ANL-6141
Metallurgy and Ceramics
(TID-4500, 15th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

THE DRIP CASTING OF ZIRCONIUM METAL
by

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Metallurgy Division
Program 2.4.2

Work Completed - March 1951
Report Written - February 1960

Portions of the material in this report have appeared in
the following Metallurgy Division Quarterly Reports:

ANL-4399 - pp. 9-10, 103
ANL-4507 - pp. 12-13
ANL-4508 - p. 10
ANL-4580 - p. 10

October 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

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THE DRIP CASTING OF ZIRCONIUM METAL

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Introduction

The drip casting process was initiated to obtain zirconium castings uncontaminated by the melting process and to remove volatile impurities from the zirconium feed rod. T. Magel¹ has shown that small castings can be made by drip casting. A feed rod of zirconium is held above the mold and the bottom of the rod is melted rapidly off into a mold to produce the casting. The melting process is carried out under high vacuum, so that very little atmospheric contamination can result, and some removal of volatile impurities is possible. Since no crucible is used to contain the molten metal, no contamination can result from this source.

Zirconium metal can be obtained as sponge or as crystal bar. Sponge zirconium is made by the reduction of zirconium tetrachloride by magnesium. Crystal bar zirconium is made by reacting sponge with iodine and reducing the zirconium tetraiodide on a hot wire. The crystal bar so produced is generally purer than the sponge stock, as is shown by the analyses of several types of zirconium listed in Table I. The crystal bar zirconium is much lower in aluminum, magnesium, oxygen, and titanium than is sponge zirconium; and some reduction in nitrogen, iron, silicon can be noted. The drip melting process was expected to accomplish a somewhat similar decrease in these minor impurity elements and to be a cheaper process for the purification of sponge zirconium.

Apparatus

The apparatus originally used by Magel was rather small - the feed rod was about $\frac{1}{2}$ to 1 inch in diameter and 1 inch long; the mold was $\frac{3}{4}$ inch in diameter by 2 inches deep. The sizes of the zirconium feed rods, the copper mold, the vacuum system, the induction coils, and generator power were all scaled up to produce a larger and more useful zirconium ingot. The general layout of the apparatus is shown in Figure 1. The drip melting apparatus is shown at the left. The zirconium feed rod (2) is screwed to a tantalum rod (1) that passes through a seal on the top of the vacuum manifold (6). The induction coil (3) is wound closely around a $1\frac{1}{2}$ -inch Vycor tube. The lower end of the Vycor tube is closed with a water-cooled plate on which the copper mold (4) is placed. The vacuum system constitutes the remainder of the apparatus.

¹T. T. Magel, P. A. Kulin, and A. R. Kaufmann, Approach to Melting Reactive Metals Eliminates Use of Refractory Containers, J. Metals 4, 1286-8 (1952).

Both crystal bar and sponge zirconium were used as feed rod. The crystal bar ranged in size from $\frac{1}{4}$ inch to $1\frac{1}{2}$ inches in diameter and from $3\frac{1}{2}$ inches to 12 inches long. The $\frac{1}{4}$ -inch diameter rods were (1) wired together in bundles of 6 or 7 rods with zirconium wire, (2) extruded to 1-inch-diameter rods, or (3) arc melted to the $1\frac{1}{2}$ -inch-diameter size. Single crystal bars $\frac{3}{8}$ to $\frac{5}{8}$ inches in diameter were generally most successful. The sponge feed rods were compacted to 1-inch diameter and 2 to 3 inches long.

The molds varied in size from 1 inch to 2 inches in diameter and 4 inches long. The most successful mold, shown in Figure 2, was made from copper, was tapered from 1 to $\frac{3}{4}$ inches in diameter, and was 4 inches long. Some molds made from stainless steel, nickel, or aluminum bronze were also tried, but the zirconium alloyed rapidly with these mold materials.

Since the zirconium was melted very rapidly, the rate of release of gas was high, and a large oversize vacuum system was designed to keep the pressure at a low value. The vacuum system built for the drip melting process is shown schematically in Figure 1. A six-inch, high-vacuum diffusion pump and a four-inch booster diffusion pump were used to provide a large liter-micron/sec throughput. In addition, an 18-inch diameter by six-inch high shell was used for a vacuum ballast manifold. The zirconium feed rod was melted inside a $1\frac{1}{2}$ -inch-diameter Vycor tube. Atmospheric pressure on the evacuated tube held it up against a flat neoprene gasket on the lower side of the ballast manifold. A second flat neoprene gasket inserted in a water-cooled plate sealed the lower end of the tube.

Several induction coils of the hyperboloid and modified hyperboloid type were used. The principal coils used are shown in Figure 3. The hyperboloid coil produces a concentrated magnetic flux field at the center of the coil. This effect is shown schematically by the dashed lines in Figure 3. The same number of flux lines pass through the coil, but they are constricted at the center. Consequently, the rod is preheated at the top of the coil and melted at the center. The hyperboloid design was changed from 3a to 3c to heat and center the falling drops by concentrating the magnetic flux at the bottom of the coil. The last coil, 3d, was used for a $2\frac{1}{2}$ -inch-diameter Vycor tube.

Four types of induction heating generators were used to make drip melts. These generators are listed in the order that they were used: (1) a Tocco motor generator set, 10,000 cycles/sec, 220 volts, 30-kw output; (2) an Ajax mercury spark gap set, 50,000 cycles/sec, 7700 volts, 40-kva input; (3) an Echo multiple tungsten spark gap set, 150,000 cycles/sec, 23,500 volts, 20-kva input; (4) a Westinghouse rf tube set, 450,000 cycles/sec, 11,000 volts, 20-kw output. The power actually generated in the coil depends on the coil design. The frequency developed by the last three units depends on the coil inductance. The motor generator set produces very high circulating currents in the coil (about 1000 to 2000 amps) at 220 volts, whereas the spark gap units and the rf set generate 100 to 200 amps in the coil at very high voltages.

Melting Procedure

Most of the melts were made in attempts to establish the proper melting procedure. To this end, several types and dimensions of zirconium feed, several coil designs, and different types of induction heating equipment were used.

The first eleven melts listed in Table III were made using 1-inch to $1\frac{1}{4}$ -inch-diameter feed rods and the 10,000-cycle motor-generator set. A 3-inch-diameter Vycor tube, a four-turn induction coil, and a water-cooled copper mold were used to make these castings. The center of the feed rod melted out and a shell was left. Alumina and zirconia insulating sleeves, even though heated to about 900°C , did not reflect sufficient heat to change this kind of melting (Castings 7, 8, and 10). When a tantalum heater was used (at about 2000°C), the entire rod of zirconium melted smoothly, but too slowly in sizes smaller than 1 inch in diameter. The zirconium sputtered onto the tantalum heater and melted through the heater. So much difficulty was encountered with this equipment that its use was discontinued. The low-frequency and high-circulating coil currents prevented uniform and steady melting.

The second type of induction heating equipment used for drip melting was an Ajax Spark Gap convertor. The copper mold shown in Figure 1 and a 16-turn hyperboloid coil in Figure 3a were used with this generator. The zirconium feed rods varied from $\frac{1}{4}$ inch to 1 inch in diameter and were made from crystal bar and extruded rods. The different feed rods melted smoothly in all sizes from $\frac{1}{4}$ inch to 1 inch in diameter. However, the drops would vibrate and miss the center of the mold. The result was that the casting would contain large holes where bridging had occurred. A typical casting, #11, is shown in Figure 4. When the hyperboloid type coil (Figure 3a) was used, the mold had to be placed six to eight inches below the center of the crucible. Otherwise, the top of the mold would get too hot, and the zirconium would alloy with the copper. Another difficulty that was encountered was caused by the size of the rod. If a rod of large diameter was used, the molten drop tended to be smaller than the rod and freeze at the end, because, even though substantially the same magnetic flux density was acting on the rod and the drop, the power induced in the work was proportional to the square of the diameter. With this induction generator and melting equipment, the soundest castings were obtained with $\frac{3}{8}$ -inch-diameter rods.

An Echo multiple spark gap convertor was the third type of induction heating equipment used for the drip melting technique study. The same coil and mold that were used with the Ajax convertor were also used with this apparatus. Representative castings, #13 to #19, made with this convertor are listed in Table III. In general, melting with the Echo was smoother than the melting obtained with the equipment of lower frequency, and good melting

was obtained with a $\frac{5}{8}$ -inch-diameter feed rod. The melting difficulties were similar to those encountered with the Ajax equipment. The $\frac{3}{4}$ -inch and 1-inch-diameter rods still melted unevenly, and drop vibration continued to make several castings imperfect. Excessive vibration, in fact, prevented the use of more than 60% of the available power. Therefore, the use of this equipment was discontinued, and the 450,000-cycle induction heater was set up.

The Westinghouse rf Generator produced the best castings made in the drip melting process. Zirconium feed rods of $\frac{1}{2}$ inch to 1 inch in diameter melted rapidly and smoothly, and the last twenty-five castings listed in Table III were made with this equipment. Both 16-turn and 12-turn hyperboloid coils were used, but the coil shown in Figure 3c produced the best castings. This coil design produced hotter zirconium drops, permitted the mold to be placed nearer the melting metal without overheating, and tended to center the falling drops. As may be noted from the data in the table, the best castings were made at full power in order to produce the most rapid melting of the feed rod. The gross casting defects were eliminated by means of this melting procedure.

Discussion

One of the better castings, #45, is shown at the right in Figure 4. A few $\frac{1}{16}$ -inch cold shuts are still visible on this casting. However, the gross defects illustrated by #11 and #22 are completely eliminated. A slow melting rate and off-center drops are the principal causes of these defects. The importance of centered drops and rapid melting is evident from these castings.

Because the sound drip-melted castings required rapid melting, the casting size was limited by the power supply. A feed rod, $\frac{5}{8}$ inch in diameter and weighing 155 grams, could be melted in about 18 seconds. The total heat required for this melting rate is about 6 kw. Approximately 30% of the heat is used to heat the zirconium through the phase transitions, and most of the remainder is used to heat the metal from 450°C to 1850°C. Only about 4% of the 6 kw is calculated as a radiation loss. These calculations are shown in the Appendix.

The drip melt castings showed little change in impurity content. Although the distilled metal that was collected on the Vycor tube analyzed high in aluminum, magnesium, silicon, and sodium, it was not possible to detect much change in impurity content between feed rod and castings (Table II). Some pickup of the nonmetallic elements oxygen, carbon, and nitrogen, as well as pickup of copper and silicon were obtained from the drip melting process. The nonmetallics are, of course, present in the vacuum atmosphere surrounding the molten metal; the copper and silicon can be obtained from the hot mold and Vycor tube, respectively. Increases

in iron or nickel (#14 and #43) might be ascribed to impurities generated in sample preparation or analytical variation. The increase in molybdenum or lead (in casting #43) cannot be explained. Large quantities of magnesium and hydrogen were definitely removed both by melting and by outgassing at 1200°C in vacuum. The more volatile impurity elements, chromium and manganese, might be reduced (#14), but the analyzed values of the feed and the casting are too close to the low limit of detection to be definite about it. Since a very rapid melting rate is essential for the production of sound castings, this requirement effectively prevents much distillation of impurity elements.

The most exacting test of zirconium material was its ability to withstand corrosion in degassed, distilled water at 315°C. A sample of the drip-melted DuPont sponge (#43) was tested in a stainless steel autoclave for about $2\frac{2}{3}$ days. A uniform, black, protective oxide film indicated that the sample was corrosion resistant. Some white corrosion product formed in the valleys of the saw marks, but this phenomenon is generally observed in saw cut material that was not wet-ground after sawing. The metal appeared to have reasonably good corrosion resistance in spite of the rather poor chemical composition, particularly as regards the nitrogen and aluminum contents.

Summary

The drip-melting process provided many castings of zirconium and zirconium alloys for various programs at ANL. These castings were made in vacuum with little contamination from the melting process. The development program showed the importance of using 450-kilocycle induction heating equipment. In order to make sound one-inch castings, a 20-kw output is needed to melt $\frac{5}{8}$ -inch-diameter feed rod rapidly. Appreciable amounts of magnesium and hydrogen are removed by drip melting, but the other elements remained about the same. In order to make two-inch-diameter castings, 50 to 100 kilowatts of rf power are probably necessary.

Acknowledgements

The authors wish to thank J. Haran, Senior Technician, who made many of the castings in this program, J. E. Draley and W. E. Ruether who made the corrosion tests, and J. F. Schumar, Associate Director, under whose direction this work was carried out.

APPENDIX

CALCULATION OF THE HEAT REQUIRED TO DRIP MELT
A ZIRCONIUM ROD

In casting #41 (H123), 160 grams melted in 16.7 seconds, and in casting #45 (H135), 150 grams melted in 20 seconds. For the purposes of this estimate we used the following data for heating the rod:

155 gm of Zr melted in 18 sec;

Average heat capacity $C_p = 7.0 \text{ cal}/(\text{gm atom})(^\circ\text{C})$ for α and β phases;

Negligible superheat in the liquid;

Rod preheated to 450°C before melting.

Then the temperature change is

$$\Delta t = 1850 - 450 = 1400^\circ\text{C},$$

and the heat change is

$$\begin{aligned}\Delta H &= (1400 \text{ deg})(7 \text{ cal}/\text{gm atom} - \text{deg})/(1000 \text{ cal}/\text{kcal}) \\ &= 9.8 \text{ kcal}/\text{gm atom}.\end{aligned}$$

The heats of transformation are as follows:

from the change from the α to the β phase,

$$\Delta H_{tr} = 0.92 \text{ kcal}/\text{gm atom};$$

from the β phase to the liquid phase,

$$\Delta H_{tr} = 4.9 \text{ kcal}/\text{gm atom}.$$

Thus the total heat of transformation is

$$\Delta H_{tr} = 5.8 \text{ kcal}/\text{gm atom},$$

and the total heat change is

$$\Delta H = 5.8 + 9.8 = 15.6 \text{ kcal}/\text{gm atom} \quad .$$

The power for melting is

$$\frac{15.6 \text{ kcal}/\text{gm atom}}{18 \text{ sec}} \times \frac{155 \text{ gm}}{91.2 \text{ gm}/\text{gm} - \text{atom}} \times 4.18 (\text{watt})(\text{sec})/\text{cal} = 6.16 \text{ kw} \quad .$$

The heat lost by radiation was calculated using a 1 - cm diameter by 2 - cm length ($=6.3 \text{ cm}^2$) at an average temperature of 1600°C and emissivity of 0.6. From the General Electric Radiation Slide Rule, the radiation is

10 cal/cm²/sec, and the total power lost is

$$P_{\text{radiation}} = (6.3)(10)(4.18) = 0.26 \text{ kw} \quad .$$

The total power used in melting is then,

$$6.16 + 0.26 = 6.42 \text{ kw} \quad .$$

About one-third of the power is used to heat through the transformations and most of the remainder is used to bring the metal up to the melting temperature. The radiation loss is about 4%.

Table I
TYPICAL IMPURITY ELEMENT CONCENTRATIONS (IN ppm) IN BUREAU OF MINES SPONGE,
DUPONT SPONGE, AND CRYSTAL BAR ZIRCONIUM

	O	C	N	Al	Cu	Fe	Mg	Ni	Si	Ti	Ag	Cr	Mn	Mo	Pb
Bureau of Mines Sponge	1000	$\frac{50}{300}$	$\frac{25}{150}$	$\frac{90}{850}$	L10	$\frac{90}{850}$	$\frac{50}{7000}$	L20	$\frac{35}{240}$	$\frac{30}{320}$	-	10	L20	-	L20
DuPont Sponge	500	215	70	500	40	300	1	3	L50	150	0.2	L2	L1	L2	3
Crystal Bar	$\frac{100}{200}$	$\frac{70}{365}$	$\frac{30}{75}$	$\frac{60}{100}$	$\frac{5}{10}$	$\frac{350}{800}$	$\frac{L1}{8}$	$\frac{60}{100}$	$\frac{L50}{150}$	L10	L1	$\frac{5}{40}$	$\frac{L1}{3}$	$\frac{L6}{20}$	L1

Elements Not Detected: L1 - B, Be, Li, Cd; L3 - Sb; L6 - Co; L30 - Bi, K, Sn;
L50 - As, Na, P, Zn; L100 - Ca

Table II
IMPURITY ELEMENT CONCENTRATION (IN ppm) IN DUPONT SPONGE AND
CRYSTAL BAR ZIRCONIUM AFTER DRIP MELTING

	O	C	N	Al	Cu	Fe	Mg	Ni	Si	Ti	Ag	Cr	Mn	Mo	Pb
DuPont Zirconium															
#43 ⁽²⁾	500	215	70	500	40	300	1	3	L50	150	0.2	L2	L1	L2	3
#43 ⁽³⁾	800	260	420	400	300	700	3	10	300	130	3	10	3	10	30
Crystal Bar															
Castings #13 and 15	100		27, 32	100	8	800	8	80	150			5	1		1
#38 ⁽¹⁾		365	29, 32	70		500	L1		L50				L1		1
#32 ⁽²⁾	200	125	43, 55												
#32 ⁽³⁾	400	135	68, 75												
#14 ⁽²⁾				60	10	350	L1	60	30	L60	L1	20	2	L6	1
#14 ⁽⁴⁾				60	5	2500	L1	400	.20	L60	L1	15	1	L6	L1

Elements Not Detected: L1 - B, Be, Li, Cd; L3 - Sb; L6 - Co; L30 - Bi, K, Sn;
L50 - As, Na, P, Zn; L100 - Ca

- (1) This material was drip melted four times - Castings 32, 36, 37, and 38. The analysis was made on casting 38.
 (2) Analysis of the feed rod before drip melting.
 (3) Analysis of the drip casting.
 (4) This material was drip melted three times and then analyzed.

Table III
DRIP MELT CASTING DATA

Casting No.	Number and Date (1)	Power Supply	Feed Metal		Vacuum (Microns)	Cast Weight (grams)	Mold	Remarks
			Material	Shape				
1	HV49A 11-11-49	Tocco-10 KC	Extruded crystal bar	1-1/4" d. x 3-1/2" long			Cu 1" x 4"	Power set at 10 kw. No melting, 3" dia. Vycor tube Fce. 3" dia., 4- turn coil.
2	HV50 12-1-49	Tocco-10 KC	Crystal bar Swaged	6 rods 1/4" d. x 6" long	0.002		Cu Water across base	Power set at 30 kw. Rods wired together. Slow drops, stalagmite casting, 4-turn coil, melting time - 5 min.
3	HV51 12-2-49	Tocco-10 KC	Same as #2	Same as #2	0.001		Cu 1" x 4"	Power at 20 kw, Ta Heater, Cu mold melted. 4-turn coil, melting time - 2 min.
4	HV54 12-15-49	Tocco-10 KC	Sponge - Bu Mines	1" d. x 2"	0.004		Cu Water Cooled	Power at 18 kw, Ta Heater, Ta heater melted through - alloyed with spattered Zr. Rapid and smooth melting. 4-turn coil, melting time - 5 min.
5	HV55 12-20-49	Tocco-10 KC	Crystal bar Foote	7 pieces 3/16" x 8"	0.006		Cu Water Cooled	Power at 30 kw, Ta Heater. Zr rods wired with Zr wire. No melt. ZrO ₂ sleeve for Cu mold protection. 4-turn coil.
6	HV56 12-21-49	Tocco-10 KC	Same as #5	Same as #5	0.02		Cu Water Cooled	Power at 30 kw, Ta Heater. 4-turn coil, slow melting, stalagmite casting. Additional wire for coupling melted through the Ta heater. Melting time - 4 min.
7	HV62 12-30-49	Tocco-10 KC	Extruded crystal bar	1" d. x 6"	0.004		Cu Water Cooled	Power at 7 kw, Al ₂ O ₃ insulation, 4-turn coil, 2" of rod melted off during outgassing
8	HV63 1-3-50	Tocco-10 KC	Same as #7	1" d. x 4- 3/4"	0.05		Cu Water Cooled	Power from 23 to 30 kw, Al ₂ O ₃ insulation, 4-turn coil. 1 drip/sec - stalagmite, drops too small (wrong power supply) rod melted out from the inside.
9	HV65 1-9-50	Tocco-10 KC	Extruded crystal bar	1" d. x 6"	0.004		Cu Water Cooled	Power at 19 kw, Ta Heater, 4-turn coil, heater melted through. Only one drop cast.

Table III (Cont'd.)

Casting No.	Number and Date (1)	Power Supply	Feed Metal		Vacuum (Microns)	Cast Weight (grams)	Mold	Remarks
			Material	Shape				
10	HV66 1-11-50	Tocco-10 KC	Extruded rod	1" d. x 5-1/2"	0.004		Cu Water Cooled	Power from 15 to 26 kw, ZrO ₂ insulation, 4-turn coil. Metal melted and formed a long thin rod.
11	H75 6-22-50	Tocco-10 KC	Extruded rod	3/8" to 1"	100		Cu 3/4" to 1" d. x 3" long	Hyperboloid coil, Fig. 3a, 16 turns, drops vibrated.
12	H76 6-22-50	Ajax-50 KC	Crystal bar and extruded rods	1/4" d. to 1" d.	100		Same as 11	16-turn coil, Fig. 3a. Rapid vibration of drops, uneven melting of wired crystal bars.
13	H77 6-22-50	Echo-150 KC	Crystal bar drip melts	1/4" d. to 1" d.	0.002 to 0.005		Same as 11	16-turn coil, Fig. 3a. Rods degassed at 1200°C to 1300°C, 3/8" to 5/8" dia. - best size drops and mold filling.
14	H90 6-27-50	Echo-150 KC	Crystal bar Grade I	3/8" d. x 12"			Cu tapered 3/4" to 1" 3" long	16-turn coil, Fig. 3a. 1-1/2" Vycor tube attached to Vac. Man. 3/8" rod melted nicely at 6 setting (10 max.).
15	H91 6-27-50	Echo-150 KC	III Crystal bar	3/8" x 12"	0.005		Cu 3/4" - 1"d.	Power at 6 setting, 16-turn coil, Fig. 3a. Drop fell off center, rod too high in coil.
16	H92 6-27-50	Echo-150 KC	II Crystal bar	7 rods 1/4" x 12"			Cu	Power from 3 to 4 kw, 16-turn coil, Fig. 3a. H ₂ gas from water corrosion testing caused metal to spatter - poor melting, rods were wired together.
17	H93 6-29-50	Echo-150 KC	II Crystal bar	4 rods 1/4" x 10"			Cu	Power at 3.9 setting, 16-turn coil, Fig. 3a. Outgassed to 0.01μ after 1 hr at 1200°C - good melting - 4th drop hit off center.
18	H94 6-30-50	Echo-150 KC	II Crystal bar	4 rods 1/4" x 10"	0.007 to 0.1		Cu	Power at 4.2 to 4.5, 16-turn coil, Fig. 3a. One drop every 40 sec, large drops, 5th or 6th drops hit off center and obstructed crucible.
19	H95 7-25-50	Echo-150 KC	II Crystal bar	4 rods 1/4" x 10"	0.004		Cu	Power at 4, 16-turn coil, Fig. 3a, melting time-18 min. Drop off center, induced currents cause drop to vibrate.

Table III (Cont'd.)

Casting No.	Number and Date(1)	Power Supply	Feed Metal		Vacuum (Microns)	Cast Weight (grams)	Mold	Remarks
			Material	Shape				
20	H99 8-24-50	Westinghouse 450 KC	III Crystal bar	3/8" x 12"	0.005		Ni	7000 v, 0.31 amp grid, 0.9 amp plate, 125 amp rf. Melted smoothly and rapidly. Zr metal alloyed with Ni, 16-turn coil, Fig. 3a.
21	H100 8-25-50	Westinghouse 450 KC	III Crystal bar	3/8" x 12"	0.005		Stainless	16-turn coil, Fig. 3a. 8000 v, 0.26 amp grid, 1.1 amp plate, 142 amp rf, rapid melting.
22	H101 8-27-50	Westinghouse 450 KC	I Crystal bar	5/8"	0.008		Cu	16-turn coil, Fig. 3a. 11,000 v, 0.5 amp grid, 1.6 amp plate, 180 amp rf, rapid melting.
23	H102 8-28-50	Westinghouse 450 KC		No Melt				11,000 v, 0.48 amp grid, 3.4 amp plate, 210 amp rf, 12-turn coil, Fig. 3a.
24	H103 8-30-50	Westinghouse 450 KC	III Crystal bar	5/8"	0.008 to 0.01		Cu Ni Bottom	5000 v, 0.2 amp grid, 1.05 amp plate, 120 amp rf (top alloyed with crucible) bottom good, drops from 5/8" rod don't fill a 1" crucible. 12-turn coil, Fig. 3a.
25	H104 9/1/50	Westinghouse 450 KC	Extruded crystal bar	5/8"	0.01	160	1/8" Wall thick Cu	5500 v, 1.2 amp plate, 12-turn coil, Fig. 3a. Mold red hot - too close to coil.
26	H105 9-1-50	Westinghouse 450 KC	Extruded crystal bar	5/8"	0.01	140	1/8" Wall thick Cu	6000 v, 1.2 amp plate, 12-turn coil, Fig. 3a. Mold cool, fast melting, coil up 1/2". The deposit on glass arced to coil when hot, two bad cold shuts at bottom and center of casting.
27	H106 9-5-50	Westinghouse 450 KC	Extruded crystal bar	5/8" x 9"	0.02	170	1/8" Wall thick Cu	8000 v, 1.8 amp plate, 12-turn coil, Fig. 3a. Mold hot, top 1/2" alloyed with the melt. Several bad shuts 1" from bottom because of poor centering of drop.
28	H107 9-5-50	Westinghouse 450 KC	Extruded crystal bar	5/8" x 9"		120		10,000 v, 2.5 amp plate, 12-turn coil, Fig. 3a. Very rapid melting, crucible cool. Shrink pipe in top of ingot. Some shuts up 1" from bottom.

Table III (Cont'd.)

Casting No.	Number and Date(1)	Power Supply	Feed Metal		Vacuum (Microns)	Cast Weight (grams)	Mold	Remarks
			Material	Shape				
29	H108 9-6-50	Westinghouse 450 KC	Extruded crystal bar	5/8" x 9"	0.08	70	Al bronze	10,500 v, 2.8 amp plate, 12-turn coil, Fig. 3a. Casting alloyed to crucible.
30	H109 9-6-50	Westinghouse 450 KC	Extruded crystal bar	5/8" x 9"	0.02		Cu	11,000 v, 2.8 amp plate, 12-turn coil, Fig. 3a. Rapid melting. Crucible hot, approximately 900°C, very slight alloy at top of casting. Casting was swaged to 0.790" and machined to 0.600", a few very small shuts. Few shuts and micro-porosity visible at 100X.
31	H110 9-18-50	Westinghouse 450 KC				100	Cu	15-turn coil, Fig. 3a. 11,000 v, 3.2 amp plate. Good cast, two bad shuts 1/16" from bottom.
32	H111 9-21-50	Westinghouse 450 KC	Extruded rod	5/8" d	0.002 to 0.04	209	Cu	20-turn coil, Fig. 3b. Considerable splashing, poor casting.
33	H113 9-28-50	Westinghouse 450 KC	Cast #31	3/4"	0.002 to 0.04		Cu	11,000 v, outgas 1 hr, mica around Vycor to prevent arc, rapid melt, 20-turn coil, Fig. 3b. Metal splashed in the mold, too far a fall. Coil too close for 3/4" dia., melting started too high on rod.
34	H114 9-29-50	Westinghouse 450 KC	Cast #27	5/8" sq.	0.0005 to 0.01		Cu 1/2" under coil	11,000 v, 1.6 amp plate, 18-turn coil, similar to Fig. 3c, crucible to 900°C.
35	H115 10-2-50	Westinghouse 450 KC	Crystal bar III	1/2"	0.02		4" Cu 3/4 - 1" d. 1" under coil	11,000 v, 2.6 amp plate, 15-turn coil, Fig. 3c. Best casting, few fine shuts, rapid melting.
36	H116 10-2-50	Westinghouse 450 KC	Cast #32	3/4 - 1" tapered	0.02	181	Cu	Many shuts in center, rapid melt. 15-turn coil, Fig. 3c.
37	H117 10-3-50	Westinghouse 450 KC	Cast #36	3/4 - 1"	0.02	175	Cu	11,000 v, 3.2 amp plate, few shuts, 15-turn coil, Fig. 3c
38	H118 10-4-50	Westinghouse 450 KC	Cast #37	3/4 - 1"	0.003	173	Cu 4"	11,000 v, 3.6 amp plate, 15-turn coil, Fig. 3c. Few shuts, better than #32, #36, #37.
39	H119 10-5-50	Westinghouse 450 KC	Cast #25	3/4 - 1"		155	Cu	11,000 v, 3.4 amp plate. 15-turn coil, Fig. 3c. Best casting with only 3 or 4 shuts.

Table III (Cont'd.)

Casting No.	Number and Date ⁽¹⁾	Power Supply	Feed Metal		Vacuum (microns)	Cast Weight (grams)	Mold	Remarks
			Material	Shape				
40	H120 10-6-50	Westinghouse 450 KC	Crystal bar	3/4" d.		180	Cu	11,000 v, 3.6 amp plate. Rapid melting, 15-turn coil, Fig. 3c. Mold at 900°C, mold was 3/4" from coil, not 1" - Zr metal alloyed with mold.
41	H123 12-1-50	Westinghouse 450 KC	Drip melt rod	5/8" d.		160		11,000 v, 3.8 amp plate, melting time - 16.7 sec, 15-turn coil, Fig. 3c. Good casting.
42	H125 11-17-50	Westinghouse 450 KC	Arc melt 1360 gms	1-1/2" x 7"			Cu 2" I.D. 2-1/4" O.D. 4" high 1-1/2" below coil	11,000 v, 2.4 amp plate, drops small and cold, stalagmite casting did not fill mold, rod became pointed. Coil - Fig. 3d.
43	H129 1-8-51	Westinghouse 450 KC	Degreased sponge BZ3S DuPont		0.007 to 0.1		Cu 4" 3/4 to 1" taper, 3"	6000 v, 2.4 amp plate, 15-turn coil, Fig. 3c. Smooth melting.
45	H135 3-5-51	Westinghouse 450 KC	III Crystal bar	1/2" d.	0.001 to 0.02	150	Cu, 4"	11,000 v, 2 amp plate, 15-turn coil, Fig. 3c, melting time - 20 sec. Crystal bar cold rolled from 1" diameter to 1/2" diameter.

⁽¹⁾Data from Log Book #1410-C, p. 50 to p. 161.

- 1) Ta SUPPORT ROD
- 2) Zr FEED ROD
- 3) HYPERBOLOID INDUCTION COIL
- 4) COPPER MOLD
- 5) LIQUID N₂ TRAP
- 6) VACUUM MANIFOLD
- 7) SLIDING 6" HIGH VACUUM VALVE
- 8) MCF 700 6" HIGH VACUUM DIFFUSION PUMP
- 9) MB 100 4" BOOSTER DIFFUSION PUMP
- 10) WELCH #1405 PUMP
- 11) VACUUM ROUGHING LINE.

Figure 1

VACUUM SYSTEM AND DRIP MELTING SETUP

Figure 2

COPPER MOLD USED IN THE DRIP MELTING PROCESS

Figure 3

TYPES OF INDUCTION COILS USED IN DRIP MELTING

ALL COILS WERE MADE WITH $1/4$ " DIAMETER COPPER TUBING

#11

#22

#45

FULL SCALE

Figure 4

DEFECTS IN DRIP MELTED CASTINGS