48 cm (3/16 in.)	0.48 cm (3/16 in.)
Electrode to work distance	0.63 cm (1/4 in.)	0.63 cm (1/4 in.)
Torch type	Linde HW-18	(Same)

on the 0.5% beryllium plate. Two Anderson impactor samples were taken, one through the first three welds and the other for the last two welds on the 0.5% beryllium plate. The electrostatic precipitator was supplied with a clean collection cylinder for each of the five welds.

Both samplers were allowed to run during each 5 min weld and for an additional 10 min after the weld to collect as much as 16% to 44% of the welding fumes produced (See Appendix A). After this "clean-out" period and before the next weld began, the gloved box was exhausted for several minutes to ensure that no build-up of fumes occurred.

Evaluation of Three Methods of Controlling Welding Fumes

The three methods evaluated to determine their effectiveness in controlling welding fumes were: (1) a local exhaust system (close cap-ture), (2) a total enclosure, and (3) an exhausted hood.

The gloved box shown in Fig. 8 was used as the total enclosure for the first experiment. A breathing

Voltage meter

Air inlet

Step up transformer

Exhaust opening

Fume collection cylinders
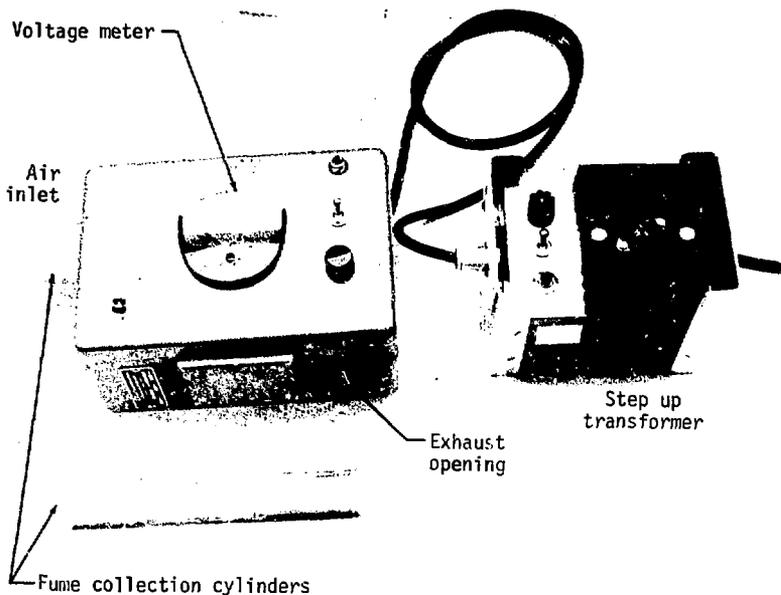
Fig. 9. Bendix electrostatic precipitator (Model 957).

zone sample on the welder was taken during the 5-minute weld to document the expected "no exposure" condition. A 37-mm Millipore filter with 0.45-μ pore size was used at a sampling of 2.8 ℓ/min.

Another experiment was done with the gloved box to simulate welding in an exhausted hood. The welding was performed in the 46.6 × 46.6 cm (16 × 16 in.) opening of the gloved box while it was being exhausted from the opposite end (see Fig. 8). The gloved box was exhausted at two different rates to give a 0.08 m/s and 0.15 m/s (150 and 300 fpm) face

velocity at the opening. The welding took place about 15.2 cm (6 in.) inside the opening. Two breathing zone samples were taken during each of the 5-min welds using the same filter type and flow rate as in the first experiment.

A final experiment was set up to determine the effectiveness of a local exhaust control. Figure 10 shows a TIG welding operation, a close capture system and a large enclosure around the operation. The 1.8 × 1.8 × 2.4 m (6 × 6 × 8 ft) enclosure includes a front wall which is not shown. The only large opening

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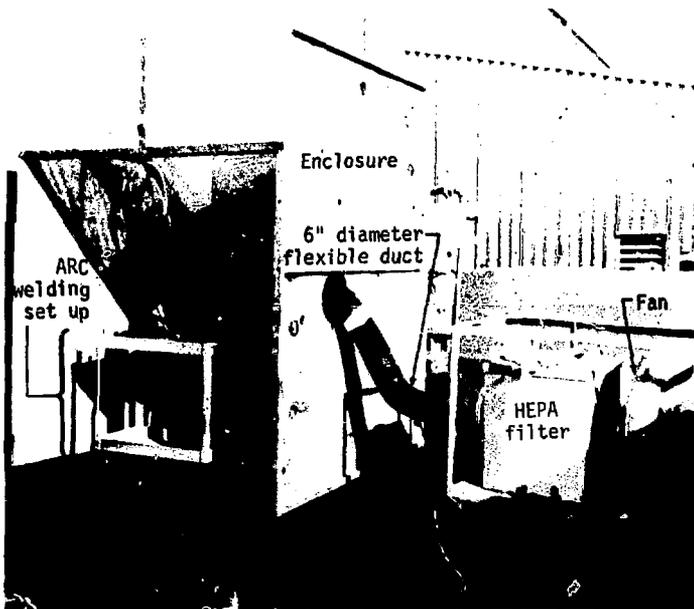
Fig. 10. Welding set-up for evaluation of local exhaust control (front panel of enclosure is not shown).

in the enclosure during sampling was a 0.6 × 0.6 m (2 × 2 ft) hole which allowed the make-up air to enter. It was necessary to enclose the welding operation to control the welding fumes which escaped the local exhaust pick-up, and also to control the wind conditions and thus simulate a welding operation inside a building.

Figure 3 shows two filter cassette samplers. One is positioned near the welding helmet to sample the welder's breathing air. The other is in a fixed position, 0.6 m (2 ft) above the 0.3 m (1 ft) over from the arc, as recommended by the American Welding Society[37] in their proposed sampling procedure. This position is also an estimate of the welder's breathing air, but has the advantage of being stationary throughout the weld, unlike the sampler on the welder. The welder wore a half-mask

respirator in addition to his normal protective equipment for this part of the experiment.

The local exhaust system consisted of a centrifugal fan, HEPA filter, 3.6 m (12 ft) of flexible duct and a 15-cm (6-in.) diameter flange. The effectiveness of the local exhaust system was tested by measuring the welder's exposure while varying the exhaust rate and the distance between the welding arc and local exhaust system. The system's capture effectiveness was tested at three distances from the arc: one-, two- and three-duct diameters. At each distance, three exhaust rates were tested: 0.24 m^3/s (500 cfm), 0.14 m^3/s (300 cfm) and 0.07 m^3/s (150 cfm).

Brazing

The brazing experiment was done inside the gloved box shown in Fig. 8. The door was kept shut and no air was exhausted during the experiment.

A small piece of brass was brazed onto a 5×5 cm (2×2 in.) piece of Be-Cu alloy using a brazing compound consisteng of 45% silver, 15% copper, 16% zinc, and 24% cadmium. The two pieces of metal are first heated slowly until they are 'red hot' and

then the brazing compound flows into the interface of the metal pieces.

To determine if any beryllium is emitted during brazing, the electrostatic precipitator (Fig. 9) was used alone to sample the gloved box environment. The precipitator sampled during the 8-minute braze and for a 10-minute "clean-out" period afterwards at a rate of 190 ℓ/m (6.7 cfm).

AIR FLOW CALIBRATION AND SAMPLE ANALYSIS

Analytical Methods

The filters, Anderson impactor samples, and electrostatic precipitator samples were all analyzed by Kyle Griggs in the LLL Industrial Hygiene analytical Laboratory. This analytical laboratory routinely handles about 6000 beryllium air samples per year.

The filter samples from the various experiments mentioned above were all sealed immediately after sampling was completed. This was accomplished by placing a lid over the open-face cassette and then securely taping the assembly. This method kept the filter isolated from the outside environment until it was ready for laboratory analysis. After the filter was removed, the cassette

assembly was washed for reuse and the back-up filter pad was discarded. A new filter and filter pad were placed in the clean cassette assembly and again taped to ensure no contact with the outside environment until ready for sampling.

Each of the filter samples from these experiments was first placed in a beaker containing about 80% nitric acid and 20% perchloric acid. The beaker was then heated to digest the cellulose filter and to boil off the majority of the acid. The dust sample remains dissolved in less than 1 mℓ of acid. To this, 5 cm^3 of 1% perchloric acid in water was added. It may be necessary to dilute this solution many additional times before the concentration is low enough to be read directly from the atomic absorption (A.A.) unit. The A.A. unit was a Perkin-Elmer Model 306 equipped with a nitrous oxide-acetylene flame. This unit can be calibrated to read directly to the nearest tenth of a microgram (0.1 μg). But because of the fluctuations in the direct read-out, the readings were also recorded on a chart to arrive at an average value more accurately.

The majority of the filter samples were analyzed for both beryllium and copper. A beryllium hollow cathode lamp at a 234.8-nm wavelength was used when analyzing for beryllium. A chromium-copper cathode at a

324.7-nm wavelength was used when analyzing for copper.

The Anderson impactor stages were made of glass instead of stainless steel to facilitate the same acid washing technique used for the filter samples. However, the metallic dust from the milling operation did not stick to these glass impaction plates. To make the plates more sticky, a 4% mixture of Apiezon grease in toluene was sprayed on the impaction surface and allowed to dry. A thin layer of grease remained which added to the impaction efficiency but caused an analytical problem. The organic grease did not digest well in the acid mixture and tended to collect on the sides of the beaker during heating. Only by repeatedly washing down the sides of the beaker with fresh acid was the grease digested.

Each impaction plate was analyzed separately to determine if any concentrating of beryllium occurred in a particular size range. The 0.65-μ pore size, 47-mm Millipore back-up filter was analyzed in the same manner as the cassette filters.

During sampling, the particles were collected on the removable aluminum tube in the Bendix precipitator shown in Fig. 9. The inside of the tube was repeatedly washed with concentrated nitric acid, scraped with a rubber policeman, and rinsed with

a 1% perchloric acid solution to collect the particles in a beaker. From this point the beaker was analyzed in the same manner as the one containing a digested filter, except that it had to be diluted several hundred times before it could be directly read on the A.A. unit.

Determination of Air Flow Rates

Calibration of the air flow rate through the Anderson impactors, cassette filters, and electrostatic precipitator was required to ensure accurate estimates of the dust and fume concentration. The calibrating instruments consisted of the following: (1) a 142 liter (5 ft^3) air spirometer,[*] and (2) a 14 liter air spirometer.[†] During calibration

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[*] American Meter Company, Model ALL 13, Serial 3586.

[†] Warren E. Collins Company, 555 Huntington Avenue, Boston, Massachusetts.

of the limiting-flow orifice set-ups, care was taken to determine the effect of dust loading. The change in the flow rate through the loaded filter did not become significant until the pressure drop across that filter was increased to 0.61 m (24 in.) H_2O from the usual 0.20 m (8 in.) H_2O) across a clean 0.8-μ pore filter.

The advantage of using a "giraffe" air sampler in much of this work was that the flow remained constant despite an increase in resistance of 0.64–0.76 m (25–30 in.) of Hg. The diaphragm valve on the "giraffe" sampler is capable of adjusting the flow automatically as the pressure drop changes during sampling.

Results and Discussion

MILLING AND SAWING

The breathing area concentrations of dust found while milling Be–Cu alloys are dependent on a number of milling conditions. The type of tool, amount of tool dulling, depth of cut, and type of alloys are all factors which may determine the

amount of dust generated. The general ventilation rate, air currents, and the operator's position also help determine the operator's exposure.

Appendix C gives the results of all sixteen sampling runs performed with the milling machine. Note that

several variations in the milling operation were tested for their effect on the dust concentrations measured. The effect of variations in the general ventilation rate was also tested. Most of the runs were performed at one particular ventilation rate, and these runs are presented in Table 2.

The breathing area concentrations reported in both Table 2 and Appendix C are average concentrations based on the two, three or four total dust samples taken during each run. There are often great variations in the amount of dust collected by the individual samplers in a particular run. This variation is a function of the distance of the different sampling heads from the source and the air currents in the immediate area.

Only two runs shown in Table 2 resulted in average breathing area concentrations greater than 1 $\mu g/m^3$. Both of these runs were performed dry with a shell mill and at above normal cutting tool speeds (1115 rpm).

Table 2. Average breathing area concentrations of beryllium in total dust samples taken during various milling operations of 1.8% Be-Cu alloy under normal general ventilation.[a]

Type of tool	Run no.	Special conditions	Average breathing area beryllium concentration ($\mu g\ Be/m^3$)
End mill	12	dry cut	0.9
Fly cutter	8	thick dry cut (0.025 in.)	0.4
Fly cutter	9	thin dry cut (0.010 in.)	0.0[b]
Shell mill	13	dry cut	0.4
Shell mill	14	wet cut	0.4
Shell mill	15	dry cut	0.3
Shell mill	10	wet cut	0.9
Shell mill	7	dulling tool; excessive heat & noise produced	7.4
Shell mill	16	dry cut	2.0

[a] Approximately 0.02 m^3/s (50 cfm) or about 12 air changes per hour.

[b] Below 0.05 $\mu g/m^3$.

Run 7 was performed under very abnormal conditions, in fact, the metal began to work-harden and milling had to be stopped because of the hard glaze that formed on the surface of the alloy.

When a tool's cutting edge begins to dull, it begins to rub against the alloy rather than cut through the metal. The increased friction results in excessive heat and noise produced. Dust generation also appears to increase during these abnormal conditions, although Run 7 is the only run which supports this statement.

Most of the runs were performed with the shell mill since it makes eight or ten cuts per revolution while the end mill and fly cutter make four cuts and one cut per revolution, respectively. Each tool did produce measurable concentrations of beryllium in air, and these concentrations were generally in the 0- to 1-$\mu g/m^3$ range.

The cutting tool speed and metal feed rate did not appear to directly affect the amount of aerosol generated. For example, Runs 1 and 2 (see Appendix C) were identical except for the feed rate. Run 1 had a feed rate which was cutting metal at a rate three times that of Run 2, and yet the latter run produced a slightly higher concentration of beryllium in air. This same lack of

correlation exists between the spindle speed (cutting tool speed) and the concentration of beryllium in air.

The depth of cut was usually kept fairly thin throughout most of the runs. Its effect on the dust concentration was not clear from the tests performed. A thick and a thin cut were made in Runs 8 and 9 using a fly cutter. The thick cut resulted in a slightly higher concentration of beryllium in air.

Each of these milling parameters may have an independent effect on the concentration of beryllium in air. Their cumulative effect on the dust concentration would be difficult if not impossible to determine. These factors, combined with the effects of tool dulling and alloy properties, make it difficult to predict how much beryllium would be given off in a given milling operation. How much of this would a worker be exposed to is determined by his position with respect to the work and the air currents in the area.

Note that the concentrations shown in Table 2 were all present during "normal" general ventilation conditions inside the enclosure. In fact, this general ventilation rate of 12 air changes per hour in a typical industrial machine shop would be an optimal condition. The effects of general ventilation rate on beryllium concentration in the enclosure

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were tested, and the results are shown in Fig. 11. Again, each data point is an average of the three or four total dust samples in a particular run. The amount of dust generated during these runs was held constant by using similar milling conditions so that any change in dust concentration is most likely due to the ventilation rate. The graph shows a dramatic increase in concentration as the general ventilation rate approaches zero. These results are only applicable to this particular ventilated enclosure, and should be used only as an aid in interpreting the data in Table 2 and Appendix C. If the general

ventilation rate had been closer to normal (10-15 air changes per hour), the concentrations of beryllium in air would have been higher for many of the runs listed in Appendix C. At a very low general ventilation rate, most of the milling operations listed in Table 2 may have resulted in beryllium concentrations exceeding the present TLV of 2 $\mu g/m^3$.

Table 2 also shows the beryllium concentrations during two wet cuts. Though care was taken to ensure that the entire cutting area was flooded, some dust still escaped contact with the liquid and became airborne. The main advantages of the coolant from an industrial hygiene aspect are the
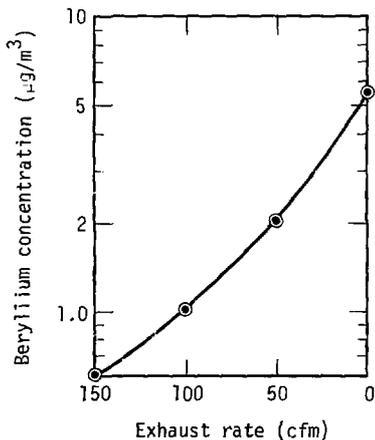
Exhaust rate		Average Be concentration ($\mu g/m^3$)
cfm	Air changes per hour	
0	0	5.4
50	12	2.0
100	24	1.0
150	36	0.6

Fig. 11. Effect of general ventilation rate on beryllium concentration under similar milling conditions.

cooling and lubrication that take place. Keeping the amount of friction and heat down is very important to prevent the tool from dulling and enable it to cleanly cut the metal rather than rubbing it. When using cutting liquids, it is important to have good housekeeping practices because much of the dust and chips are entrained in the liquid which often splashes on the floor and evaporates, enabling the dust to be reentrained into the air.

Very little respirable dust was found in any of the cyclone samples taken. The respirable dust concentrations averaged 0.1 $\mu g/m^3$ or less. An Anderson impactor sample showed about 90% by weight of the airborne dust was above 7 μ aerodynamic equivalent diameter (see Appendix B). The Be-Cu ratio remained fairly constant on each of the impactor plates; therefore, no appreciable concentration of beryllium took place in any particle size range.

The background air sampler located immediately outside the milling enclosure recorded concentrations of beryllium consistently below 0.002 μg of Be/m^3. This concentration was considered to have a negligible effect on any air sampling inside the enclosure.

In any of the filter samples it was difficult to determine in what form or compound the beryllium

existed. The beryllium particles may have been encapsulated by the copper, or found in some other form. In the analysis, the beryllium would have been released and analyzed the same as a free beryllium particle. This was one of the limitations of the analytical method used. However, it was the analytical method recommended by NIOSH in their criteria document.[2] The assumption must be that any type of airborne beryllium may be hazardous.

The sawing of Be-Cu alloys generated about a 1-$\mu g/m^3$ concentration of beryllium in air when performed dry and less than 0.1 $\mu g/m^3$ during wet cuts (see Appendix D). The cutting liquid was much more effective in reducing dust generation in sawing than in milling. This may be the result of the slower cutting edge speeds used in sawing or the different method of applying the coolant. The cutting liquid was also needed to keep the blade lubricated and prevent the blade from binding while passing through the metal and coming to a complete stop.

Accurate estimates cannot be made of dust concentrations expected during other fabrication methods such as grinding, reaming, or drilling. The amount of dust generated is greatly dependent on the specific operating conditions. One should

assume that any type of fabrication of the alloy will give off beryllium dust and/or fume, and air sampling measurements should be made to establish what levels of contaminant are present.

One may assume that the concentrations of Be in air that are associated with a grinding or polishing operation would be higher than those found in machining operations, and there is some evidence to support this assumption. The NIOSH Criteria Document[2] presents air sampling data in Table 3 which shows concentrations of beryllium in air associated with machining and polishing operations.

The machining operation resulted in concentrations similar to those found in these experiments (0.08 to 1.6 µg Be/m^3). The polishing operation reported concentrations of 208 and 346 µg Be/m^3. We may assume that a grinding operation would result in concentrations somewhere between those found in machining and polishing operations.

WELDING AND BRAZING

A welder's exposure to the fumes produced while welding will depend on how much fume is generated and how much of this fume enters his breathing zone. An attempt was

Table 3. The effect of local exhaust rate and capture distance[a] on breathing area concentrations of beryllium in air.

Capture distance[a]	Local exhaust rate m^3/s (cfm)	Average concentration of beryllium (µg/m^3)
15.2 cm (6 in.) or one duct diameter	0.24 (500)	0.0[b]
	0.14 (300)	0.0[b]
	0.07 (150)	0.0[b]
30.4 cm (12 in.) or two duct diameters	0.24 (500)	0.0[b]
	0.14 (300)	0.0[b]
	0.07 (150)	1.3
45.6 cm (18 in.) or three duct diameters	0.24 (500)	0.9
	0.14 (300)	1.3
	0.07 (150)	10.4

[a] Distance from the point of welding to the local exhaust opening.

[b] Below 0.05 µg/m^3.

made to determine how much fume was generated during welding on two types of Be-Cu alloy. To accomplish this, the operation had to be completely enclosed in order to capture all of the fumes. The majority of the fumes were then removed from the air and analyzed.

The amounts of beryllium and copper in the welding fumes collected while welding the two types of Be-Cu alloy plate are shown in Table 4. Generally, the amount collected by the electrostatic precipitator (e.s.p.) are seven times that collected by the impactor since the e.s.p. sampling rate is seven times that of the impactors. There is

good agreement between the two sampling methods except for the 39,850 µg of copper from the electrostatic precipitator. This value is low when compared proportionately to the Anderson impactor sample. It is suspected that the collection efficiency of the instrument decreased with the excessive fume loading in the collection tube.

Since the majority of welding fumes were collected, a conservative estimate of a fume generation rate can be made. Table 5 gives a beryllium and copper fume generation rate for both types of alloy.

At these fume generation rates the hazard to the welder is obvious,

Table 4. Beryllium and copper fumes collected while TIG welding Be-Cu plates in a total enclosure.

Type of Be-Cu plate	Individual sampling methods (air-flow rate)				Total of two methods	
	Electrostatic precipitator 190 ℓ/m (6.7 cfm)		Anderson impactor 28.4 ℓ/m (1 cfm)			
	Be(µg)	Cu(µg)	Be(µg)	Cu(µg)	Be(µg)	Cu(µg)
1.8% beryllium 0.95 cm (3/8 in.) thick not age-hardened	2,700	33,300	400	4,400	3,100	37,300
0.5% beryllium 1.27 cm (1/2 in.) thick age-hardened	1,450	39,850	200	9,600	1,650	49,450

Table 5. Estimated generation rate for beryllium and copper welding fumes.

Type of Be-Cu plate	Total welding time (minutes)	Total collected fume		Welding fume generation rate (micrograms per welding minute)	
		Be(μg)	Cu(μg)	Be	Cu
1.8% beryllium 0.95 cm (3/8 in.) thick not age-hardened	16	3,100	37,300	195	2,330
0.5% beryllium 1.27 cm (1/2 in.) thick age-hardened	7	1,650	49,450	235	7,060

although there is no visible hazard while welding. For example, if a welder performed a 2-minute weld on a piece of 0.5% Be-Cu, he would generate approximately 470 μg of beryllium (2 minutes × 235 μg/min). Depending on his body position, etc., the welder would be exposed to some percentage of this amount. If this welding was performed in a weld shop without proper ventilation, the problem may be compounded by the continuous exposure of the other welders in the area.

The next part of this study evaluated three of the methods used in controlling these fumes. When the gloved box was exhausted and used as a total enclosure, the breathing zone samples on the welder showed no beryllium.

When the opening in the gloved box was used as an exhaust hood with the welding done inside the opening, an exposure of 0.2 μg/m^3 was found at both 0.08 m^3/s (150 fpm) and 0.15 m/s (300 fpm) face velocities. This exposure may be a result of the welder's tendency to bend over his work wo that part of his head and helmet may "break" the face of the hood. At no time did the samplers "break" the hood face.

The local exhaust control was evaluated for the effect of distance and exhaust rate. The "average concentrations" shown in Table 5 are an average of the fixed and personal sampler results. The fixed sampler usually had a greater amount of collected fume than the personal sampler. This may be a result of its position within the welding fume plume rising from the hot metal surface.

To calculate the capture velocity at the point of fume generation, the following formula was adapted from the Industrial Ventilation Manual:[38]

$$V = \frac{Q}{0.75(10\ x^2 + A)}$$

where V = capture velocity at
distance x from the hood

X = distance from the point of
fume generation to the
exhaust hood

Q = air flow cfm

A = area of hood opening in ft^2

If x is equal to 0.3 m (1 ft) and Q
is equal to 0.14 m^3/s (300 cfm), the
capture velocity at the point of fume
generation is equal to 0.02 m/s
(40 fpm). When compared to the 0.05-
0.10 m/s (100-200 fpm) capture
velocity recommended by the Industrial
Ventilation Manual,[38] the 0.02 m/s
(40 fpm) velocity appears to be
insufficient. However, for this
particular welding operation, the
0.02 m/s (40 fpm) capture velocity
resulted in a non-detectable concen-
tration of Be in the breathing zone.

The electrostatic precipitator in
the brazing operation collected 10 μg
of beryllium, 310 μg of copper and
16 μg of silver. The brazing material
consisted of 15% copper and 45%
silver. It is interesting to find
this much beryllium coming off a
small piece of heated alloy. It is
assumed that as the surface area of
the heated alloy increases, so would
the amount of beryllium fume given
off. About 51 cm^2 (8 $in.^2$) of plate
surface was exposed to the air in
this experiment.

Conclusions

GENERAL

Beryllium-copper alloys should be
considered toxic materials and
proper controls must be used when
they are machined, heated, or other-
wise fabricated. Air samples should
be taken for each type of fabrication
to determine the worker's exposure
and the effectiveness of the controls
in use.

It has been shown that aerosols
containing beryllium are generated
during the four methods of fabrication
tested, and that these aerosols can
be reduced through local exhaust to
undetectable levels. Considering
the acute, chronic and possibly
carcinogenic effects of exposure to
beryllium, effective controls should
be required because they are feasible
both technologically and economically.

MILLING AND SAWING

Under optimal milling conditions
(proper cutting speed, sharp cutting
tool and good general ventilation)
the concentration of beryllium in
the breathing zone is generally below

1 μg/m^3 for the three types of milling tested. However, slight variations from these optimal conditions (dulling tool, poor general ventilation, etc.) may result in concentrations of beryllium exceeding the present TLV of 2 μg/m^3. The fact that measurable concentrations of beryllium do exist under optimal conditions and that less than optimal conditions result in increases in the beryllium concentration is enough evidence to warrant the use of local exhaust controls during these operations.

Anderson samples taken during various milling operations showed about 10% weight of the airborne dust as respirable. These samples also showed no change in the beryllium/copper ratio with respect to particle size.

There appears to be a metal fume generated during the machining operations. Some evidence exists that the fume particles consist mainly of beryllium. Further research on this phenomenon is needed before any firm conclusions can be made (see Appendix F).

The mechanical sawing of Be-Cu alloy without coolant resulted in concentrations of beryllium in air around 1 μg/m^3. The particular cutting liquid set-up tested was very effective in reducing the airborne concentrations of beryllium to 0.1 μg/m^3. This control alone appears sufficient for controlling the dust generated during this type of sawing.

The use of a cutting liquid while milling did not significantly reduce the concentrations of airborne dust. In both milling and sawing the liquid lubricates and cools, and this reduces friction and therefore helps prevent the generation of excessive quantities of dust. For this reason, the use of a cooling liquid is highly recommended for all machining operations.

WELDING AND BRAZING

Tungsten inert gas (TIG) welding of Be-Cu alloys produces fumes at rates warranting controls, although no visible plume was generated.

The total enclosure tested is very effective in controlling the welding fumes.

Welding in an exhausted hood may expose the welder to some welding fumes, depending on his body position.

According to the data presented in Table 5, local exhaust ventilation is an effective control when the 15.2 cm (6 in.) diameter duct, close capture hood is kept within 30.4 cm (12 in.) of the welding point and exhausts at a rate of 0.14 m^3/s (300 cfm) or more. Another local exhaust set-up can be used providing it has similar capture characteristics.

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The brazing experiment showed that the simple heating of Be-Cu alloys will release beryllium to the air in measurable concentrations.

Acknowledgments

Appendix A. Computation for Decay Curve in Gloved Box Welding Experiment.

How much of the welding fumes in the gloved box are collected during the 10-min "clean out" after each weld?

Need to know: $\dfrac{C}{Co} = \dfrac{\text{concentration after 10-min "clean out"}}{\text{initial concentration}}$

decay equation $\quad C = Co\, e^{-\frac{Q}{V}t}$

where: $\quad Q$ = exhaust rate = 7.7 cfm

$\quad V$ = air volume of gloved box = 45 ft^3

$\quad t$ = time = 10 minutes

assume Co = 20 mg/m^3 (initial concentration)

therefore: $\quad C = (20\ mg/m^3)\ e - \dfrac{7.7cfm\ (10\ min)}{45\ ft^3}$

$\quad\quad\quad = 3.6$

$\dfrac{C}{Co} = \dfrac{3.6}{20} = 18\%$

conclusion: If there is perfect mixing in the gloved box, about 18% of the
initial amount of fume in the gloved box will remain after a
10-min clean out. Generally a K factor must be considered to
account for imperfect mixing. In this case the K factor may
range anywhere from 1/3 to 1/10 which would result in 56% to
84% of the original concentration remaining in the gloved box.
Realistically, about 44% to 16% of all the fume generated was
collected.

Appendix B. Size Distribution of Airborne Milling Dust Using Anderson Impactor Sample for Run 12 with AA Analysis.

Weight % > stated size

ECΔ	Stage No.	μg of Be	%	μg of Cu	%	cum %
7.0	1	50	92.1	2750	92.1	92.1
4.7	2	2.8	5.2	137.5	4.6	96.7
3.3	3	0.7	1.3	40	1.2	97.9
2.1	4	0.5	0.9	30	1.4	98.9
1.1	5	0.2	0.4	12	0.4	99.3
0.7	6	0.1	0.2	8.5	0.3	99.6
0.4	7	0.0	0.0	6	0.2	99.8
<0.4	filter	0.0	0.0	2.5	0.1	99.9
	Total	54.3		2986.5	99.9	

Conc. of 6.4 μg of Be/m^3 with
no general ventilation (5-hr
sample @ 1 cfm) s.g. of 2%
Be-Cu   8.4

Weight % < stated size
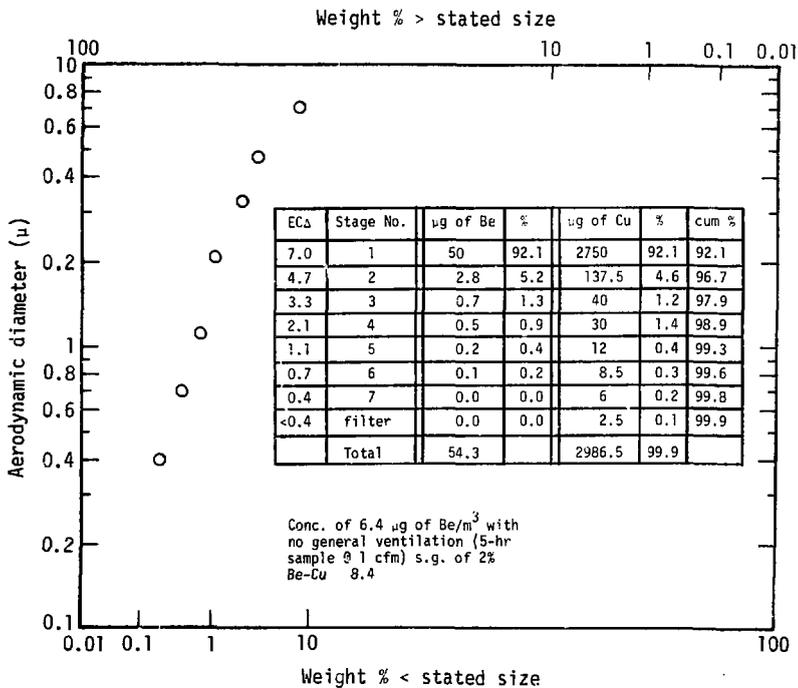
Appendix C. Amounts of Beryllium and Copper Aerosols Collected During Various Milling Operations on 1.8% Be-Cu Alloy.

Run no.	Exhaust rate in cfm and air changes/hr	Spindle speed (rpm)	Feed rate (in./min.)	Depth of cut (thousandths of inch)	Type of tool	Wet or dry cut	Micrograms of Be-Cu collected at the four sampling positions				Sampling time (hours)	Average total dust conc. of Be-Cu in air (mg/m³)	Comments
							1	2	3	4			
1	150 (36)	660	7 5/9	1	shell 2"	dry	1.5 / n.d.	0.0 / n.d.[a]	0.0 / n.d.[a]	1.1 / n.d.[a]	1.7	4.3 / n.d.	
2	150 (36)	660	2 9/16	1	shell 2"	dry	2.0 / 105	0.0 / 2.3[a]			2.5	4.8 / 552	
3	150 (36)	660	2 9/16	1	shell 2"	dry	1.0 / 5	1.0 / 45	0.7 / 34		2.5	2.2 / 199	new tool with sharp cutting edge
4	150 (36)	1115	5 3/4	1	shell 2 3/8"	dry	0.4 / 21	0.2 / 19	0.0 / 2.5[a]		4.25	0.4 / 30	
5	100 (24)	1115	7 5/8	2	shell 2 3/8"	dry	0.7 / 33	0.2 / 11	0.4 / 19	.08	1.75	1.5 / 73	approximately 100 g of metal chips produced
6	100 (24)	1115	4 3/8	2	shell 2 3/8"	dry	0.5 / 23	0.4 / 23	0.5 / 23	2.7	2.5	1.0 / 55	
7	50 (12)	1115	5 3/4	2	shell 2 3/8"	dry	1.4 / 60	4.8 / 220	0.1 / 1.4[a]		2.5	7.4 / 334	respirable Be dust conc. was 0.2 ug/m³
8	50 (12)	1750	2 9/16	25	fly 1 3/4"	dry	0.1 3 0.1 / 7 5	0.2 / 9.5	0.04[a] / 1.6[a]		2.5	0.2 / 19	
9	50 (12)	1750	5 3/4	10	fly 1 3/4"	dry	0.0 0.0 / 1.5 2.5	0.0 / 4.5	0.0 / 1.2[a]		2	0.0 / 10	
10	50 (12)	1750	5 3/4	4	shell 1 3/4"	wet	0.9 6.4 / 3y 11	0.5 / 16	0.2 / 3[a]		4	0.9 / 33	respirable conc. was 0.3 ug/m³
11	0 (0)	1750	5 3/4	2	shell 1 3/4"	dry	3.5 0.1 / 190 5[*]		0.1 / 3[a]		4	5.4 / 293	Anderson Impactor (see Appendix B)
12	50 (12)	325	5 3/4	5	end mill 3/4"	dry	0.2 0.3 / 13 14	0.5 / 23	0.1 / 2[a]		2.5	0.9 / 41	
13	50 (12)	325	5 3/4	5	shell 2"	dry	0.1 0.2 / 6 8	0.25 / 8.5	0.1 / 2[a]		2.5	0.4 / 16	
14	50 (12)	325	5 3/4	5	shell 2"	wet	0.1 0.2 / 2 2	0.1 / 1.5	0.1 / 2[?]		2	0.4 / 6	
15	50 (12)	325	5 3/4	1-5	shell 2"	dry	0.1 0.1 / 4 4				2	0.3 / 12	Rotron sampler attempt
16	50 (12)	1115	5 3/4	2	shell 2"	dry	0.6 0.6 / 26 28	0.8 / 31			2	2.6 / 85	

[a]Respirable sample.

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Run no.	% Be in alloy tested	Coolant (wet or dry)	No. of cuts made	Blade speed (fpm)	Blade type	Blade pressure 0-low 8-high	AA analysis of 3 cassette filters (µg Be/µg Cu) 1	2	3	Sampling time (min)	Average conc. of Be-Cu in air from three sampling cassettes µg/m³	
1	0.5% Be 6.35 cm (2 1/2 in.) diam rod	dry	9	125	old carbide tipped	0-1	0.06 / 8	0.6 / 120	0.1 / 15	60	0.5	103
2	0.5% Be 6.35 cm (2 1/2 in.) diam	wet	10	125	old hss	0-1	0.0 / 3	0.0 / 2	0.0 / 1	90	0.0	3
3	1.8% Be 5.1 cm (2 in.) diam rod	dry	6	125	new hss	0-1	0.1 / 8	0.0 / 3	0.0 / 2	40	0.1	14
4	1.8% Be 5.1 cm (2 in.) diam rod	wet	8	125	new hss 10 teeth/inch	0-1	0.0 / 1	0.1 / 5	0.0 / 0.6	60	0.1	4.8

Air sampling flow rate = 7.7 ℓ/min.

Appendix E. Scanning Electron Microscope Analysis.

One additional experiment not previously mentioned was performed with the milling operation to determine the constituents of the dust being generated. A milling operation was set up using a shell mill and 1.8% Be-Cu alloy. A filter sample of the milling operation was taken using a 0.3-μ pore size Nucleopore filter. The 5-min sample was taken at a flow rate of about 10 ℓ/min and at a distance of about 15.2 cm (6 in.) from the cutting point. A section of this filter was cut from the edge to the center of the filter. This section was gold-coated to provide a medium for the electrons to go to ground while under the electron microscope.

At this point, the sample was ready for the electron probe. A 20-keV electron beam scanned a particular area of the sample, and the wavelengths of the x rays emitted during this scan were mapped on photographic paper. A black and white photograph of the same area was taken to see which particles were giving off the x rays. The electron beam could be focused on an individual particle to determine the makeup of that particle.

The black and white photograph of the filter face shows several irregularly shaped particles about 5 μ or larger in diameter. Along with these large particles are numerous small spherical particles of about 0.5 μ and smaller in diameter. The ratio of the number of small particles to the number of large particles is about 100 to 1.

These small particles are most likely metal fume generated during the milling process. Very high temperatures 538-1093°C (1000-2000°F) are present right at the cutting point during milling or any cutting operation. These temperatures are enough to generate metal fumes at the cutting point each time a cut is made.[1]

Individual particle analysis with the electron probe was performed on three of the large particles and six of the small particles to determine their makeup. The three large particles consisted mainly of copper since they emitted x rays associated with this element. The six small particles were then probed, but none of them showed any presence of copper. In fact, they emitted no x rays associated with any element other than the gold used to coat the filter.

[1]Conversation with Werner Bergman, aerosol physicist at Lawrence Livermore Laboratory on October 13, 1976.

The reason for this absence of x-ray emissions is that elements below sodium in atomic number are poor emitters of x rays and cannot be seen by this instrument, so it is assumed that the particles are a form of one of these elements. There are a few possibilities in this group including lithium, boron or carbon, but the most logical choice would be some form of beryllium. Is it possible that a pure beryllium fume is generated when machining Be-Cu alloys? There is some evidence to support this supposition. Literature published by Kawecki Berylco Industries, Inc.[2] explains that beryllium-rich

deposits form from the solid solution state when the alloy is overheated. This separation occurs even though beryllium has a melting point about 200°C higher than copper which would suggest that the copper would melt first. Possibly the heat is transferred through the better heat-conducting copper to the beryllium where it is absorbed.

Further research in this specific area may better explain this behavior of beryllium copper alloys during machining operations. For the present, this study has determined only that the metal fume generated during milling does exist, but does not significantly contribute to the total mass of particulate collected.

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