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Product Research and Development
GENERAL METALLURGY

Rockwell International

Atomics International Division
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SUBJECT DESCRIPTORS

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Casting
Melting
Ingots

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CONTENTS

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Richard R. Corle, Robert W. Krenzer, and Kenneth E. Voiles

Abstract. Beryllium casting is a relatively new technology with the successful cast of large ingots being developed during the last decade. In 1961, Rocky Flats initiated a beryllium ingot-sheet fabrication process that included the development of new techniques to consistently cast large sound beryllium ingots. This report reviews the casting technology that was developed to cast these beryllium ingots on a production basis along with some of the remaining technical problems requiring additional development work.

SUMMARY

The static casting of large beryllium ingots 23 X 23 X 51 cm has been developed to the point where the operation has become a routine production process. The ingot yield has been poor (45%), however, because of contamination (high-density stringers and oxides, for example), shrinkage cavities, hot cracking, and large columnar grains. Ultimately increased demands for cleaner beryllium, free from inclusions associated with the casting process, eroded the cost effectiveness initially visualized for the process.

Development work on the centrifugal casting of beryllium also has been initiated. Some thin wall (<0.64 cm) casting has been produced successfully; however, additional major technical development efforts are required to make this a viable process.

INTRODUCTION

Beryllium casting is a relatively new technology that began about three decades ago. Early efforts focused on casting small ingots free from defects such as gas porosity, pipe, and cracking due to thermal stresses and multidirectional solidification. Small ingots were cast successfully, using a variety of casting techniques.[1] Attempts to cast larger ingots, however, met with limited success. The reasons were primarily the large columnar grains that formed during freezing and because heat extraction could not be controlled during solidification.

In 1961, Rocky Flats initiated an ingot-sheet beryllium fabrication process that involved rolling and forming cast product to manufacture various beryllium components.[2] The ingot-sheet process provided a valuable means of producing usable beryllium shapes from large quantities of available scrap. Reduced cost of wrought beryllium products over powder-source product provided a major justification for developing such technology. To maintain a cost effective process, however, it was necessary to cast large beryllium ingots. At that time, the development of new techniques was required to consistently cast large, sound beryllium ingots. This goal was accomplished, and the ingot-sheet process proved a viable source of beryllium for over 15 years.

Increased demands for cleaner beryllium, free from inclusions associated with the casting process, reduced the cost advantage of the process. In the beginning, a major selling point of the process was utilization of available scrap with loose controls of feed chemistry (to reduce costs). Ultimately this contributed to a higher priced product because of the rejection rate, which was caused by high-density inclusions. Efforts to improve control of feed chemistry are required to make ingot-sheet a more cost effective source of beryllium for current technology.

This report reviews the technology that was developed to cast large beryllium ingots at Rocky Flats; however, properties of beryllium fabricated by the ingot-sheet process (i.e., formability, weldability, ductility) will not be discussed. It represents the efforts of many individuals who were associated with the process since 1961. It is important that their individual revelations and reflections about the casting process be organized in a concise manner to provide a basis for the next generation of development. In this regard, the equipment used, details of furnace setup, special precautions necessary to produce sound ingots, and optimum casting practice are reviewed in this report.

EQUIPMENT

Producing sound cast beryllium ingots requires the use of sophisticated equipment and techniques. The standard equipment used at Rocky Flats for melting and casting beryllium ingots are discussed in the following paragraphs.

Furnace

All beryllium ingots produced at Rocky Flats are melted in bottom-pour vacuum-induction casting furnaces. The melting is accomplished in predominantly two furnace sizes. Small castings are produced in a 107-cm inside diameter (I.D.) Consolidated Vacuum Corporation furnace that has a 30-cm I.D. coil powered by a 50-kW, 3000-Hz motor generator set. The coils are protected by a liner fabricated from Kaiser Super Hi-cast refraction cement. This small induction furnace also is equipped with a centrifugal casting capability. Large castings are produced in a 165-cm I.D. Stokes vacuum-induction furnace that has a 74-cm I.D. coil 107 cm long and is powered by a 250-kW, 960-Hz motor generator set. The coils are protected by Kaiser M28 refractory brick.

Both induction furnaces are equipped with Stokes roughing pumps that provide an adequate vacuum (100-500 micron) for casting beryllium.

Miscellaneous Equipment

The thermocouples used to measure mold temperature are chromel-alumel enclosed in an inconel sheath. Melt temperatures are measured with a radiation pyrometer. Remaining equipment such as scales, hoods, and loading carts are typical of those used in normal foundary practices.

MOLDS, CRUCIBLES, AND AUXILIARY HARDWARE

Most of the molds, crucibles, stopper rods, hot tops, vent tubes, bungs, and sprues are fabricated from sound high-density graphite (Great Lakes HLM or National Carbon CS312). (Other materials that are used will be discussed later.) These components must be machined to a smooth, hard surface since rough and/or porous graphite will spall when heated and will contaminate the melt.

Rods

Two diameters (3.18 cm and 5.08 cm) of graphite rods are used, but the 5.08-cm-diameter rod works best. It provides a better seat, it lasts longer, and it is not as susceptible to breakage. Stopper rods normally last for 10-25 runs. Exceptional care must be taken when machining a radius at the bottom of the rod so as to provide a sound seating surface.

In addition to graphite rods, 3.18-cm-diameter aluminum oxide (ceramic) rods have been used successfully; however, because of thermal expansion of aluminum oxide, care must be taken to make certain the rods are not seated too tightly. Expansion of the rod during the melting operation can bend the rod sufficiently to break the seat seal at the bung hole and create a leak path for the molten beryllium. Ceramic rods work well in the tapered crucible, which will be discussed later.

Crucibles

Several shapes of graphite crucibles have been used successfully. The standard-shaped crucible, shown in Figure 1, is designed with an inset in the sides containing two layers of graphite felt (Union Carbide grade WDF). The felt is tied in place with graphite twine and is protected with a graphite ring. The purpose of the felt is to help maintain the temperature of molten beryllium and thus avoid premature freezing in the bung. The thermocouple well shown in the crucible is to be used when automatic control of the induction furnace is desired. The double taper shown in the figure is not required when a hot top is used. Graphite crucibles normally last for more than 100 runs.

The crucible shown in Figure 2 is used for small charges. The taper will provide a deeper molten pool, which results in a better yield by minimizing the skull area. In addition, the molten beryllium during casting is transferred from the crucible in a fast, even flow, which is an effective aid in producing sound ingots. The crucible illustrated in Figure 3 is used when the desired charge is larger than the tapered crucible will accept but smaller than that which warrants use of the standard-shaped crucible.

A beryllium oxide (BeO) crucible was used with limited success. The BeO crucible was positioned in a graphite container, and a solution of aluminum oxide was poured around it to provide support. The crucible cracked after each run, however, and required patching. Patching of these crucibles resulted in the high probability of the patch coming loose and contaminating the melt. Although no investigation was conducted, the excessive cracking experienced in the large BeO crucibles was attributed to thermal shock. This type of crucible proved too expensive because of its short life cycle (two to five runs).

Hot Tops and Molds

The main purposes of a hot top are to (1) screen out high density inclusions, (2) help provide directional solidification from the bottom of the mold, and (3) provide feed for the ingot as it shrinks during solidification. The original molds were not used in conjunction with a hot top; instead, a mold was placed directly under the bung in the center of the crucible, and the crucible acted as a hot top. This setup funneled contamination into the ingot. Therefore, the alternate mold and hot-top setup, as shown in Figure 4, was designed for production ingots. The hot-top bung hole is off-center with respect to the mold and crucible and extends above the surface of the hot top. The main purpose of the offset bung hole is to preclude dirt and other high-density contamination from getting into the ingot. It has been recommended that the bung hole in the crucible be offset instead of the one in the hot top. In theory, this should provide an improved solidification pattern for the ingot.

The mold and hot top used to provide feed ingots is shown in Figure 5. This mold makes a series of two or more donut-shaped feed ingots.

The molds shown in Figure 6 have been utilized successfully to cast hemispheres and spheres whereas the two hemishell molds and hot tops shown in Figure 7 were used with limited success. Their use was discontinued. The normal life of a mold is from 25 to 50 runs, and the normal life for a hot top is from 25 to 35 runs. Graphite felt is sometimes wrapped around the hot tops for additional insulation.

Bungs

There are many types of bungs. The more common bungs in use for casting beryllium are shown in Figure 8. A comment on the normal use of each bung is also included in Figure 8. The normal size bung hole ranges from 1.9 to 2.5 cm, and bungs generally have a very short life—10 to 15 runs. Beryllium oxide bungs have been used successfully; however, their cost precludes continuous use.

Sprue and Vent Tubes

The application and shape of sprues and vents used in beryllium casting are shown in Figures 6 and 7. The pouring portion of the sprue contains a 1.9- to 2.5-cm hole. Some sprues contain a larger diameter to form a funnel shape that aids in feeding the casting. Vent tubes are nominally 1.27-cm (0.5-in.) diameter by 0.318-cm (0.125-in.) wall graphite tubing. The normal life of these parts is one casting operation.

COATINGS

A beryllium oxide and beryllium sulfate wash coat is applied to all graphite or aluminum oxide surfaces and mating surfaces that contact molten beryllium. This coating is applied to prevent a reaction between the beryllium and graphite. The wash coating is composed of a beryllium oxide slurry (85%) and a fresh, saturated solution of beryllium sulfate (15%). The slurry is comprised of 50 wt % low-fired 99% pure beryllium oxide and ~50 wt % water. The beryllium sulfate solution is ball-milled for a minimum of 24 hours and preferably up to 100 hours.

Prior to the parts being coated, they must be thoroughly cleaned with a vacuum cleaner and be washed with water. Immediately after washing (while the parts are still wet), apply a liberal layer of coating and hand rub it into all applicable surfaces. Repeat this operation three times (initial coating only) to ensure that 100% coverage is obtained and that all pores are filled with the wash coating. (Spray coating was tried but was not as effective as hand rubbing.) Next, place the parts in a furnace and dry (bake) at 1450 °C for 0.5 hour or 1350 °C for 2 hours. Parts such as vent tubes that cannot be hand rubbed should be coated as thoroughly as possible. All crucibles and molds receiving the initial wash coat and bake must be subjected to a molten beryllium environment. Contact between the coating and molten beryllium forms a protective film of beryllium carbide (Be_2C) that is extremely beneficial. The crucibles and molds should be used a minimum of two times (preferably three) with a small furnace charge of 10 to 30 kg with all power being cut as soon as the cast is completed. Drip-casting (not using stopper rod) large pieces of feed stock is another good method for "breaking in" a mold or crucible. The resulting ingots can then be used for feed stock.

After the mold has been broken in, the only areas requiring recoating are the mating surfaces between the bottom and the top. In addition, a 2.54-cm (1-in.) band on the inside surface of the top of the mold should be recoated. To ensure a good seal, the mold should be coated each time it is used. When cleaning the mold after each run, remove all of the loose buildup. This must be accomplished with caution to ensure that the protective layer is not broken, which would expose the graphite.

Crucibles, stopper rods, hot tops, and mold covers must be recoated and baked after each use. All of these parts must be cleaned to remove loose particles prior to recoating, and particular attention must be paid to cleaning of the crucible. The coating on the bottom and a short distance up the side of the crucible turns into a brownish powder (beryllium carbide) with a hard surface beneath it. Most of the coating in these areas will come off after each run; however, the coating above these areas will build up to a thickness of 0.48 cm (0.19 in.) or more prior to coming off. Experience has indicated it is best to permit the thicker coating in these areas to build up and break loose by itself rather than to be removed by scraping. After several runs, the mold will be larger at the bottom, which will require the ingot to be removed from the bottom.

Proper application of the coating is one of the most important operations in obtaining a sound ingot. During repair, coating of the proper viscosity must be worked into the damaged areas with a brush. If the coating is too thin it will not cover the graphite properly; if the coating is too thick it will (1) not penetrate the rough spots, (2) ball up, and (3) come off. The proper coating viscosity for repair work is relatively thick at room temperature. In the event the applied coating slurry is too thick and does not adhere, the coating must be removed and reapplied. Special care must be exercised when applying the coating to bungs and stopper rods. The coating tends to run and collect in globs that are easily broken off in the molten beryllium stream and are carried into the ingot.

Molds, hot tops, and auxiliary hardware that exhibit erosion from previous use must be realigned in the exact location relative to each other as they were during the original assembly. This can be accomplished by using a match marking system. Crevices that form because of a mismatch of these erosion areas initiate localized chemical reactions. These reactions will significantly shorten the life of the components and will contaminate the melt and/or cause leaks.

FEED STOCK

The optimum feed stock consists of powder metallurgy scrap material mixed with recycled metal from previous casting runs. The first and most important step in obtaining good feed stock is to check the powder source and ingot sheet scrap and to remove foreign materials such as aluminum, stainless steel, iron, copper, and glass. Next the scrap is crushed or sheared to provide a high-density charge for the furnace. After the scrap has been sized, it is cleaned in a solution of 85% nitric acid, 1% hydrofluoric acid, and 14% water. The scrap charge then must be thoroughly rinsed in water and furnace dried. To optimize chemical analysis, reduce contamination, and provide higher packing efficiencies, the scrap then should be melted and cast into feed ingots. After chemical analysis, these feed ingots can be charged with selected ingot scrap of known chemistry from previous runs to provide a high packing density and a balanced chemistry. The ingot and ingot scrap material must be degreased prior to charging. Overflows from previous ingot casting should be handled as primary scrap for feed ingots because of possible contamination.

Briquetted high-purity flake was tried as a feed stock, but this material proved extremely difficult to melt and it produced a poor yield. A minimum effort was expended in this area, however. With additional work it is anticipated that a good yield and an extremely clean ingot can be obtained. Beryllium bead also was tried as a feed stock; however, ingots made from this feed stock were too high in magnesium.

CASTING SETUP

Beryllium has been cast using static and centrifugal techniques. The setup for each casting method is sufficiently different that they will be discussed individually.

Static Casting

During static casting, mold temperature is controlled by the mold-crucible assembly's location within the induction coils. Figure 9 illustrates the typical setup used for normal production casting of beryllium. The graphite felt insulation is used to alter the mold temperature gradients and to make certain that the beryllium remains molten in the hot top area for a sufficient time to feed the ingot. A water-cooled copper chill plate is placed on the bottom of the mold to promote directional solidification from the bottom toward the top of the mold. The bung hole in the hot top is offset relative to the one in the crucible and is raised above the bottom surface of the hot top.

During all assemblies the mold and the hot top should be coated and joined prior to drying. These joints do not require baking. The joints also should be inspected for assurance that the coating is uniformly applied and that no leak paths exist. The end of the stopper rod should be similarly coated to ensure a good seal between it and the bung.

Rectangular ingots 10 X 23 X 25 cm were cast successfully in tandem as shown in Figure 10. The 23- X 23- X 51-cm mold shown in Figure 9 is the most common, however, and produced the soundest ingots. The specialized casting setup illustrated in Figure 11 is used for special research studies such as alloying. The setup also is amenable to producing small, sound beryllium ingots. Rectangular or square beryllium ingot have been static cast successfully in various sizes from approximately 5 X 5 X 10 cm to 28 X 28 X 39 cm. Cylindrical ingots with length-to-diameter ratios of 5 to 25 cm in diameter and from 5 to 38 cm in length also have been cast successfully. A few beryllium rods (6.7-cm diameter) have been cast by pouring the molten beryllium into a mold containing multiple cavities. A gating system is provided so each cavity is filled. The quality of cast rods, however, is inferior to the soundness of the ingots. One major problem that has been experienced is premature solidification that results in large voids being present in the rods. A photograph of typical "as cast" rods is shown in Figure 12.

Centrifugal Casting

A limited amount of work has been performed toward developing centrifugal casting techniques. A furnace with a 30-cm inside diameter coil has been used for this application. The crucible is centered over the mold, which is fixed on a rotating table (Figure 13). The sleeve shown in Figure 13 is required to avoid splashing the side walls of the mold during pouring. The rotational speed is variable from 0 to 1000 revolutions per minute, and the mold temperatures can be controlled by adjusting the position of the mold relative to the furnace coils. While setting up, caution must be exercised to ensure a 2.5-cm clearance between all static and rotational interfaces. This is necessary to allow for wobble initiated by the metal buildup. Some of the more common castings produced are illustrated by the mold sketches shown in Figure 14. The size of these castings ranges from 7.6 to 33 cm in diameter, and from 7.6 to 33 cm in length. Wall thicknesses greater than 0.63 cm tend to initiate cracks on the inside diameter.[2]

MELTING AND CASTING

The feed material discussed previously is placed in the crucible with a 15% overcharge. Following the nominal thermal cycle, shown in Figure 15, the charge is melted. The 1450 °C superheat is required to ensure melting of the entire charge. The temperature is then dropped to 1380 to 1400 °C prior to pour to eliminate superheating at the time of pour.

The molten metal (15% overcharge) remaining in the crucible and/or hot top after the pour is heated to 1450 °C to allow continuous feeding of the ingot during solidification. The cooling cycle from 1450 °C was determined by experience as the fastest decline that would not cause cracks in the ingot.

When the melt temperature reaches 1000 °C, the vacuum furnace is back-filled with helium to promote more rapid cooling.[2] The pouring temperature should not fall outside the range of 1350 to 1400 °C. Temperatures above 1400 °C promote a chemical reaction with the mold, and temperatures below 1350 °C promote the formation of cold shuts. The temperature of water in the chill plate prior to casting should be between 20 and 60 °C and should flow at a maximum rate to promote directional solidification.

Experience has shown that the casting of a sound ingot is not dependent on the furnace pressure in the range of 10 microns of mercury to atmospheric pressure of helium.[2] The amount of beryllium vaporization during melting and casting under vacuum conditions is negligible because of the oxide blanket that is formed by the skull over the molten beryllium. Typically, ingots poured at 200 microns of mercury exhibit a fine grain structure on the surface, which is caused by evaporation at the solidification point. When ingots are poured under atmospheric pressure of helium, however, the surface is charged grain and exhibits a washboard texture. Most castings at Rocky Flats are conducted in a vacuum.

To illustrate the types of shapes that can be centrifugal cast, the parameters utilized to produce an approximately 44.5-cm diameter by 2.54-cm wall hemishell containing a 5.7-cm straight section are as follows: a 10 to 16 kg charge of beryllium scrap is superheated to 1450 °C and cooled to a pour temperature of 1400 °C. A slow heating rate is employed in an effort to heat the mold by radiation from the funnel because the mold is not heated directly by the coil. Various spinning parameters have been tried with the most satisfactory being

1. Start mold rotating at 20 rpm.
2. Increase speed slowly to 75 rpm 20 seconds after pour.
3. Hold 5 seconds at 75 rpm, then cut speed to 20 rpm.
4. Hold at 20 rpm for 15 seconds.
5. Increase slowly to 175 rpm and hold for 15 minutes.

The above parameters, with a mold temperature of about 300 °C at pour, yields visually sound castings. Slowing of the spinning action after the initial spin allows chilled metal to flow back into the mold bottom and to thicken the pole of the hemishell. Hemispheres formed by this centrifugal casting process have not been structurally sound because of the presence of tight cracks (detected by radiographic inspection) in the 2.54-cm thick wall; however, a minimum amount of work was done to develop the process. An improvement in the cooling characteristics should minimize the cracking problem experienced in thick wall castings.

CAST DEFECTS

Since beryllium has a high latent heat of fusion and a relatively low thermal conductivity, heat removal during solidification becomes a major factor. Limited ability to remove heat, particularly in larger ingots, contributes greatly to the formation of large columnar grains. Inability to rapidly remove heat also generates high thermal stresses during cooling, and it increases the probability of hot tearing or cracking.

Furnaces used at Rocky Flats are limited in controlling cooling rates within the ingot. Shrinkage cavities and hot cracking in the top of large ingots are common experiences. At one time, 60% of the bottom part of a 23- X 23- X 51-cm ingot was used for rolling into sheet. With greater radiographic resolution, it was found that unsound product extended further, and that only the bottom 45% of the ingot could be used. Therefore, two billets were cut from the bottom of the ingot, as shown in Figure 16, and a thin slice between the billets was used for radiographic examination.

Low-energy radiographs of cast beryllium provide an excellent fingerprint of cast integrity. Several segregation effects have been observed by studying such radiographs.

Relatively pure beryllium solidifies in the classical manner, with an outer chill zone adjacent to the mold walls and a central columnar zone making up the bulk of the ingot structure. The columnar to equiaxed transition does not occur because of the high latent heat of beryllium and the lack of sufficient impurities to promote supercooling during solidification. Typical columnar grains are shown in Figure 17.

Although recycled beryllium used in the ingot-sheet process is relatively pure, impurities in the hundreds-of-ppm levels are sufficient to cause extensive segregation effects in the ingot. Figure 18 is a low-energy radiograph of a section through the center of an ingot. The bottom of the photograph corresponds with the bottom of the ingot, and the top is approximately midway up the ingot. Lighter regions of the radiograph correspond to higher density impurity segregation. The columnar grain flow pattern can be seen superimposed on the radiograph, growing inward from the sides and bottom and turning upward in the center. The dark lines on each side of the section are traces of the chill line and show the extent of initial solidification in the mold. Although not readily apparent in the radiograph, linear arrays of high-density stringers (HDS) are commonly associated with the chill line. Typical V-type segregation occurs in the central part of the ingot. The V-type segregation extends through the darker mottled region in the center and occurs during steady-state freezing where thermal gradients and the solidification rate are slow. The V-segregation pattern is parallel to the solidification front.

Several secondary inclusions have been identified in cast beryllium. These impurity phases are commonly associated with chill lines and form the HDS previously described. Figure 19 is an example of one stringer. The main phases present were examined by X-ray analysis and found to be as shown in Figure 19. Such stringers are major contributors to high-density defects in wrought beryllium products. Another common type of inclusion is shown in Figure 20 together with non-dispersive X-ray scans.

Ingots sectioned in different regions and then radiographed show numerous BeO and Be_2C primary inclusions. Many of these inclusions are found along the chill line, as shown in Figure 21. Many of the inclusions also are pocketed in certain regions, as shown in Figure 22—a horizontal cross section of an ingot. The inclusions are poured mainly from the crucible and are deposited in corners of the ingot by convective fluid flow. Figures 23 and 24 show a large BeO inclusion and smaller Be_2C inclusions, respectively. Such inclusions will be rolled out in the sheet and will contribute to surface defects in finished parts, as pictured in Figure 25.

Gas porosity and shrinkage cavities are minor problems in recycled beryllium ingots. Both can be controlled by proper pouring and hot topping practice. Employing a 15% overcharge and keeping the metal molten in the top of the mold and hot top until the final stages of solidification provides adequate feeding of the ingot. This also will restrict the shrinkage cavity to a small region in the top of the ingot.

Cast defects such as HDS, Be_2C, and BeO are major problems in wrought product. Although the extent of segregation could be reduced by reheating after pour and by cooling slower during freezing (compare Figure 26a and 26b), high-density defects have not been eliminated entirely.

Efforts to reduce impurities in recycled beryllium are necessary to make further improvements. Primary inclusions could be reduced by using a hot top with an offset bung, which provides a trap for contamination from the crucible. The high-density defects described resulted in an inferior cast product. The source of such defects has been identified. There remains the task of making major processing and equipment changes to purify the molten beryllium stream.

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ILLUSTRATIONS ⟶

(Figures 1-26)

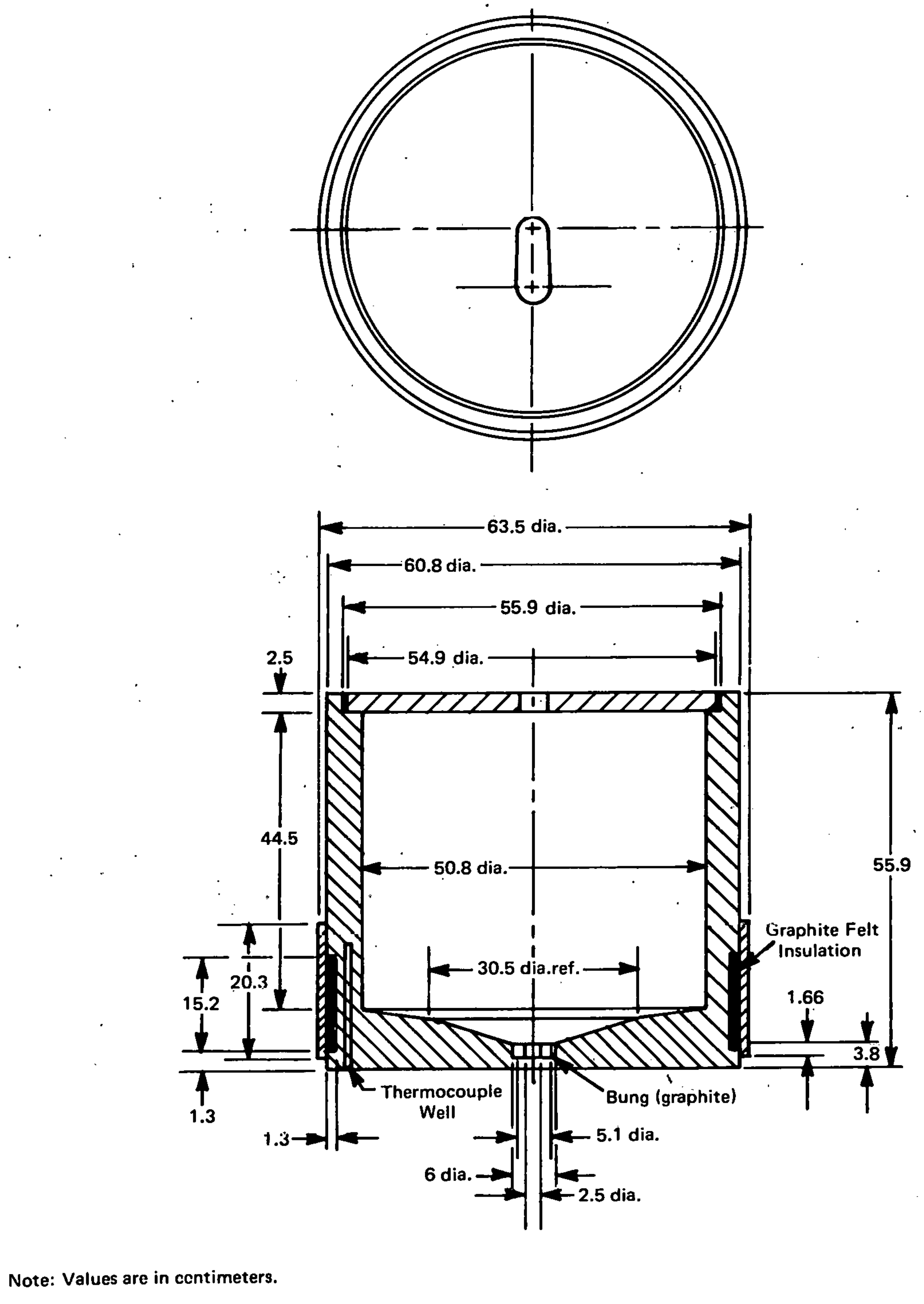

FIGURE 1. Standard Production Crucible

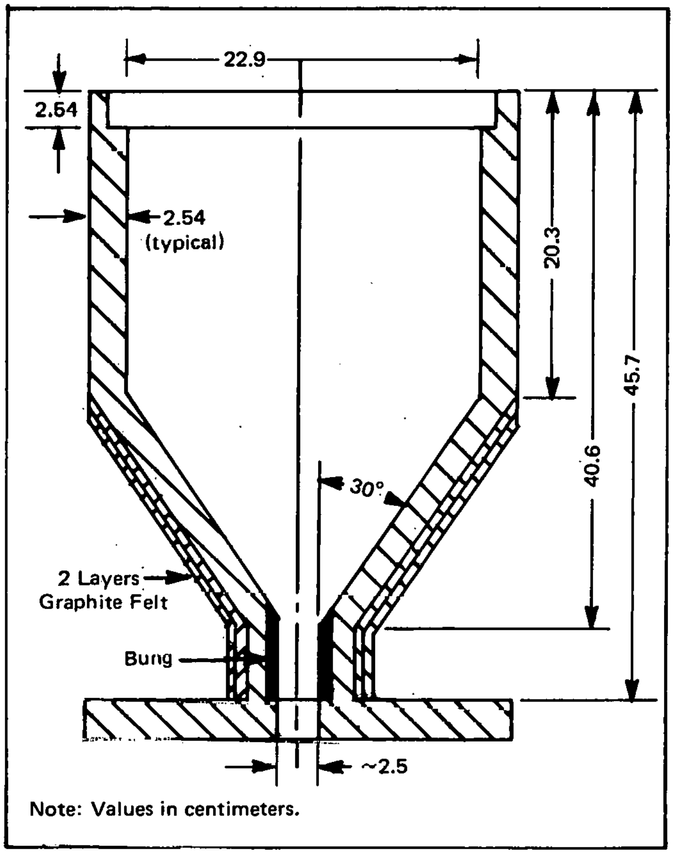

FIGURE 2. Tappered Crucible

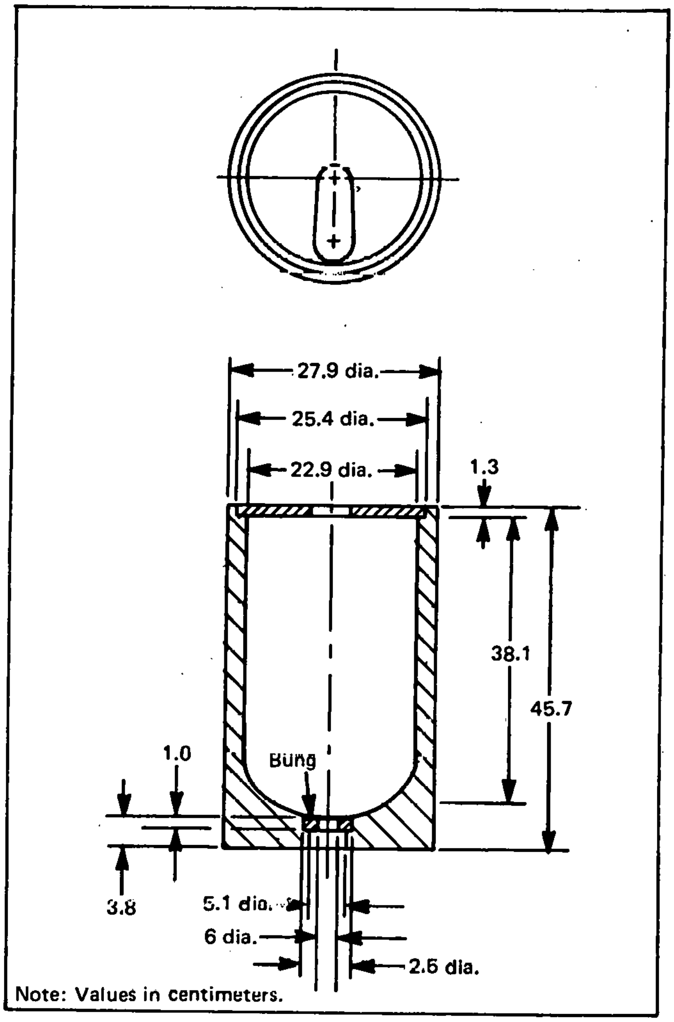

FIGURE 3. Small Crucible

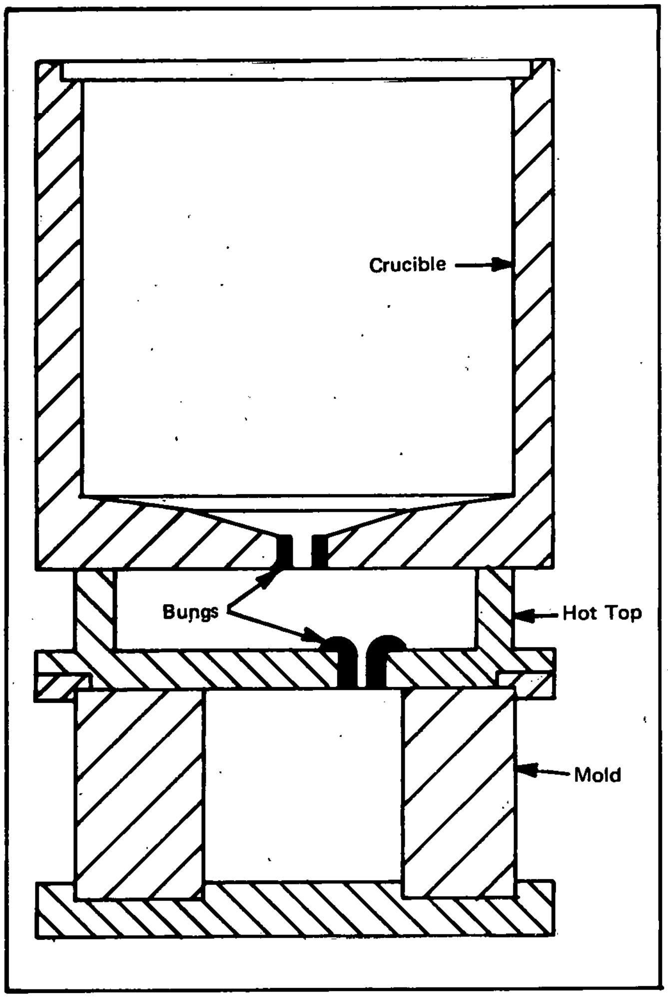

FIGURE 4. Relationship Between the Crucible, Hot Top, and Production Mold

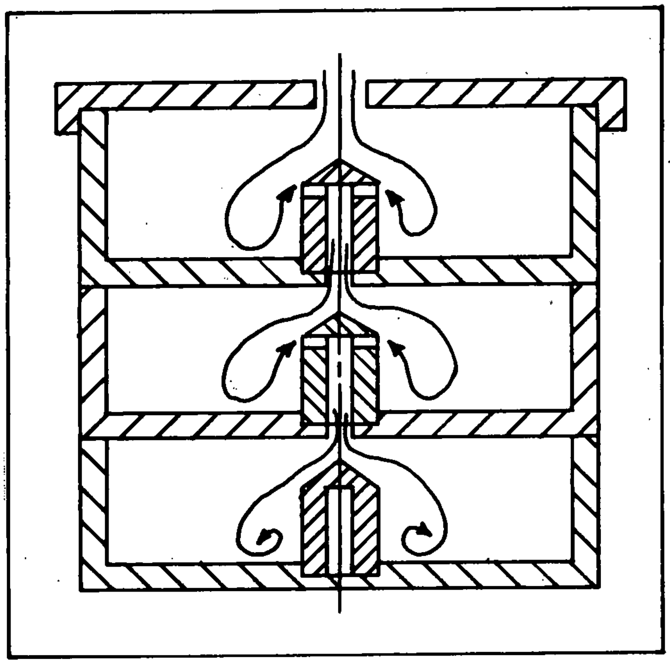

FIGURE 5. Feed Ingot Mold Setup. The Number and Size of the Molds Are Variable. Arrows Indicate Metal Flow.

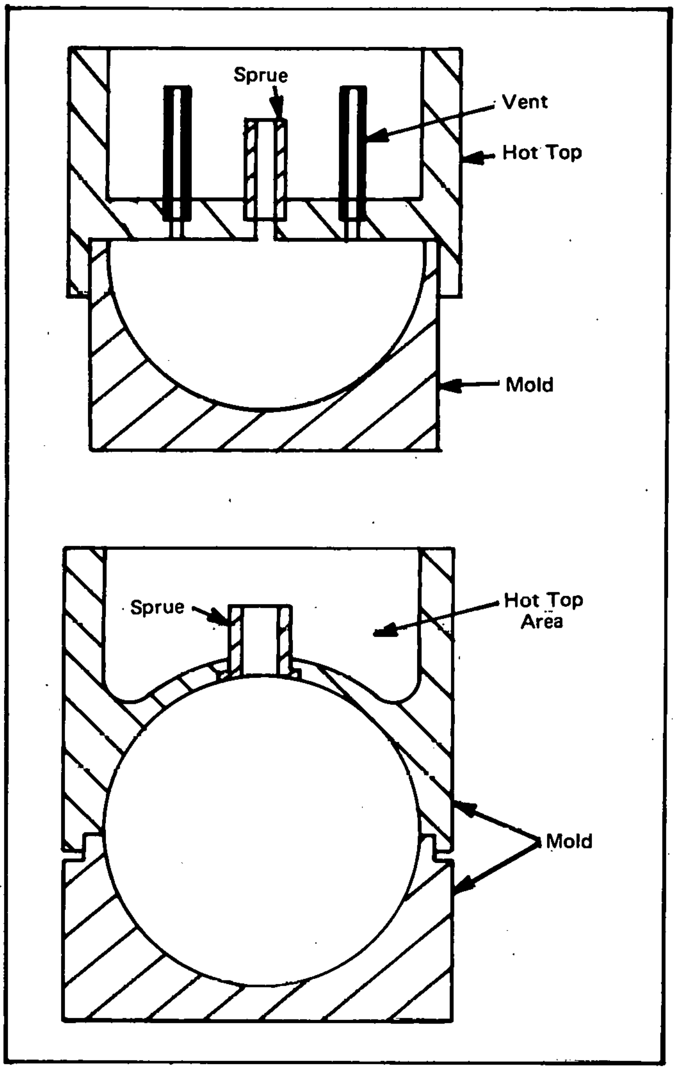

FIGURE 6. Molds and Hot Tops Used for Casting 11.5- to 44.6-cm Spheres and Hemispheres

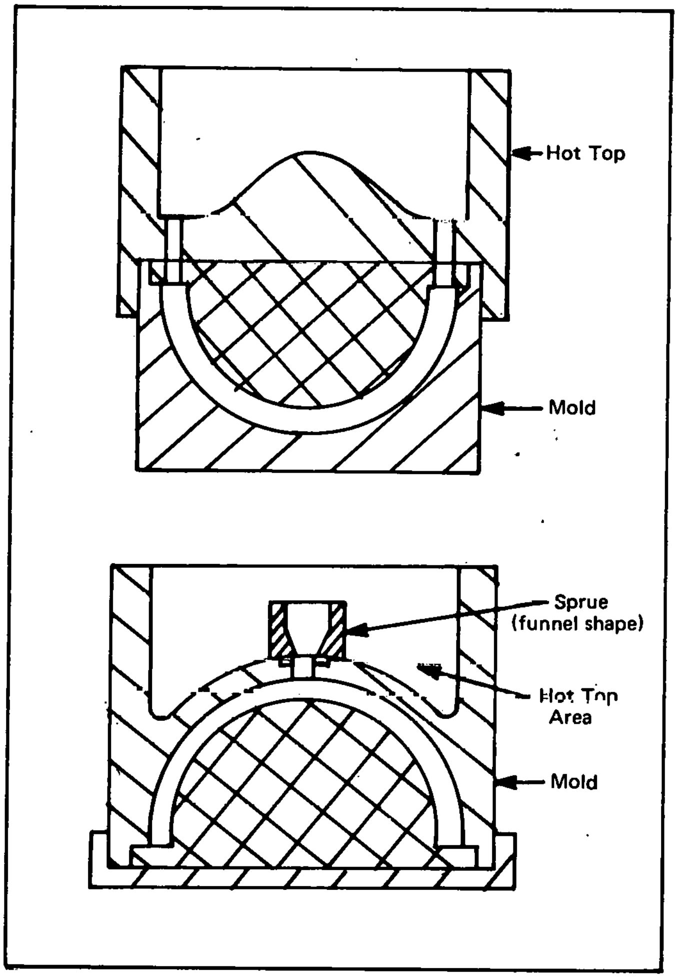

FIGURE 7. Two Types of Hemishell Molds Used with Limited Success

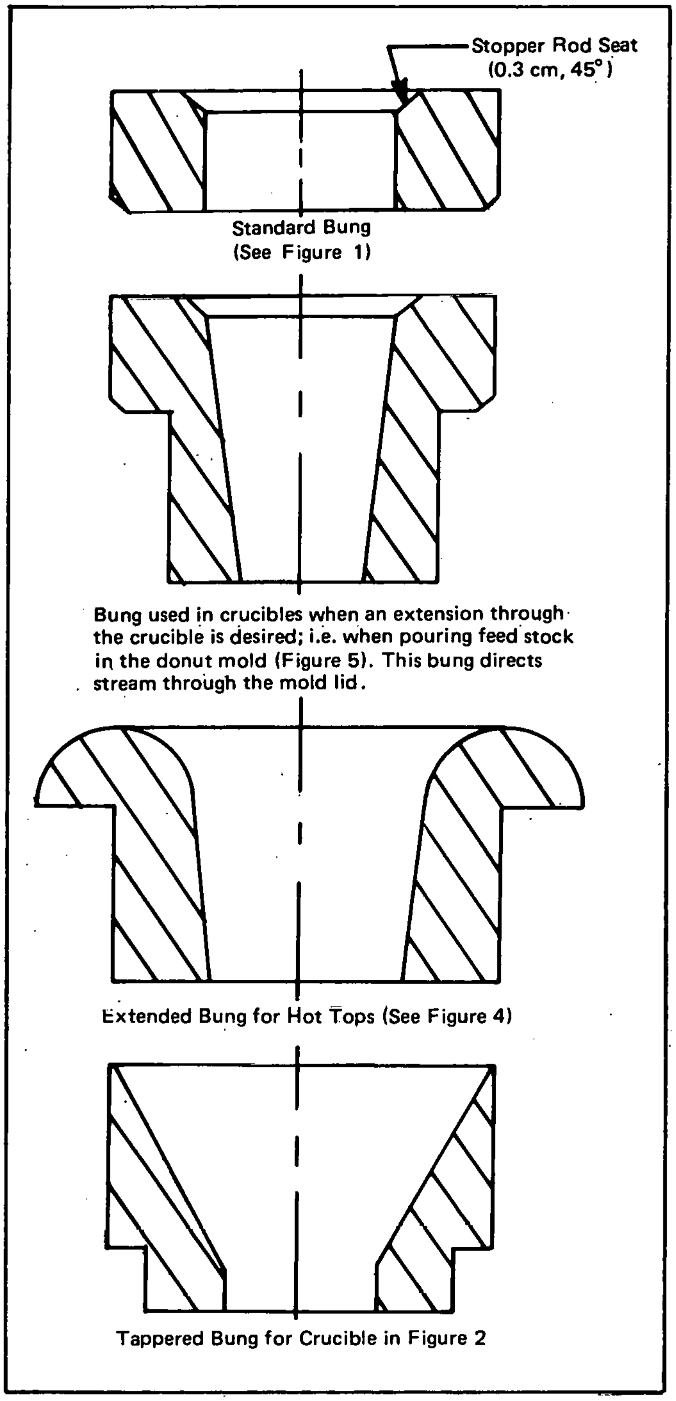

FIGURE 8. Common Bungs Used in Casting Beryllium

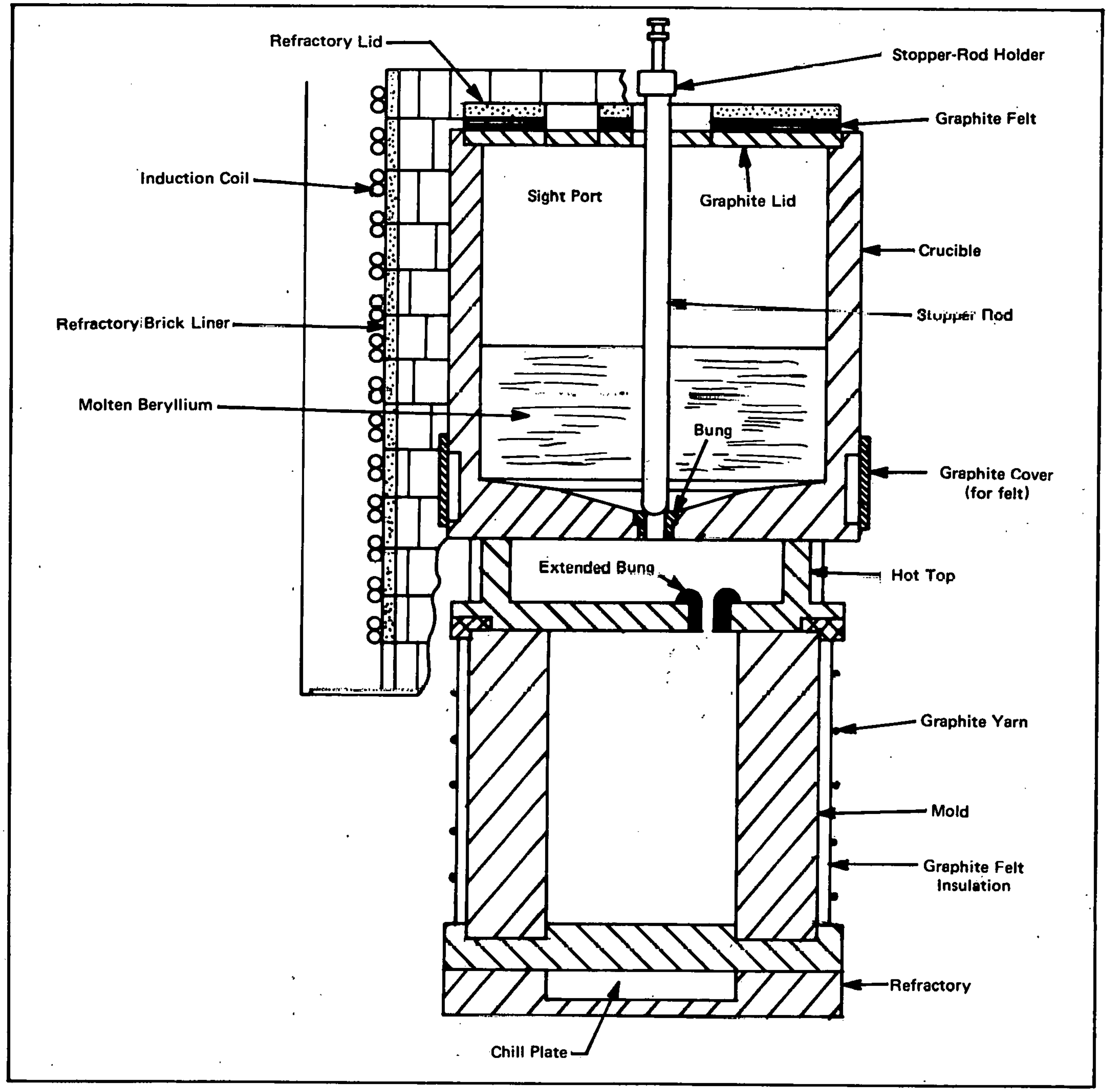

FIGURE 9. Cross - Sectional View of the Mold - Crucible Arrangement Used to Cast Large Beryllium Ingots

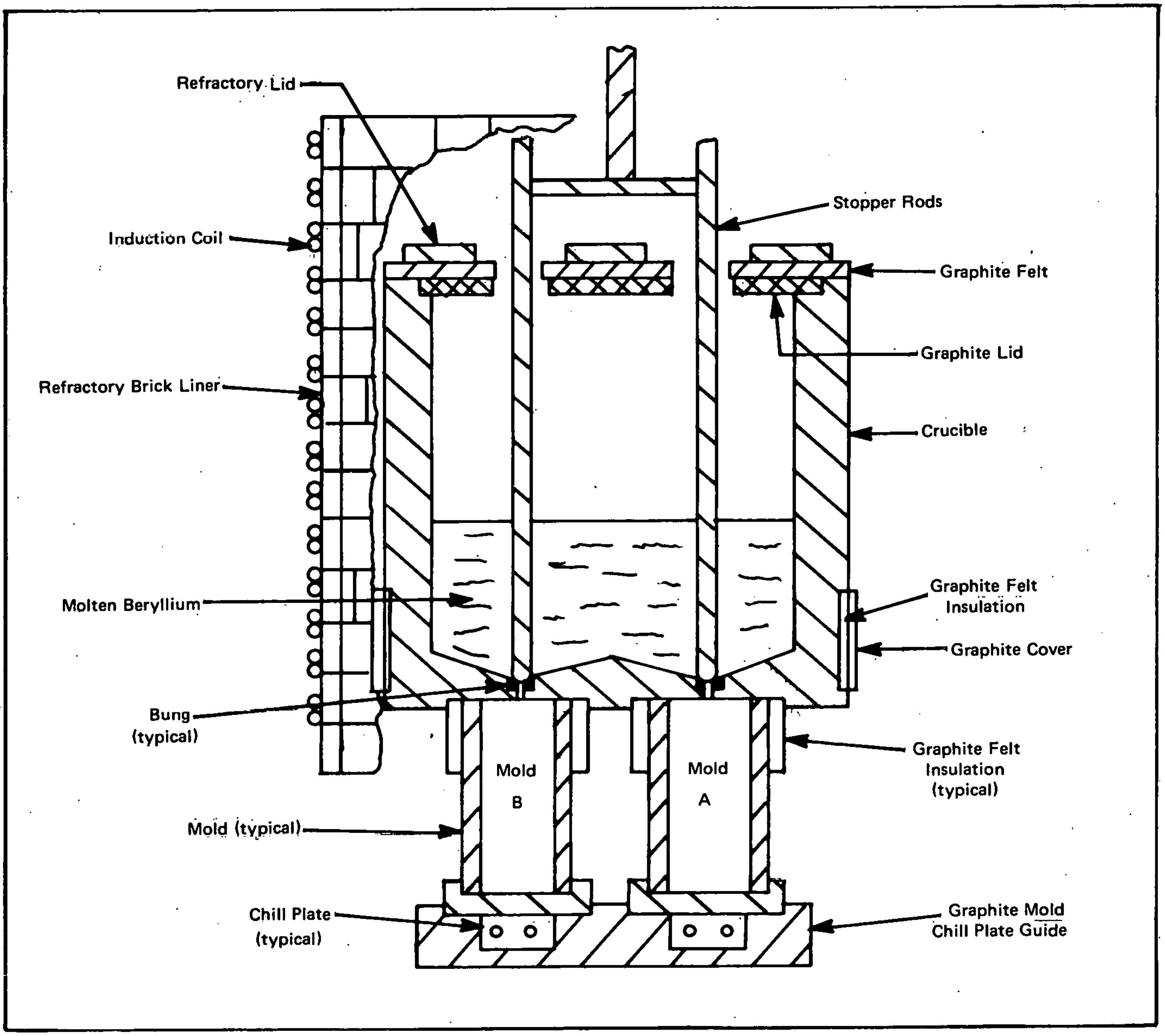

FIGURE 10. General Setup for Tandem Casting. Hot Tops Such as the One Illustrated in Figure 9 May Be Used in This Casting Operation.

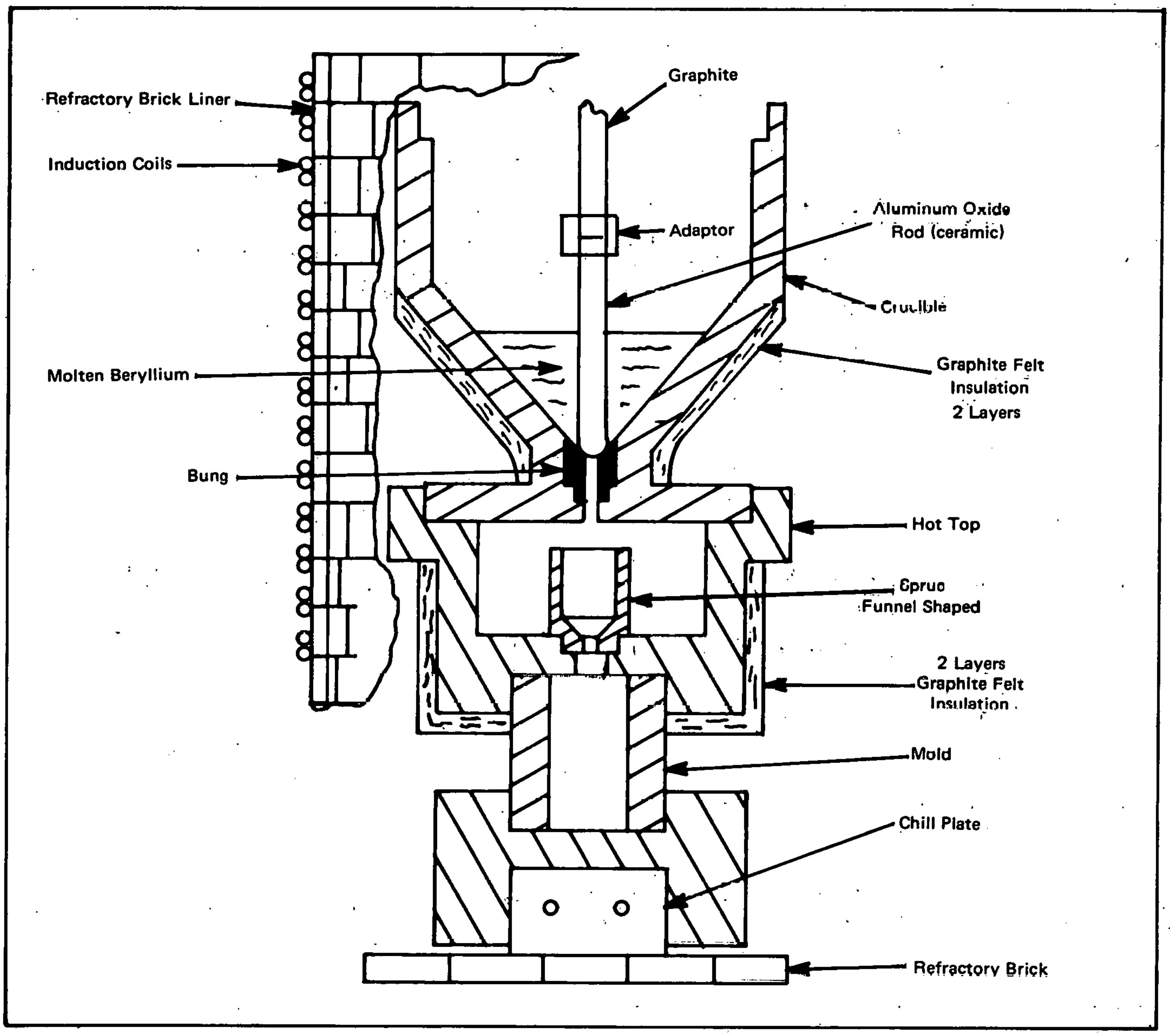

FIGURE 11. Casting Setup Used for Casting Small Research Ingots

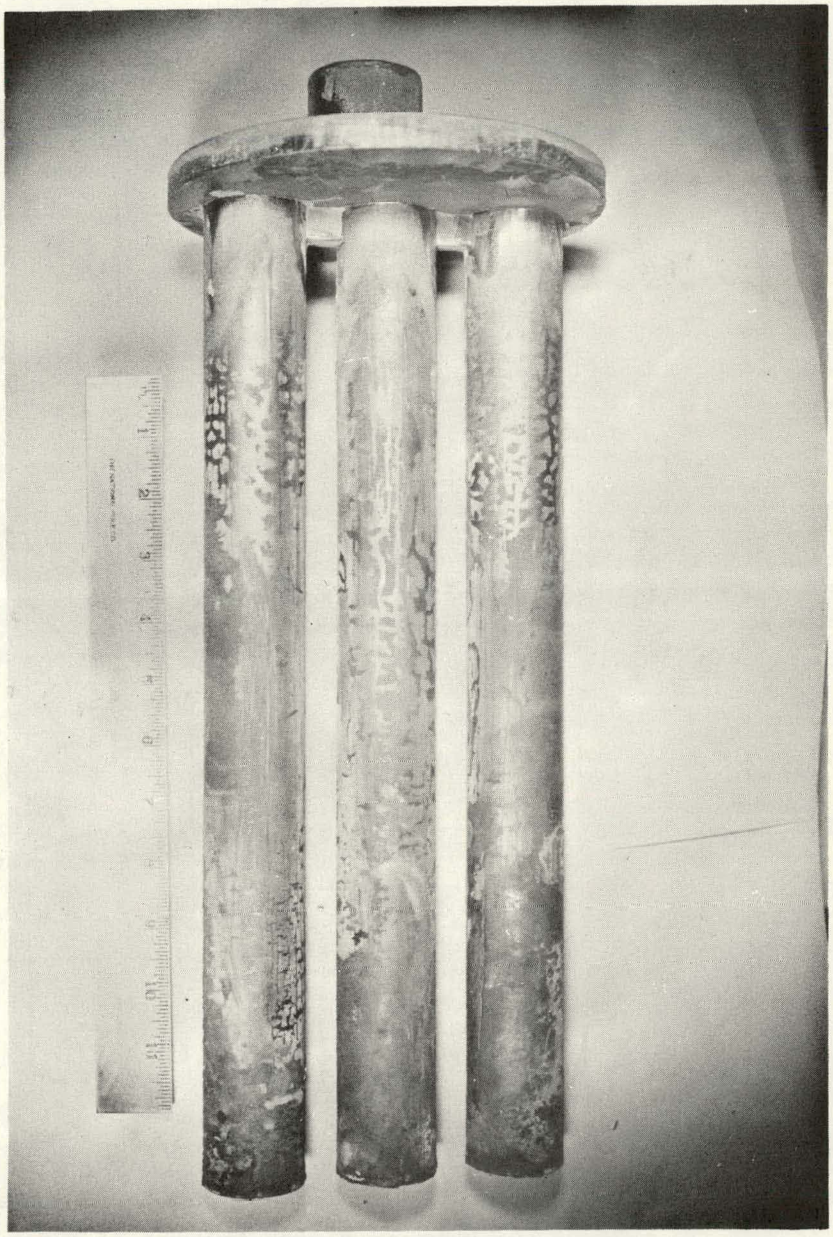

FIGURE 12. "As Cast" Beryllium Rods

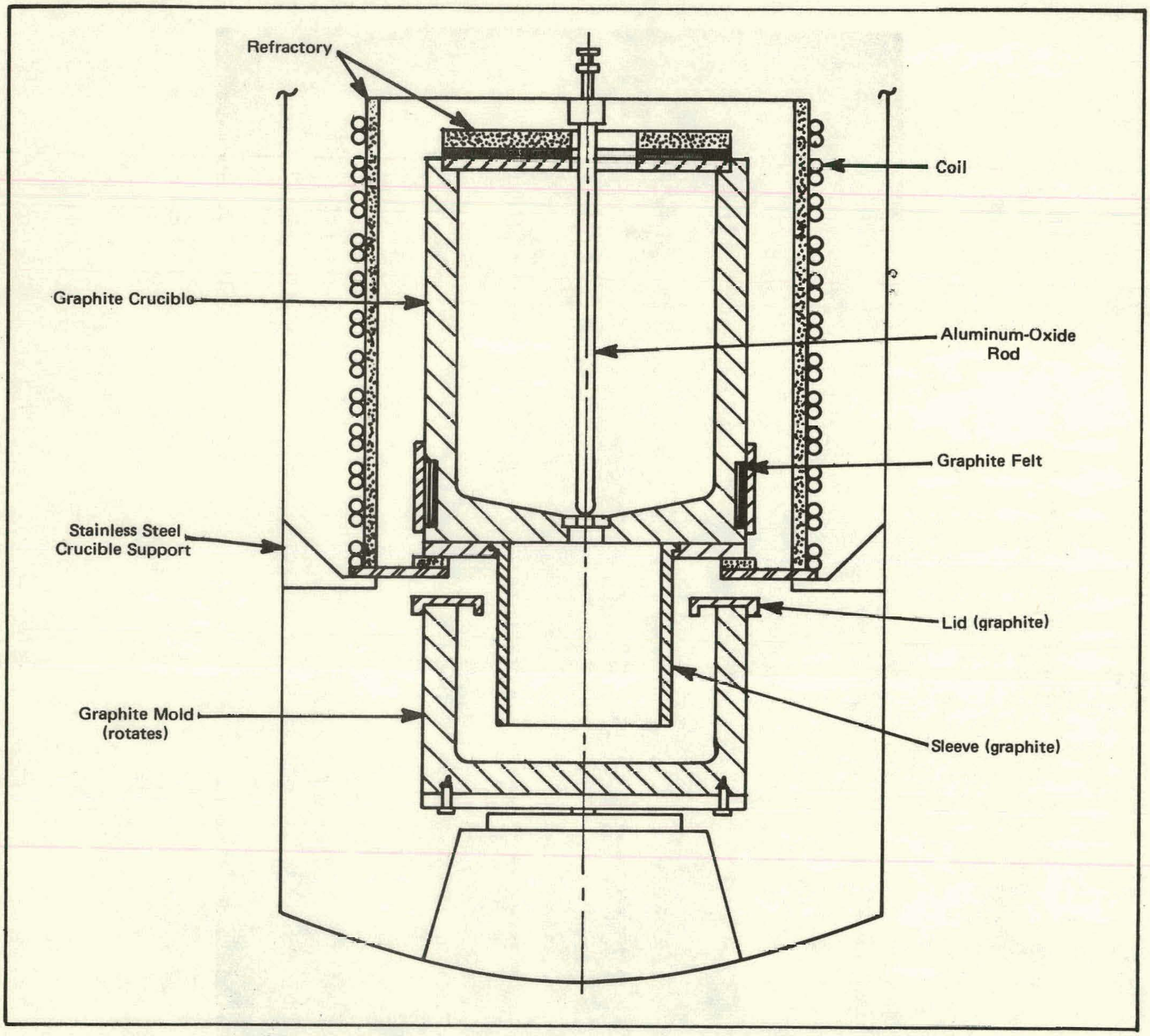

FIGURE 13. Centrifugal Casting Assembly. The Mold Rotates About a Vertical Axis.

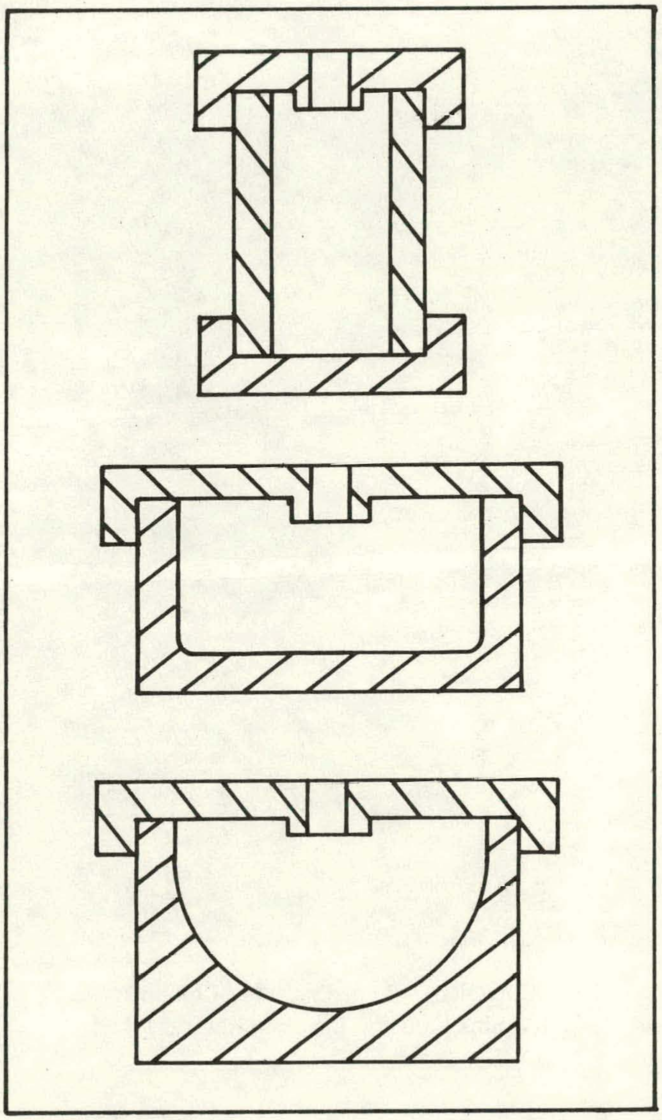

FIGURE 14. Centrifugal Casting Molds

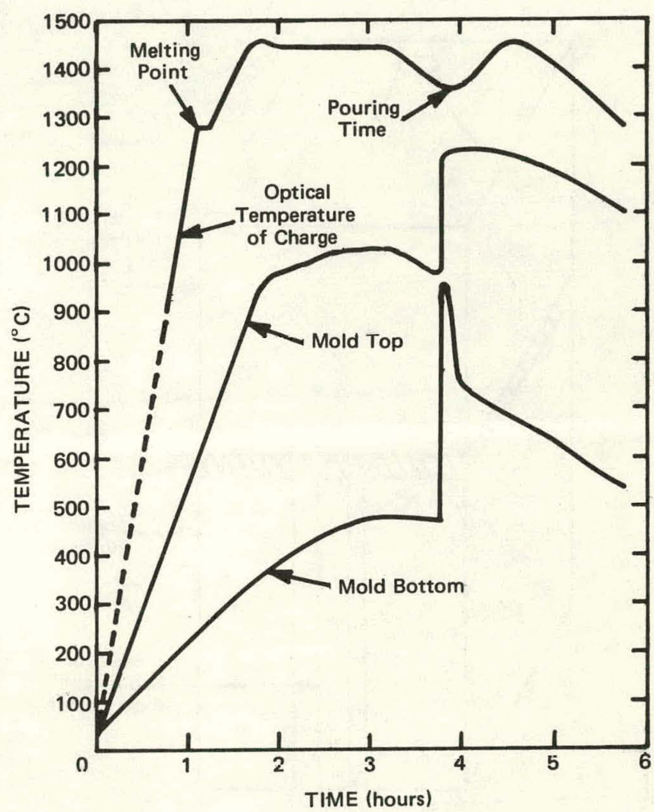

FIGURE 15. Thermal Cycle Used in the Vacuum Induction Casting of Beryllium at Rocky Flats. The Temperature of the Charge is Used to Control Power Input and the Temperature of the Mold Depends Upon the Position of the Mold Within the Induction Coil. (Reference 2)

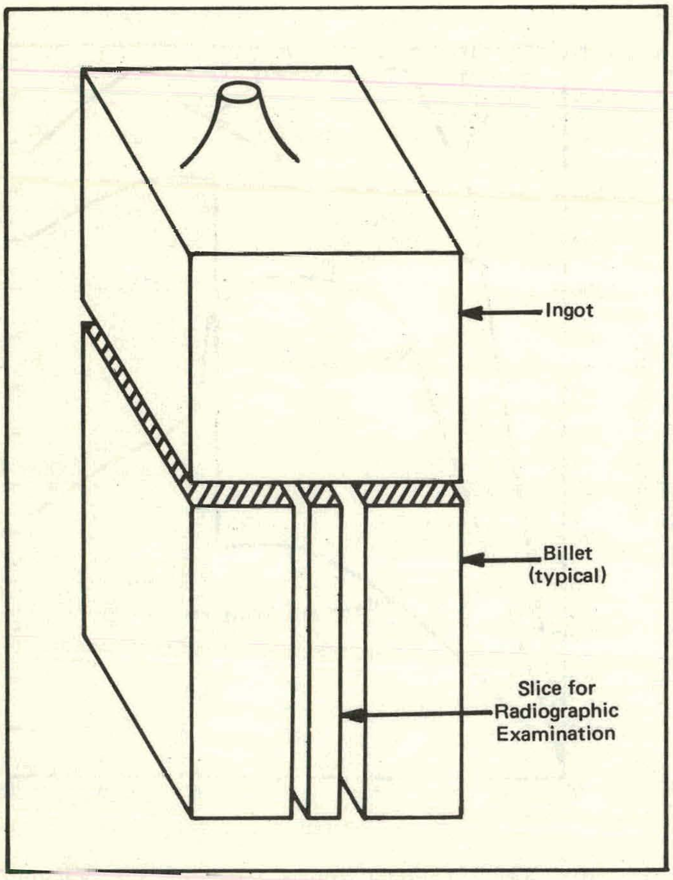

FIGURE 16. Ingot Area From Which the Two Billets for Sheet Rolling and the Slice for Radiographic Inspection Were Sectioned. The Top Portion of the Ingot Was Returned to Feed Stock.

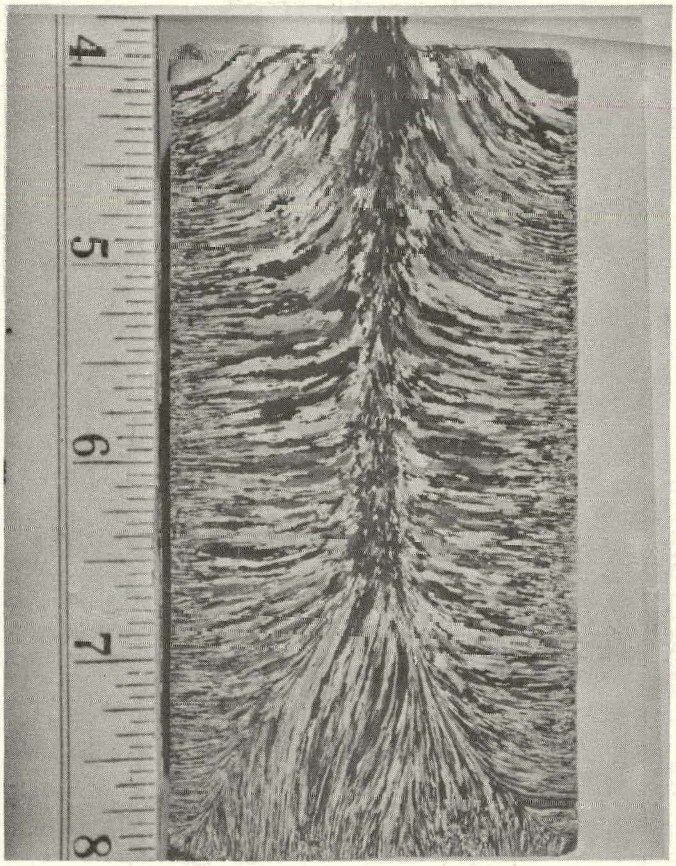

FIGURE 17. Typical Columnar Grains Found in Cast Beryllium Ingots

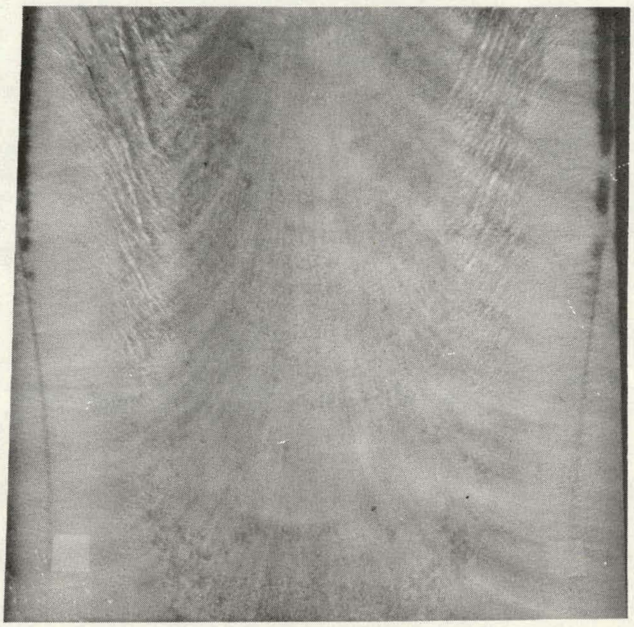

FIGURE 18. Low-Energy Radiograph of a Section Through the Center of an Ingot

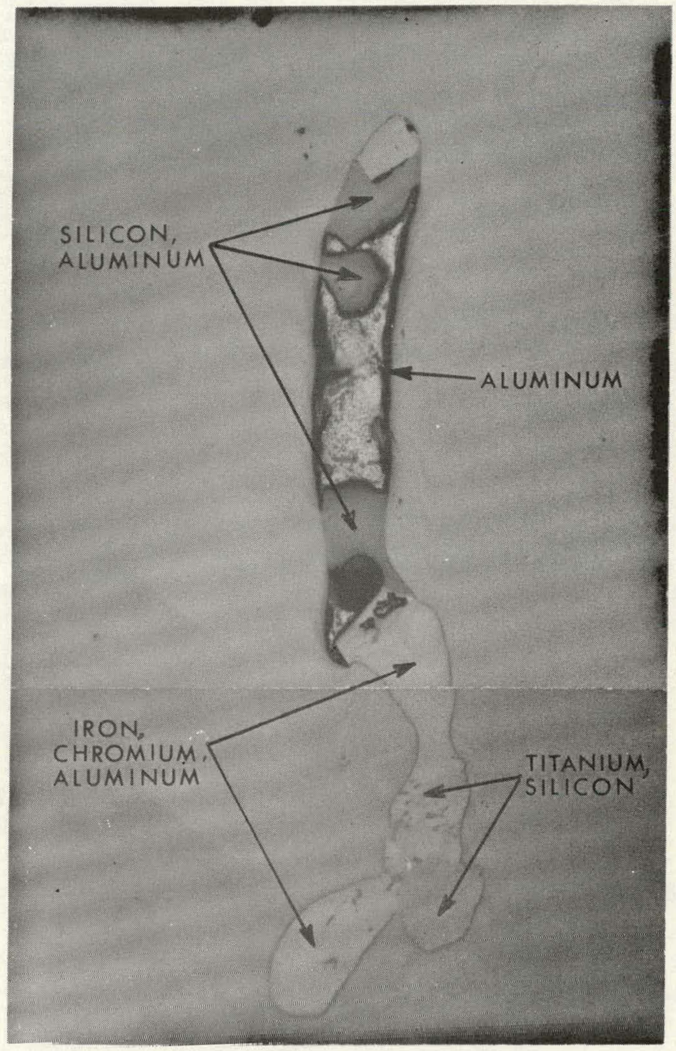

FIGURE 19. High-Density Stringer Found in a Beryllium Ingot. Qualitative results of the major impurity phases are identified. (330X)

A

B

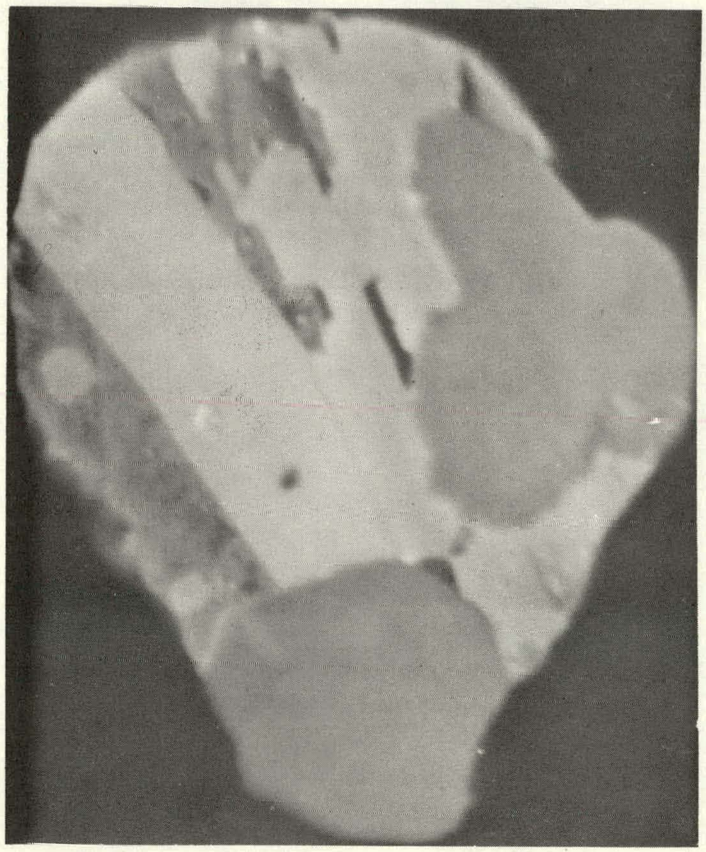

FIGURE 20. Common Types of Inclusions. Figures A and B Show Dispersive X-Ray Scans of Corresponding Areas in the Third Photograph. These Scans Identify Major Elements.

IDENTIFICATION	X-RAY IMAGE
A	Dc (Si, $K\alpha$*)
B	Be (Al, $K\alpha$*)

*$K\alpha$ = X-ray line

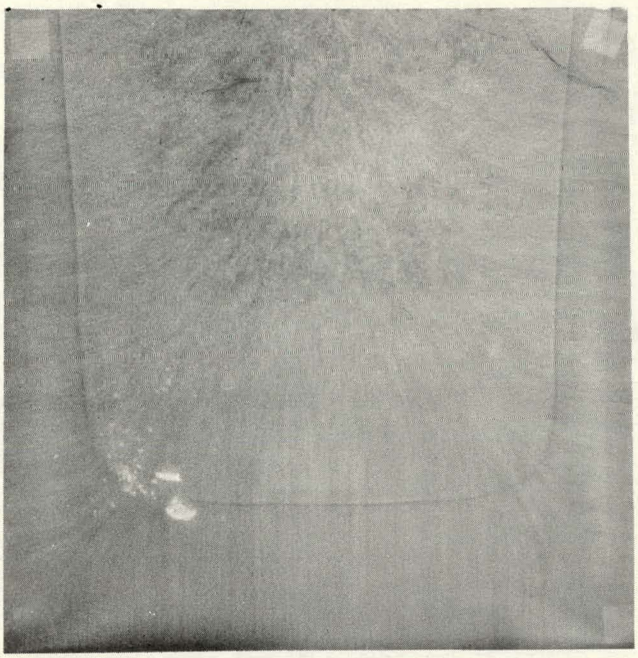

FIGURE 21. High-Density Inclusion in the Left-Hand Corner of the Ingot—Along the Chill Line

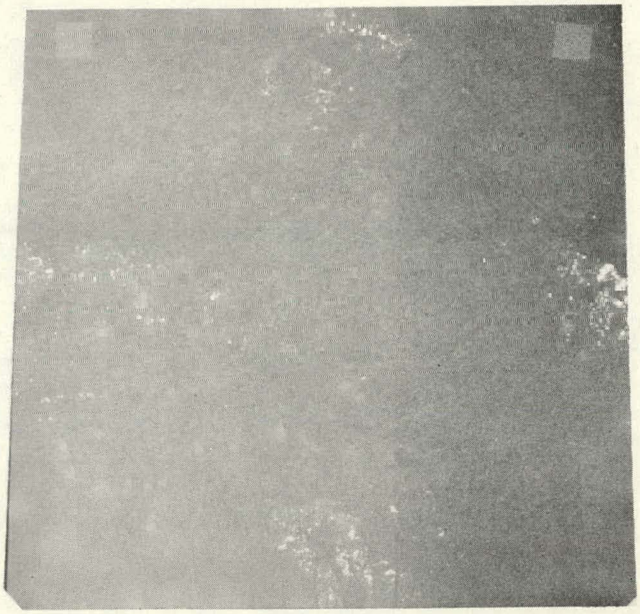

FIGURE 22. Horizontal Cross Section of an Ingot Showing Pockets of High-Density Inclusions

FIGURE 23. Large Beryllium Oxide Inclusion Found in an Ingot (40X)

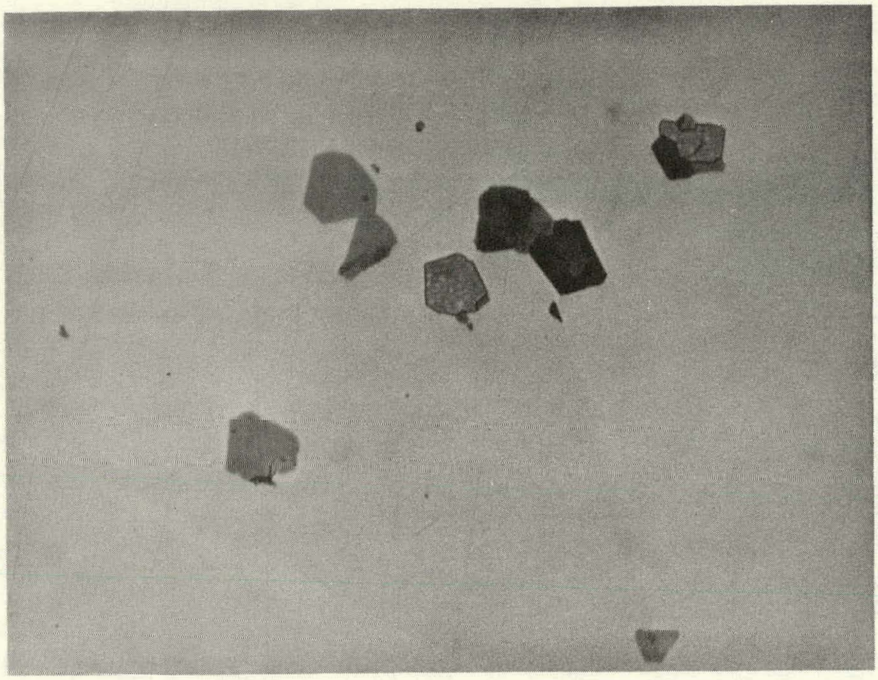

FIGURE 24. Typical Beryllium Carbide Inclusion Found in Ingots (600X)

FIGURE 25. Surface Defects in Finished Parts Caused by Inclusions (1000X)

(a) Ingot reheated after pour
and then slow cooled

(b) Normal cooling rate with induction
furnace turned off at pour time

FIGURE 26. Low-Energy Radiographs Showing Inclusion Contents as a Function of Cooling Rate