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A REPORT ON SOME ATTEMPTS TO CAST CENTRIFUGALLY FUEL ELEMENTS OF SMALL DIAMETER

by

F. L. Yaggee

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ABSTRACT

The applicability of the centrifugal casting technique to the production of multiple castings of fuel pins of small diameter and of thin fuel plates was investigated.

Fuel pins measuring 0.185 in. in diameter by $4\frac{1}{4}$ in. long of unalloyed uranium and of a uranium-2 w/o zirconium alloy were cast successfully in batches of sixteen pins per melt. Sixteen different metals and alloys were used as mold materials.

Smaller and longer fuel pins, 0.165 in. in diameter by $9\frac{3}{4}$ in. long, of similar compositions were cast successfully in brass and copper molds. Thirty-six pins of the same diameter and length were cast simultaneously in each casting run.

Attempts to cast centrifugally thin uranium plates measuring 9 in. long by 2 in. wide by 0.04 in. thick proved to be only partially successful, but encouraging. These plates were cast into graphite molds at the rate of six plates per run. The maximum usable length of the unalloyed uranium plates cast did not exceed six inches.

INTRODUCTION

Dimensional stability under irradiation and thermal conductivity, in that order, are the most decisive properties of any solid fuel alloy in determining its suitability for application in fast reactors. Since the actual selection of a particular fuel alloy is based largely on dimensional stability, the attendant thermal conductivity is of necessity a compromise value.

Unlike the thermal conductivity, the dimensional stability of a fissile material can be improved by such metallurgical manipulations as alloying, heat treatment, and selection of the method of fabrication. The addition of certain carefully chosen alloying elements to a fissile material can enhance the dimensional stability of the latter through grain refinement and/or the stabilization of a desirable phase over the proposed range of operating temperatures. Heat treatment can be used for the dual purpose of grain refinement and randomization of grain orientation in the case of a wrought fuel alloy. Finally, the randomly oriented as-cast structure is preferred to the highly oriented wrought structure from the standpoint of dimensional stability.

Once the fuel alloy composition has been selected, its thermal conductivity is automatically stipulated and not subject to appreciable modification through metallurgical manipulation. The same alloy additions which improve dimensional stability behave as do most impurities in affecting the thermal conductivity adversely. As a result, the usually low thermal conductivity is compensated by a more favorable fuel element design. Thus, the dictum of thin cross sections for fast reactor fuel elements is an attempt to compensate physically for a low thermal conductivity in a fuel alloy which is otherwise desirable.

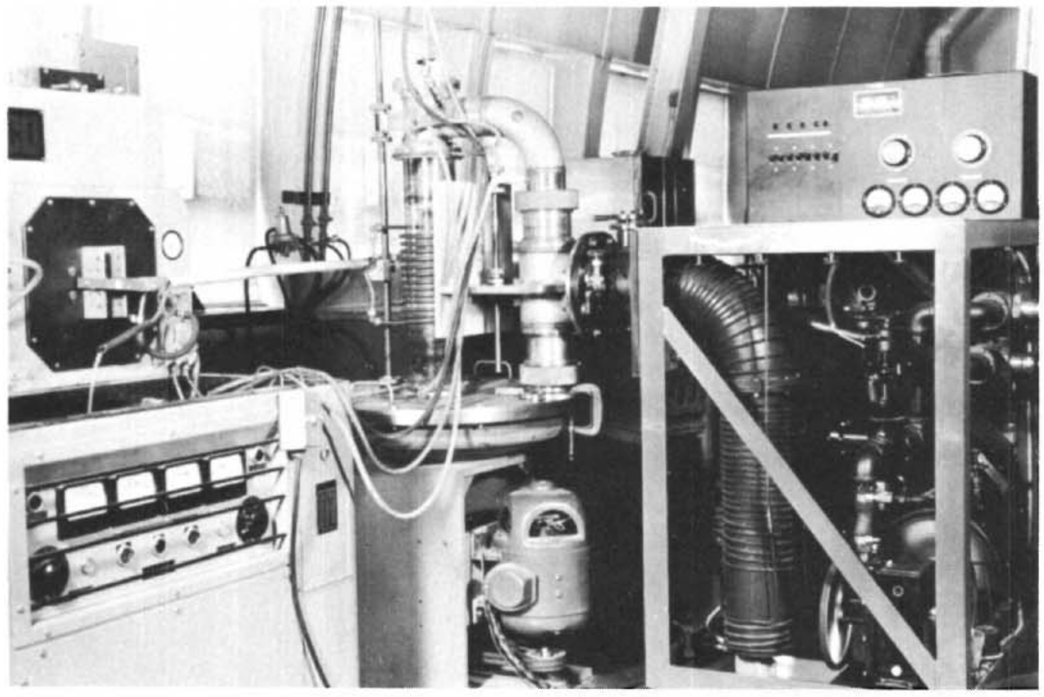
The impetus behind the present investigation into the feasibility of casting thin sections centrifugally was provided, for the most part, by the successful completion of the Mark II fuel loading for EBR-I by this method.[2] Furthermore, the prospect of producing such an element by multiple casting appeared sufficiently intriguing to warrant an effort in this direction. Since thin plate elements are an extension of the basic fast reactor fuel concept, their inclusion in this investigation was a natural one.

DESCRIPTION OF CASTING MACHINE

The centrifugal casting machine is shown in Figure 1 with its associated vacuum pumping system and motor-generator power supply.

Figure 1

Centrifugal Casting Machine with Associated Vacuum Pumping System and Power Source for Inductive Melting.



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A more detailed drawing of this equipment is shown in Figure 2. Because this equipment has already been described in earlier reports,[1,2] only a brief resume of its operating principle will be given here.

The centrifugal casting machine consists of two major parts: a conventional vertical-tube induction melting furnace, and a specially designed centrifuge. The furnace is mounted over the centrifuge and both sections are evacuated simultaneously by a common vacuum system. During a casting run, the fissile material and the alloy additions in the desired proportions are melted and blended in the crucible located in the upper furnace section. The melting is done inductively by means of the water-cooled copper coil located external to the system. Fifteen kilowatts of 10,000-cycle power are furnished to the induction coil by means of a water-cooled bus bar.

When the molten charge has been superheated and held at temperature for a sufficient length of time to ensure a homogeneous composition, the graphite distributor-copper mold assembly in the lower centrifuge section is set into motion in a clockwise direction. The casting is made by lifting the stopper rod and causing the molten stream to fall into the graphite distributor, which diverts it into the surrounding copper molds with a minimum of splashing (see Figure 3).

CASTING PARAMETERS

The important casting parameters are the rate of feeding, the pouring temperature, and the mold speed. The feeding rate is determined by the cross-sectional area of the hole in the bottom of the crucible. This hole should be large enough to permit the crucible to empty rapidly and to provide a pool of metal in the distributor for continuous feeding into the molds. Although a 1:1 ratio between the cross-sectional area of the crucible pour-out hole and the sum of the areas of mold cavities would seem desirable, successful castings have been made in cases for which this ratio was of the order of 1:3.[2]

The pouring temperature is influenced by such factors as the thermal conductivity, the temperature range of fluidity, and the heat content of the alloy at the time of pouring. It is further modified by the thermal conductivity of the mold material, the ratio of surface to volume of the casting shape, and the number of pieces being cast simultaneously. The ratio of surface to volume of the casting shape can be regarded as a direct indication of the expected rate of solidification.

Figure 2

A Detailed Representation of the Centrifugal Casting Machine.

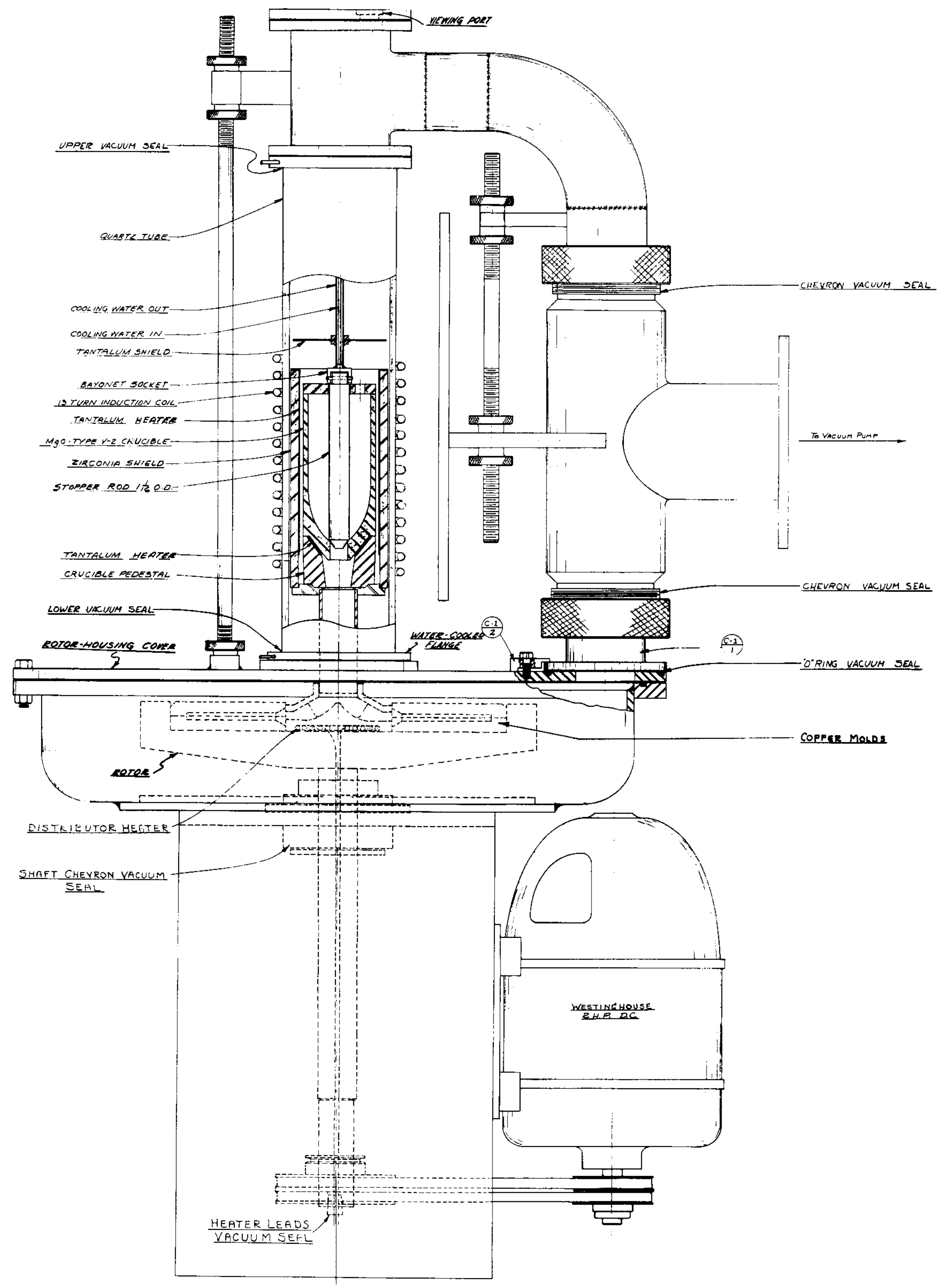
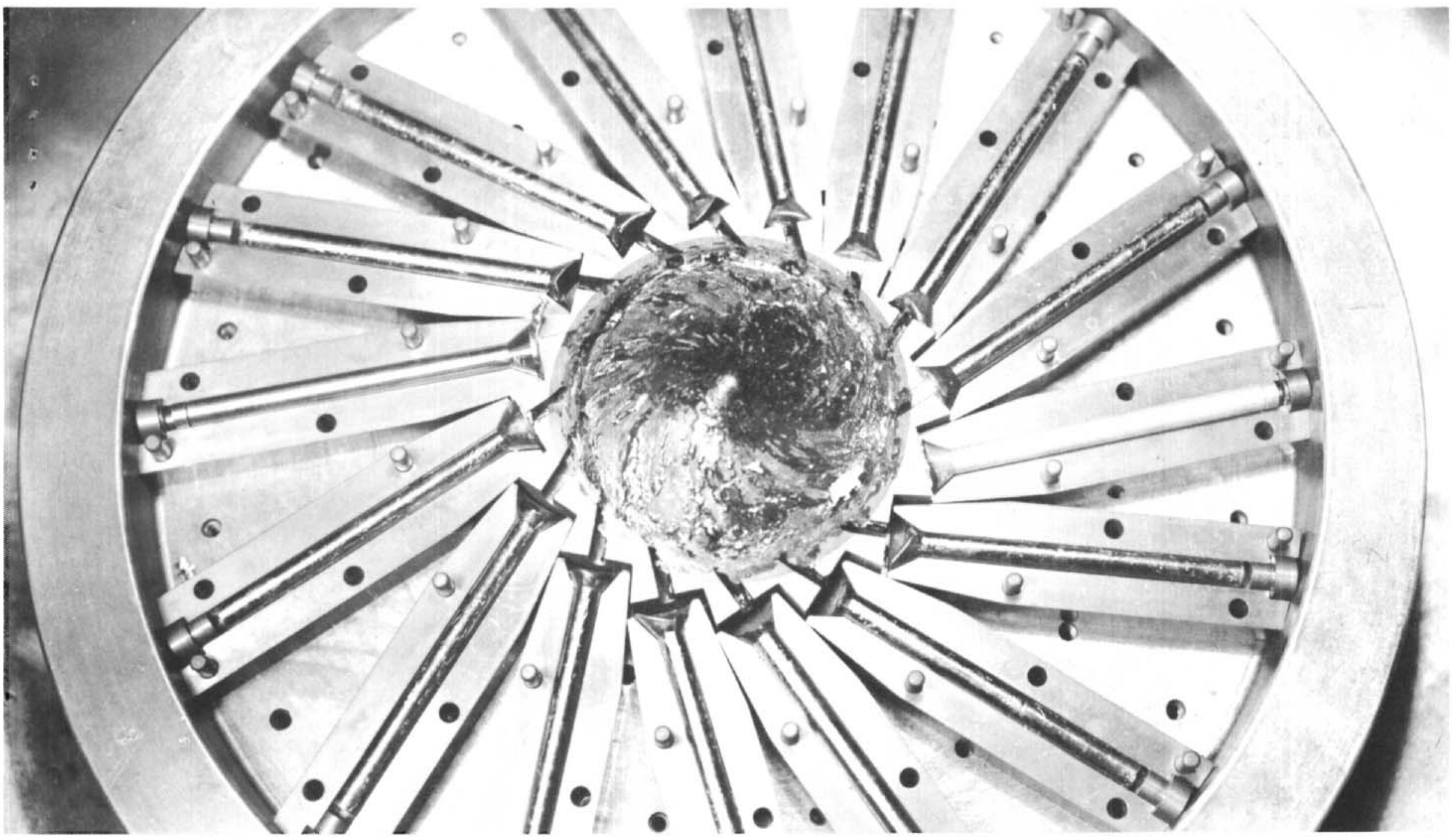


Figure 3

Graphite Distributor-Copper Mold Arrangement Used in the Fabrication of the Mark-II Fuel Loading for EBR-I. The cast U-2 w/o Zr slugs shown were replaced with various metal inserts in the initial attempts to centrifugally cast 0.185 in. diameter by $4\frac{1}{4}$ in. long pins. (Ratio of surface to volume was 21.6 to 1.)



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In general, an increase in pouring temperature would be associated with the following factors:

(1) a reduced temperature range of fluidity of the alloy being cast;
(2) a reduced specific heat of the alloy being cast;
(3) an increased thermal conductivity of the alloy or mold material;
(4) an increase in the number of pieces being cast simultaneously; and
(5) an increase in the surface-to-volume ratio of the pieces being cast.

Finally, the optimum casting speed decreases as the number of simultaneous castings increases and their section size decreases.

The optimum casting parameters are usually found through experimentation, since the demand for centrifugally cast pins of a particular prototype fuel alloy for in-pile irradiation damage studies always precedes actual property studies.

DISTRIBUTOR DESIGN

The design of the graphite distributor is perhaps the most important single aspect affecting the successful operation of this equipment. Since its primary function is to receive the vertical stream of molten metal and divert it to a horizontal direction, the design should be such as to accomplish this with a minimum of splashing or turbulence. The base of the distributor should be a smooth conical surface and the vanes should be as short as practicable to minimize chilling of the molten alloy stream. This latter point is particularly important in the casting of very thin rods as reported herein. In the fabrication of the Mark II fuel loading for EBR-I(2) as in the present investigation the simplest distributor design was found to be the best design.

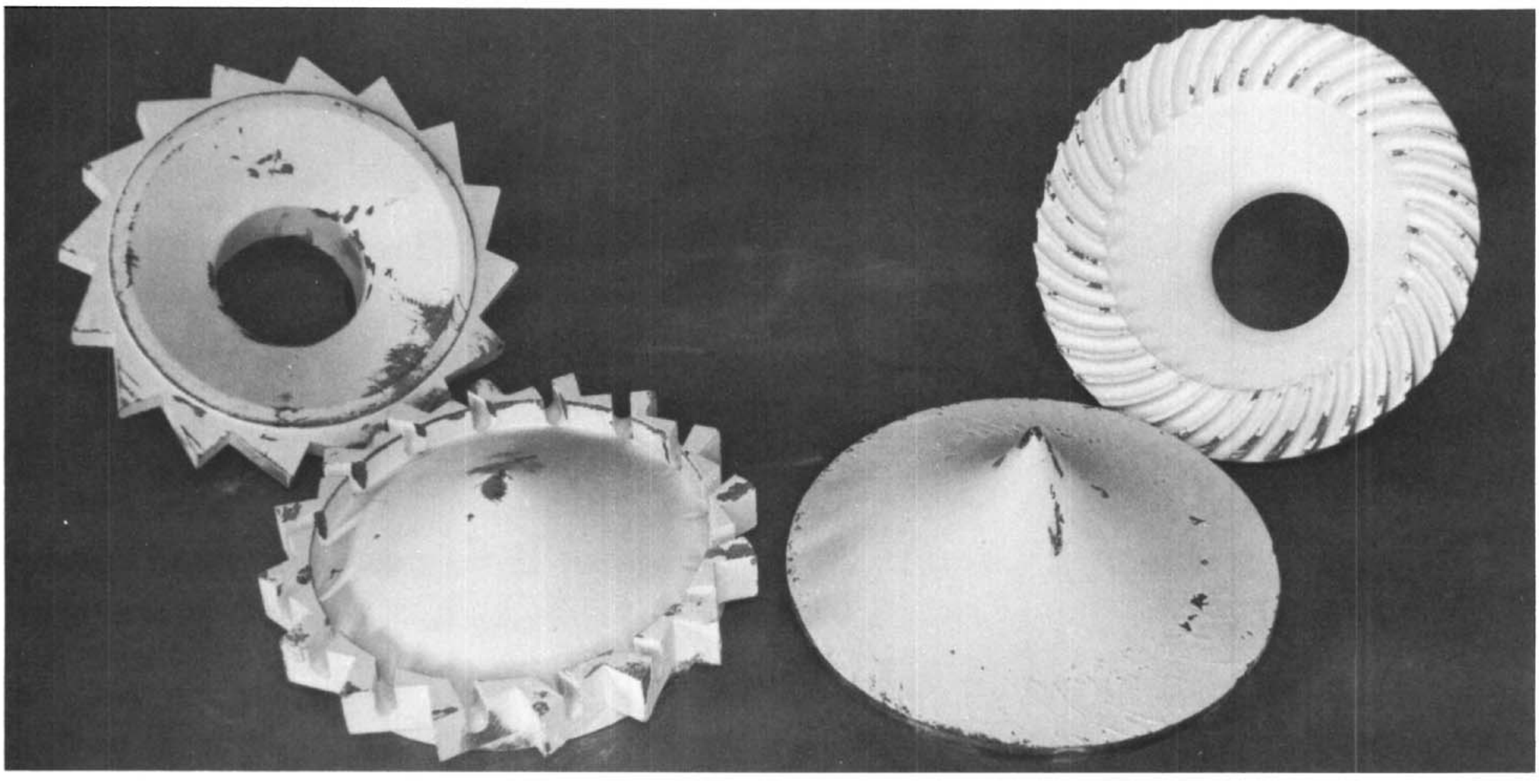
Two successful distributor designs are pictured in Figure 4. The distributor on the left was used to centrifugally cast 0.384-in.-diameter by $4\frac{1}{4}$-in.-long EBR-I fuel slugs in the arrangement shown in Figure 3. It was also used to centrifugally cast the 0.185-in.-diameter by $4\frac{1}{4}$-in.-long experimental fuel pins described in this report.

Figure 4

Thoria-coated Graphite Distributors Used in the Centrifugal Casting of Fuel Alloys.

Left: Design used to cast 0.384-in.-diameter by $4\frac{1}{4}$-in.-long EBR-I Fuel Slugs.

Right: Optimum design for casting 0.165-in.-diameter by $9\frac{3}{4}$- in.- long fuel pins.



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The distributor on the right in Figure 4 is shown in greater detail in Figures 5 and 6. It was designed especially for the simultaneous casting of 36 fuel pins measuring 0.165 in. in diameter by $9\frac{3}{4}$ in.-long, and replaces the more complicated and less successful design shown in Figure 7.

The distributor shown in Figure 8 was used in attempts to centrifugally cast 0.040-in.-thick uranium fuel plates.

A white thoria coating was usually sprayed onto the distributor surface to protect it against heat checking and to reduce carbon pickup by the alloy. Distributors machined from high-density reactor-grade graphite have a longer useful service life than do those machined from less dense graphite.

CASTING PROCEDURES

A. Pin Castings (0.185-in.-Diameter x $4\frac{1}{4}$-in.-Long)

The first castings of small diameter to be attempted were pins measuring 0.185-in. in diameter by $4\frac{1}{4}$-in.-long. These were centrifugally cast with the same graphite distributor-copper mold assembly as that shown in Figure 3. Metal inserts were used, in the manner illustrated in Figure 9, to reduce the original casting diameter of 0.384 in. to the desired 0.185 in. Since it was reasonable to assume that the high thermal conductivity of copper might preclude its use as a mold material for thin sections, the metal inserts were machined from sixteen different metals and alloys, indicated in Table I. Thus, these first tests also served as a guide for the selection of an optimum mold material.

Three casting runs were made to establish the feasibility of centrifugally casting 0.185-in.-diameter by $4\frac{1}{4}$- in.-long fuel pins. Unalloyed uranium was used in the first two casting runs, and a uranium-2 w/o zirconium alloy was used in the third.

B. Pin Castings (0.165-in.-Diameter x $9\frac{3}{4}$-in.-Long)

A special graphite distributor-mold assembly design was necessary before attempting to cast the smaller 0.165-in.-diameter by $9\frac{3}{4}$-in.-long fuel pins centrifugally. The distributor design is shown in Figures 4, 5, and 6, and the mold design is shown in Figure 10. In this assembly provision was made for the simultaneous casting of 36 fuel pins.

Copper was selected as the mold material on the basis of the results obtained from the metal inserts used in the casting of the 0.185-in.-diameter pins. The brass, copper, and silver inserts produced the best pins from the standpoint of surface appearance.

Figure 5

Base of Graphite Distributor Shown on Right in Figure 4.

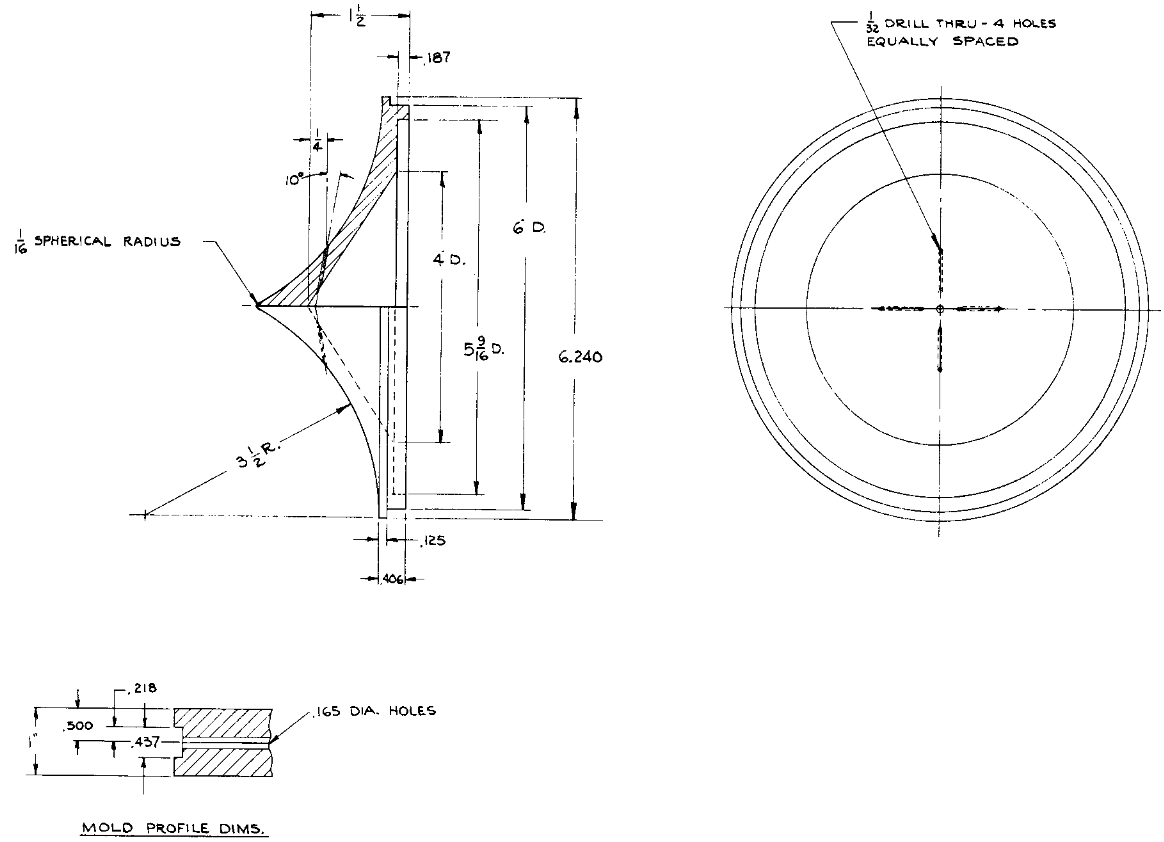

Figure 6

Cover of Graphite Distributor Shown on Right in Figure 4.

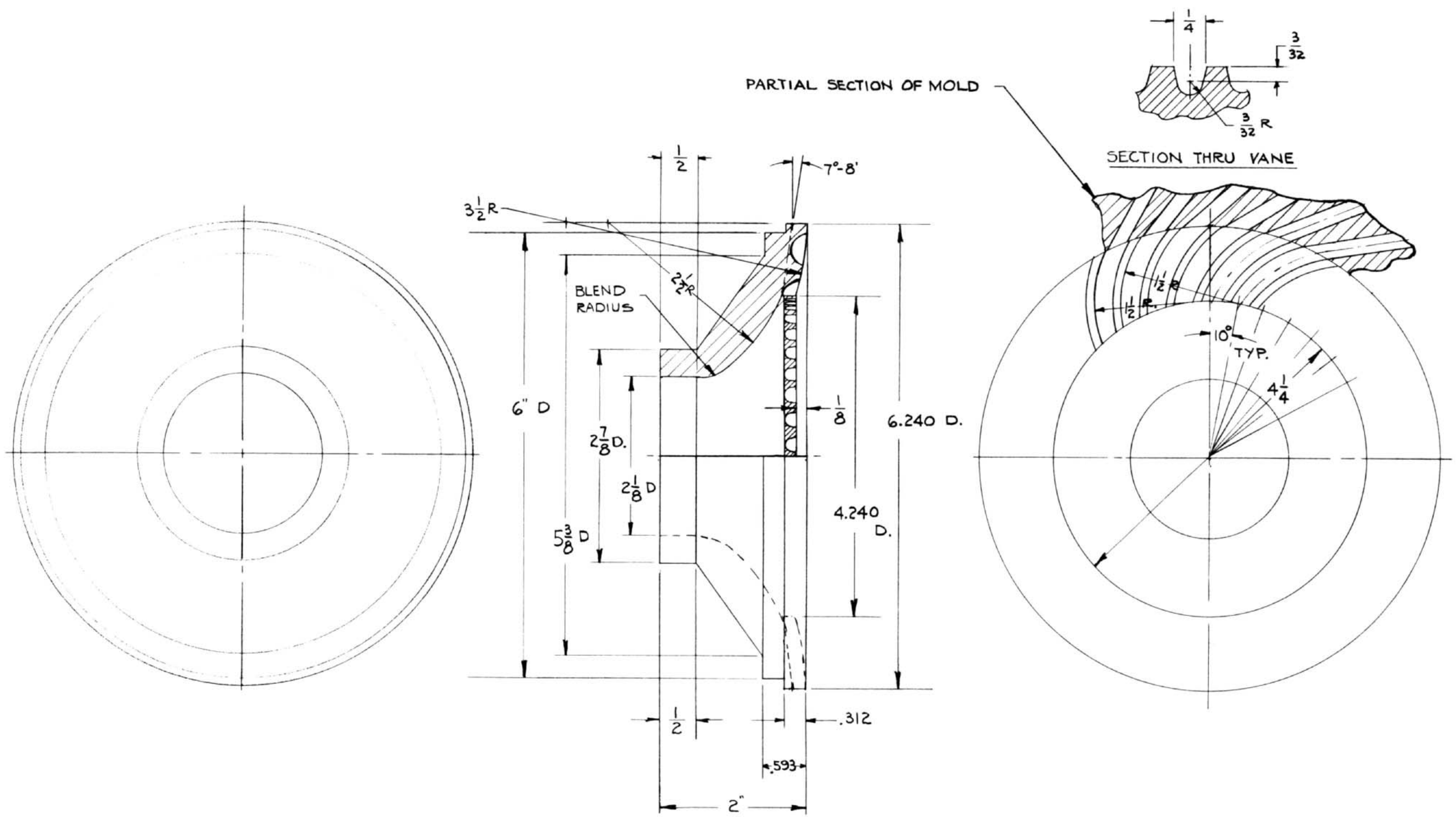

Figure 7

Original Distributor Design Used in Attempts to Centrifugally Cast 0.165-in.-diameter by $9\frac{3}{4}$-in.-long Pins.

Left: Distributor Cover Right: Distributor Base

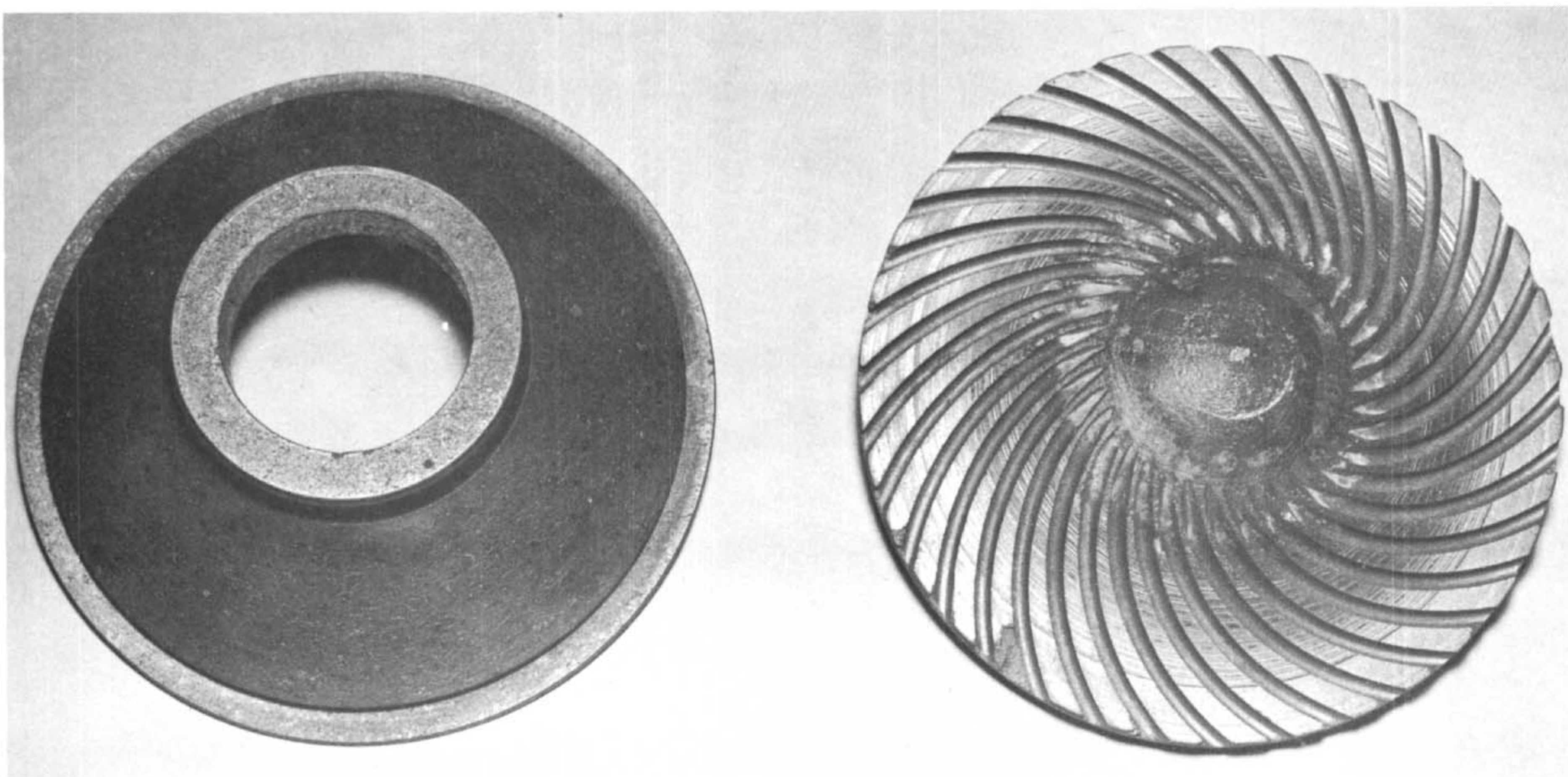

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Figure 8

Graphite Distributor Design Used in Attempts to Centrifugally Cast 0.040-in.-thick Uranium Fuel Plates.

Left: Distributor Cover Right: Distributor Base

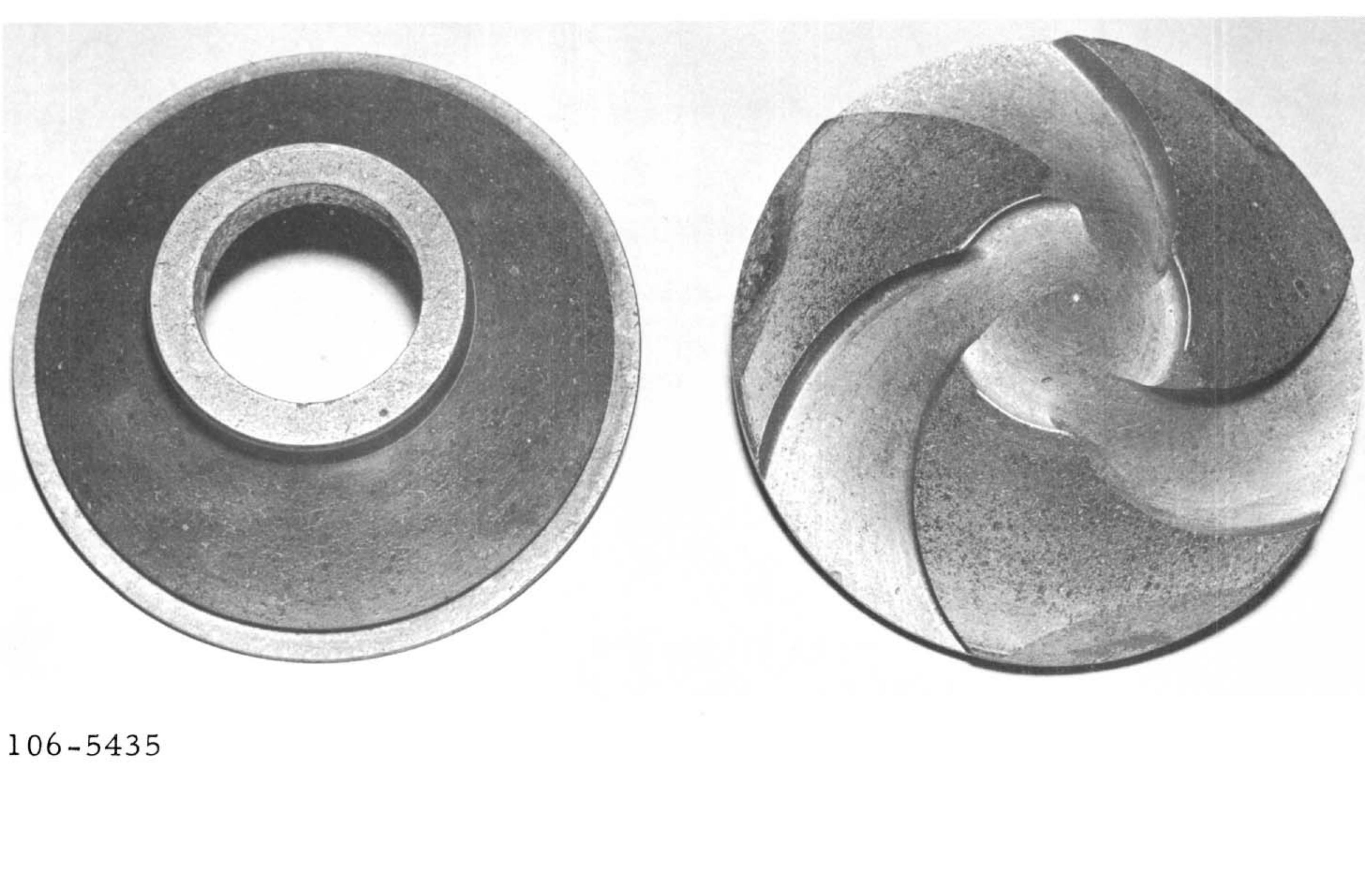

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Figure 9

A Schematic Representation of the Relationship Between the Mold Insert and the EBR-I Size Mold Used in the Casting of 0.185-in.-diameter by $4\frac{1}{4}$-in.-long Pins.

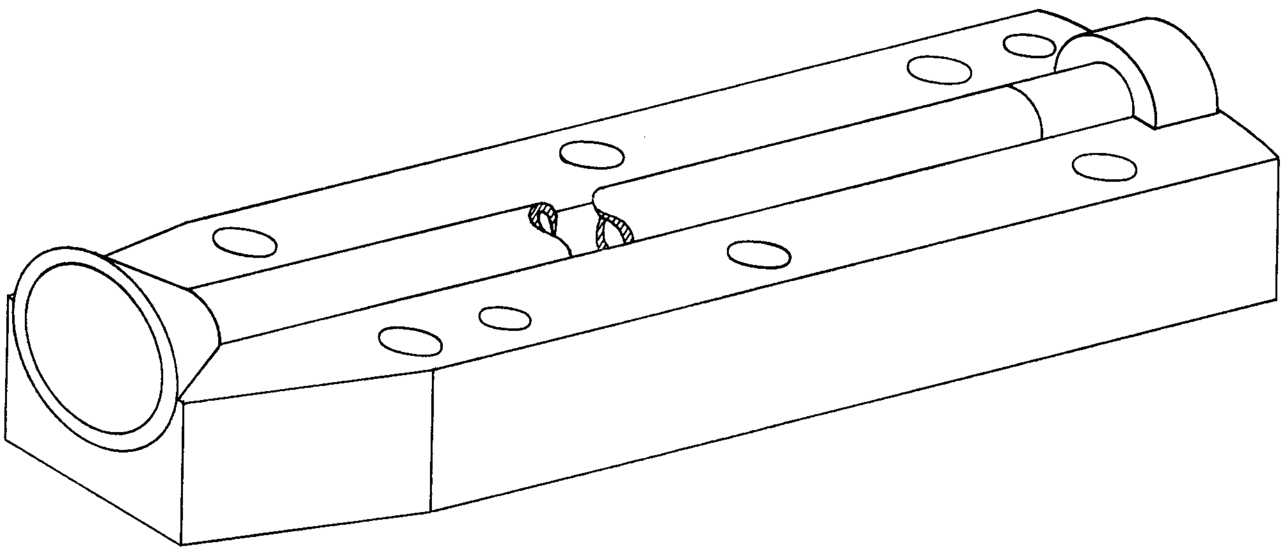


Table I

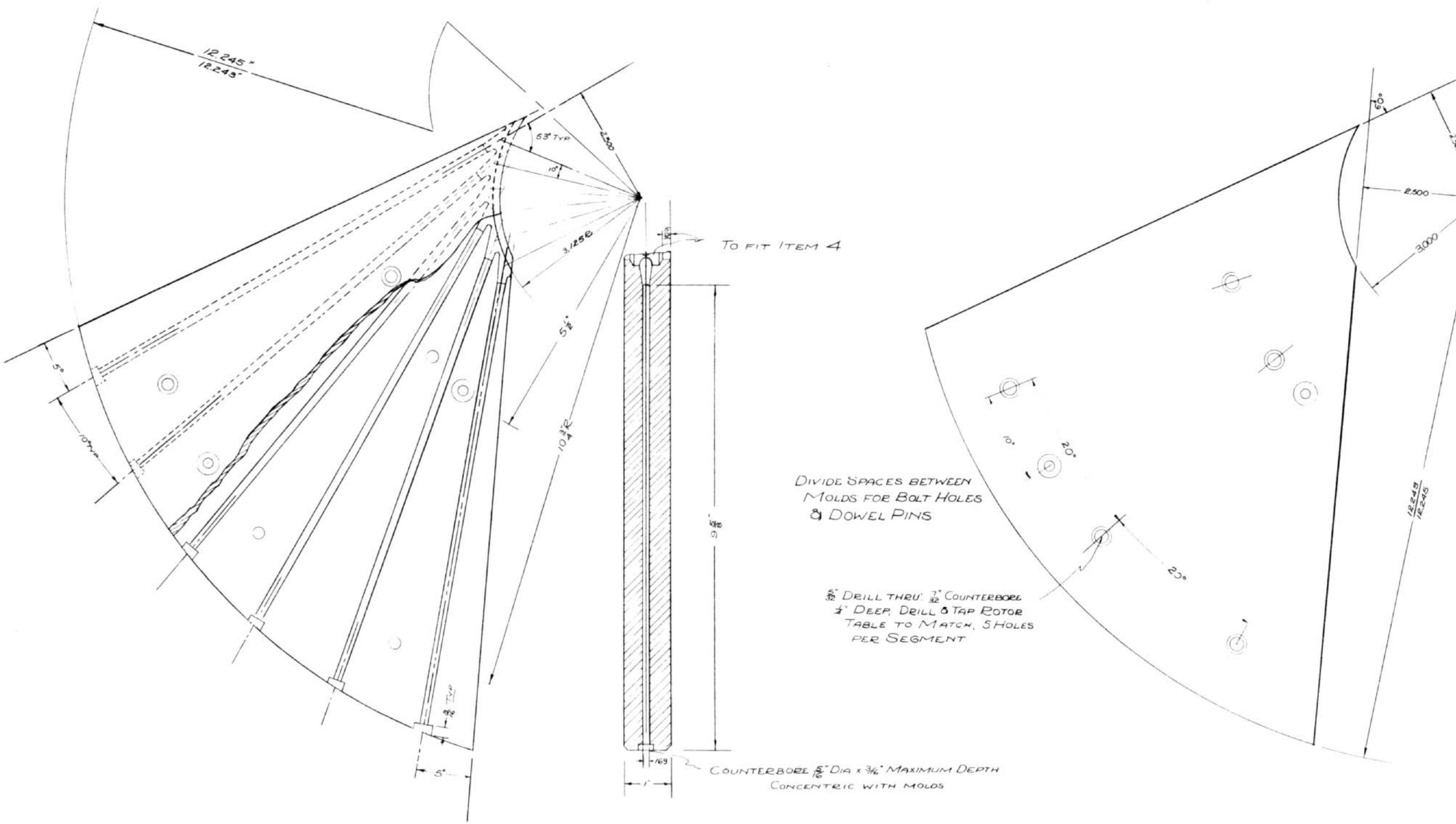
MATERIALS USED AS MOLD INSERTS IN MELTS CNY-13, CNY-14 AND CNY-15

Mold Material	Melting Point or Range (°C)	Specific Heat [cal/(gm)(°C)]	Thermal Conductivity [cal/(cm)(sec)(°C)]	Ref.
Armco Iron	1539	0.10	0.18	1
Mild Steel (SAE 1020)	1492 - 1530	0.10	0.115	1
Type 347 Stainless Steel	1399 - 1427	0.12 (20°C)	0.038 (100°C)	2
Type 440 Stainless Steel	1371 - 1510	0.11	0.058 (100°C)	2
Brass (60Cu-40Zn)	890 - 900	0.0917	0.29	1
Copper	1083	0.092	0.94	1
Inconel (80Ni-14Cr-6Fe)	1425	0.109 (20°C)	0.036 (20°C)	1
Monel (67Ni-30Cu-1.4Fe-1Mn)	1300 - 1350	0.127 (20°C)	0.062 (20°C)	1
Molybdenum	2625 + 10	0.061 (20°C)	0.35 (20°C)	1
Nickel	1455	0.105 (20°C)	0.22 (20°C)	1
Silver	960.5	0.056 (20°C)	1.0 (20°C)	1
Tantalum	2996 ± 50	0.036 (20°C)	0.13 (20°C)	1
Thorium	1718	0.0284 (100°C)	0.090 (100°C)	3
Titanium	1660 ± 10	0.129	0.041 (25°C)	3
Uranium	1133	0.0278 (27°C)	0.058 (25°C)	3
Zirconium	1830	0.168 (127°C)	0.035 (125°C)	3

1. ASM Handbook (1948 Edition)
2. Stainless Steel Handbook, Allegheny Lundlum Steel Corp., Pittsburgh, Pa.
3. Atomic Energy Materials, 3rd Edition, National Lead Company, New York, N. Y.

Figur 10

Copper Mold Segment Used in Casting 0.165-in.-diameter Pins



The completed copper mold assembly consists of six matching segments of the type shown in Figure 10. Their combined weight, when assembled, was 132 pounds. In addition, two similar mold segments were also machined in brass as a further test of the relative worth of these two mold materials. The brass segments are easily distinguished from the copper segments in Figure 13 by their brighter appearance.

Seven casting runs of 36 pins each were attempted: five with unalloyed uranium and two with a uranium-2 w/o zirconium alloy.

C. Plate Castings (0.040 in. x 2 in. x $9\frac{3}{4}$ in.)

The graphite distributor used in the attempts to cast 0.040-in.-thick uranium plates centrifugally is pictured in Figure 8. The three corresponding mold segments were also machined of graphite in accordance with the drawings shown in Figure 11. In each mold segment provision is made for casting two plates, one above the other, in an effort to compensate for the extremely thin cross section. The external dimensions were purposely made identical with those of the copper mold segments described above (see Figure 10) so that they could be interchanged. During the plate-casting runs, the three graphite mold segments were substituted for three alternate copper mold segments.

Only three casting runs were made, all with unalloyed uranium.

RESULTS

The casting results obtained in this investigation are summarized in Table II.

A. Pin Castings (0.185-in.-diameter x $4\frac{1}{4}$-in.-long)

In each of the three casting runs, CNY 13, 14, and 15, fifteen of the 16 metal inserts used produced full-length pins in both unalloyed uranium and a uranium-2 w/o zirconium alloy. Upon inspection, the 15 pins from each of the three melts were found to be internally sound and possessed a smooth surface appearance. The pins with the smoothest surface came from the brass, copper, and silver inserts.

The zirconium insert was the only one which failed to fill completely in each of the three casting runs. Furthermore, the surface of the casting removed from this insert was always very porous.

An as-cast 0.185-in.-diameter pin is compared with a similarly cast 0.384-in.-diameter EBR-I fuel slug in Figure 12. The ratio of surface to volume for these two pieces was 21.6 to 1 and 10.4 to 1, respectively. The alloy in both instances was uranium-2 w/o zirconium, and both pieces were cast in a copper mold.

Figure 11

Graphite Mold Segment Used in Casting 0.040-in.-thick Plates

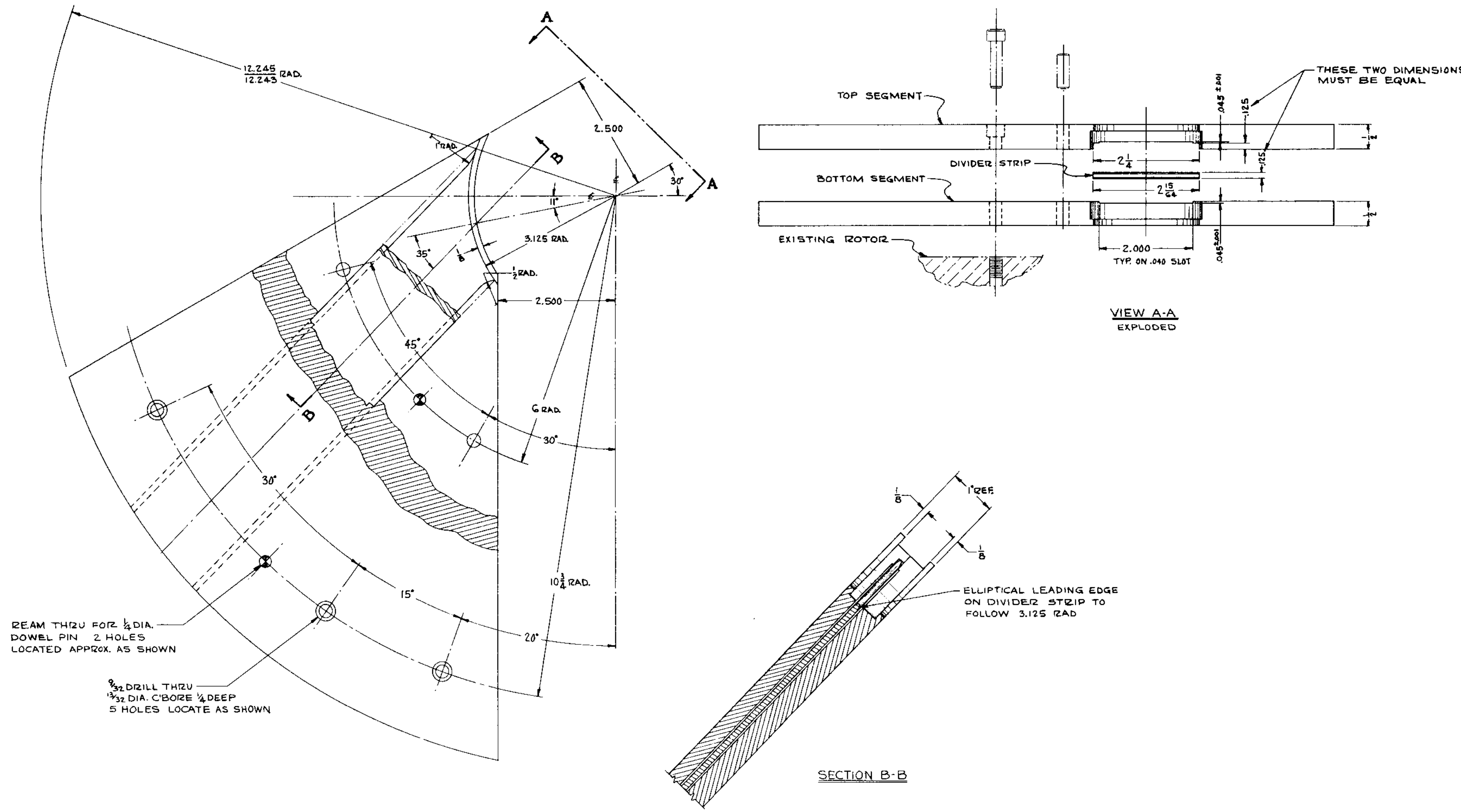


Table II

A SUMMARY OF ATTEMPTS TO CAST FUEL ALLOYS CENTRIFUGALLY IN THIN SECTIONS

Melt No.	Casting Shape	Ratio Surface/Vol	Ratio Length/Dia	Alloy	Charge Weight (gm)	Casting (rpm)	Pouring Temp (°C)	Graphite Distributor Design	No. of Pins Cast	Casting Results: No. of Full Length Castings	Casting Results: Max Acceptable Length Cast (in.)	Remarks
CNY-13 CNY-14 CNY-15	Fuel Pin, 0.185 in. in dia x 4-1/2-in. long (See Fig. 12)	21.6/1	23/1	Uranium U-2 w/o Zr	925 940 1000	250 250 250	1425 1410 1480	Same as design used in production of Mark-II fuel loading for EBR-I (See Fig. 4)	16 16 16	15 of 16(93.8%) 15 of 16(93.8%) 15 of 16(93.8%)	4-1/4 4-1/4 4-1/4	Zirconium mold insert failed to fill completely in each of the three casting attempts. Casting CNY-15 poured at the higher temperature to compensate for the higher melting point of the U-2 w/o Zr alloy. Distributor heater operated throughout melt. Brass copper and silver appear to be best mold materials.
CNY-16	Fuel pin 0.165 in. in dia x 9-3/4-in. long (See Fig. 15)	24.6/1	47/1	Uranium	3165	560	1500	Similar to design shown in Fig. 4 Vanes on distributor base	36	1 of 36(2.78%)	9-3/4	Poor results attributed to excessively high casting rpm. Distributor heater burned out before pouring.
CNY-17					2400	250	1450	Original design for small pin castings (See Fig. 7)	36	None	3	Poor results attributed to excessive cooling effect of complex distributor design. In Melt CNY-17 molten charge solidified largely in distributor. Both melts poured without distributor heater.
CNY-18					2447	250	1550		36	None	9	
CNY-19	Fuel pin 0.165 in. in dia x 9-3/4-in. long (See Fig. 15)	24.6/1	47/1	Uranium	2900	200	1450	Similar to design shown in Fig. 4 Vanes on distributor base	36	1 of 36(2.78%)	9-3/4	Improvement in casting yield of CNY-20 over CNY-19 is attributed to a higher pouring temperature. Both melts poured without distributor heater.
CNY-20				Uranium	2900	200	1600		36	23 of 36(64%)	9-3/4	
CNY-23				U-2 w/o Zr	2437	250	1600	Design shown in Figs. 4, 5, and 6	36	19 of 36(52.8%)	9-3/4	Melts held at temperature 20 min longer before pouring to compensate for the higher melting point of the U-2 w/o Zr alloy. Both melts poured without distributor heater.
CNY-24				U-2 w/o Zr	2895	250	1650	Vanes machined into distributor cover	36	20 of 36(55.5%)	9-3/4	
CNY-25	Fuel plate (0.040 in. x 2 in. x 9 in.) (See Fig. 11)	50/1	Length/Thick 225/1	Uranium	2300	250	1500	Design shown in Fig. 8	6	None	5	Surfaces of cast plates appear somewhat rough as a result of casting into bare graphite molds. Coating the graphite molds with thoria would tend to improve the surface condition of these plates Absence of distributor heater appears to have a greater effect on casting length than it did in the case of the fuel pins
CNY-26					2300	300	1600		6	None	6	
CNY-27					2300	300	1650		6	None	6	

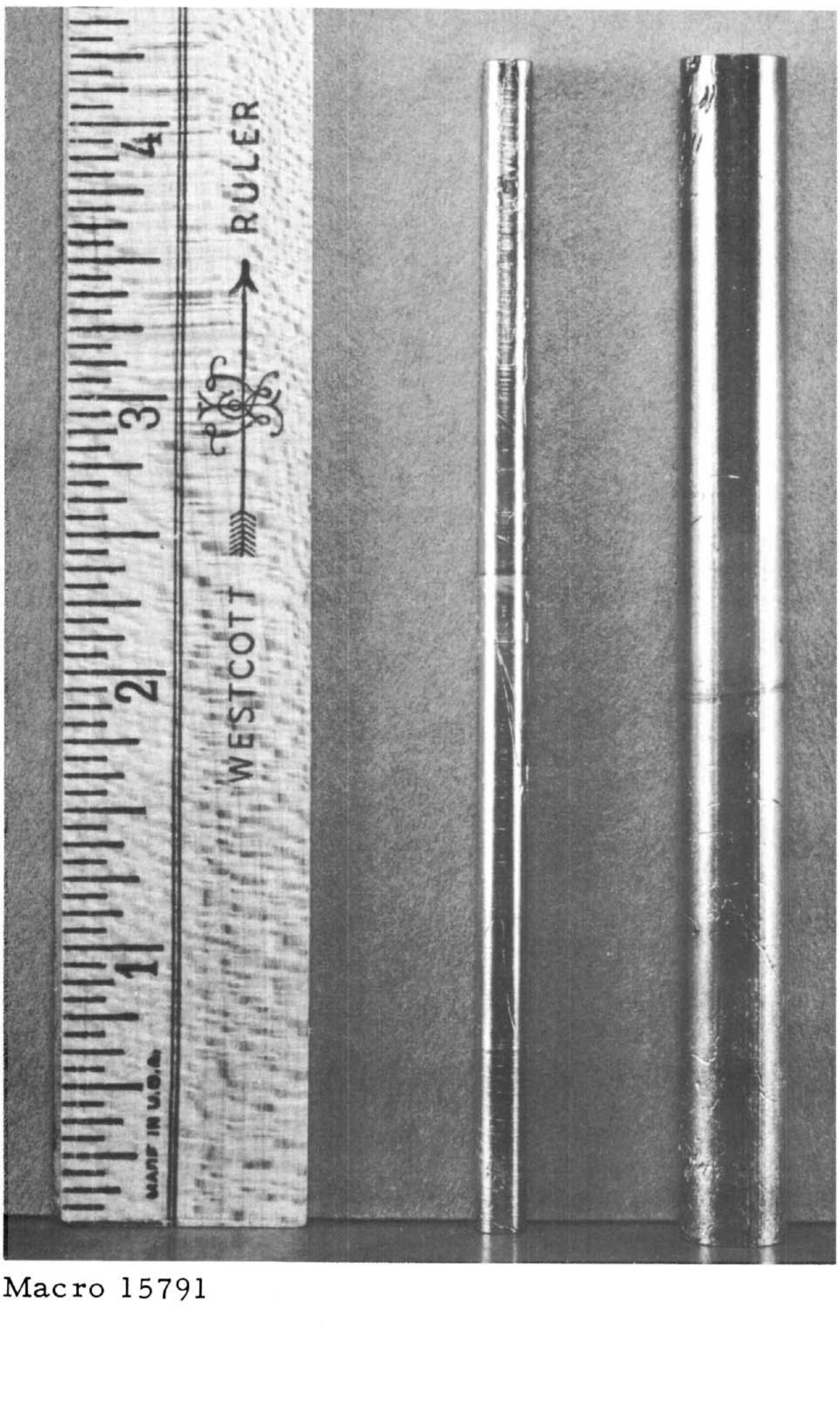
Figure 12

A Comparison of Centrifugally Cast U-2 w/o Zr Alloy Fuel Pins

Left: Pin dimensions: 0.185-in.-diameter by $4\frac{1}{4}$-in.-long.

Right: EBR-I Fuel Slug: 0.384-in.-diameter by $4\frac{1}{4}$-in.-long.

Both pieces were cast in copper molds.



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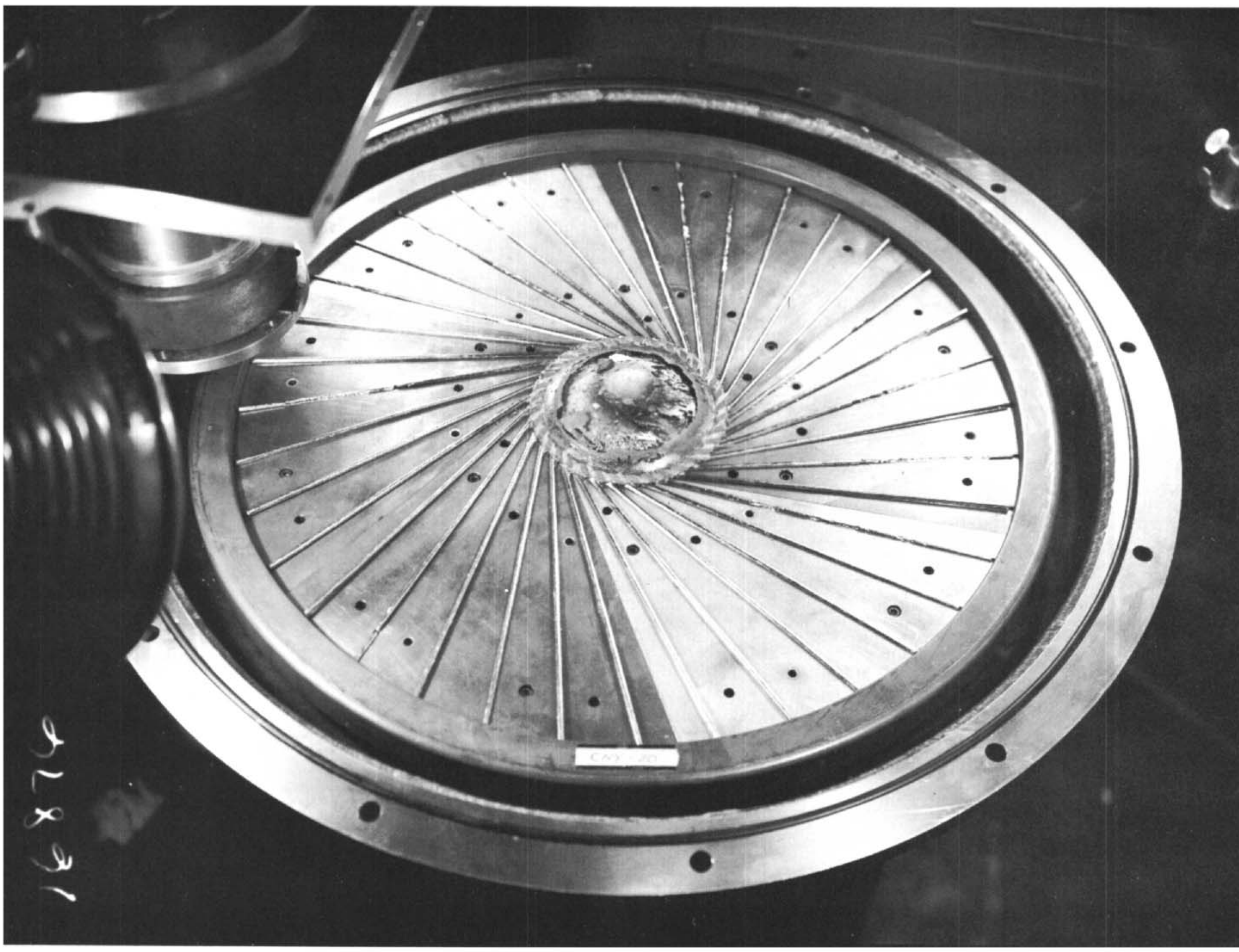
B. <u>Pin Castings (0.165-in. in diameter x $4\frac{1}{4}$-in.-long)</u>

A complete summary of the results of castings CNY-16, 17, 18, 19, 20, 23, and 24 is given in Table II. The as-cast pins produced in run CNY-20, the most productive of the seven attempts, are shown in Figure 13.

Figure 13

0.165-in.-diameter Pins Produced in Casting Run CNY-20. Bright segments are of brass; dull segments are of copper.



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The lengths of individual pins produced in five of the seven casting attempts are represented graphically in Figure 14. For convenience, the acceptable pin lengths are arbitrarily grouped into half-inch length intervals from 0-in.-long to the full casting length of $9\frac{3}{4}$in. The number of pins falling within a particular length interval in each of the five casting runs (CNY-16, 18, 19, 20, and 23) are indicated by the height of each bar. Pins cast to the full length of $9\frac{3}{4}$ in. are indicated by a thin bar at the extreme right-hand side of each graph.

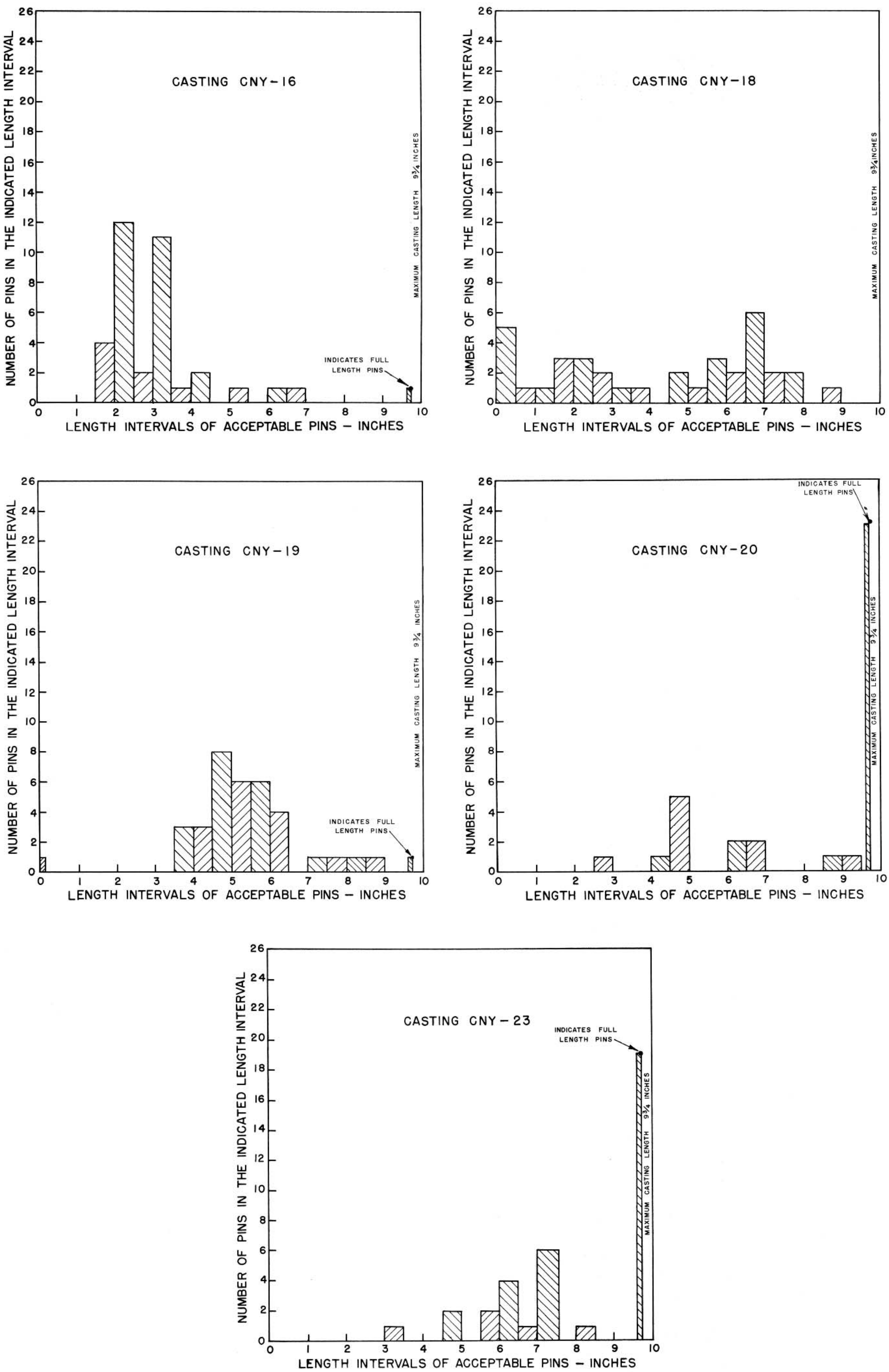
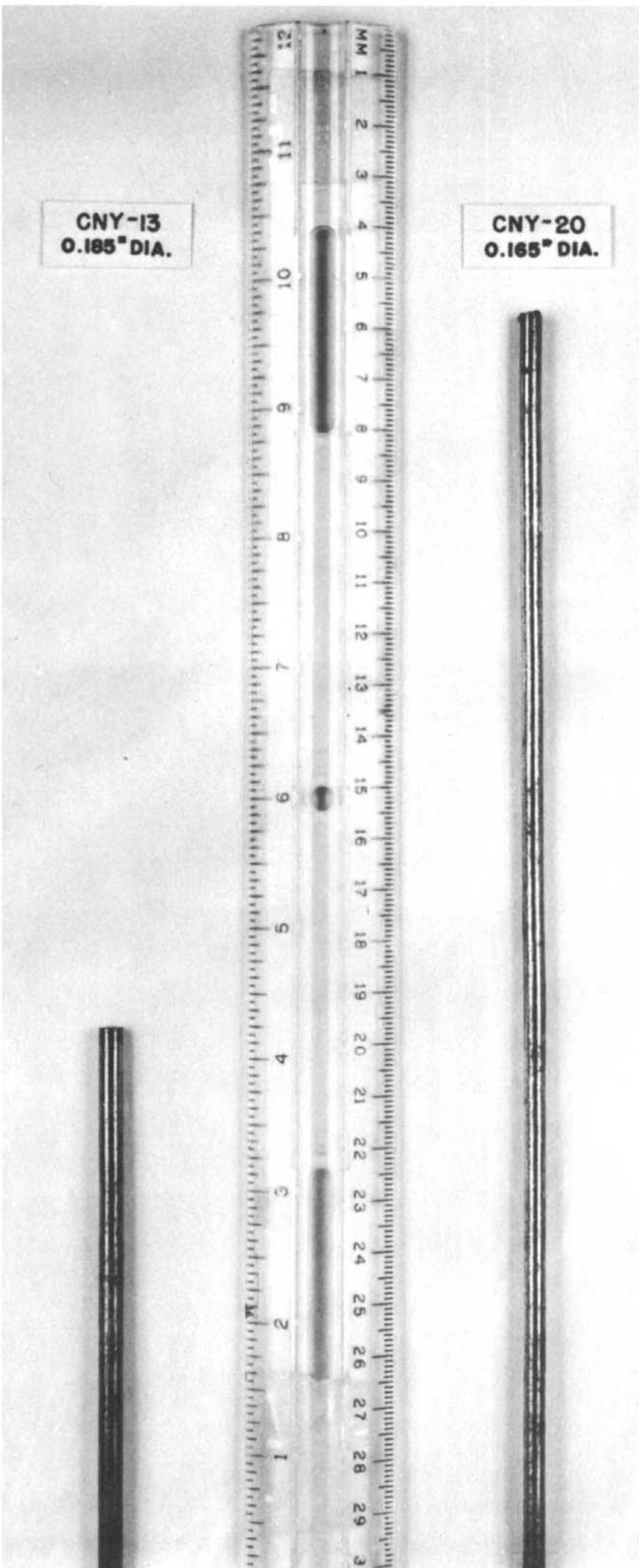


Figure 14

A Graphic Representation of the Length Distribution of Centrifugally Cast 0.165-in.-diameter Fuel Pins for Five Pourings.

Figure 15

A Comparison of Centrifugally Cast Unalloyed Uranium Fuel Pins. Both Pieces Were cast in Copper Molds.



The 0.165-in.-diameter by $9\frac{3}{4}$-in.-long pin with a surface-to-volume ratio 24.2 to 1 represents the thinnest and longest rod-type fuel element to be cast centrifugally. One such pin from casting run CNY-20 is compared for surface appearance with a 0.185-in.-diameter by $4\frac{1}{4}$-in.-long pin in Figure 15. Both pins are unalloyed uranium, and both were cast in copper molds.

C. Plate Castings (0.040-in. x 2 in. x 9 in.)

The success achieved in casting thin uranium plates, as summarized in Table II, was somewhat less spectacular. With a ratio of surface to volume of 50 to 1, these fuel plates were quite the most difficult sections to cast by the centrifugal technique. All of the plates produced in runs CNY-25, 26 and 27 exhibited a rough surface appearance when compared with the previously described pin castings. This is attributed to the fact that the graphite distributor and the graphite molds were used without a prior outgassing and without the refractory coating of thoria. In addition, the molds themselves were machined from low-density graphite.

The six plates produced in run CNY-25 had a usable length of 5 in., although the castings themselves were slightly longer. This usable length was increased to 6 in. in runs CNY-26 and 27 by a slight increase in rotor speed and a significant increase in pouring temperature. No improvement in surface condition was noticed.

REMARKS

The following comments can be made regarding the feasibility of producing thin fuel sections by the centrifugal casting technique.

(1) Rod-type fuel elements with a ratio of surface to volume of 26 to 1 and a ratio of length to diameter of 59 to 1 can be centrifugally cast to size.

(2) Brass, copper, and silver are of equal relative worth as mold materials.

(3) The design of the distributor has a profound influence on the successful application of this technique to the fabrication of thin fuel sections.

(4) Fuel plates measuring 0.040 in. by 2 in. by 6 in. have been centrifugally cast successfully, and it seems that this length and the surface appearance of these plates could be improved by a refinement in technique.

The immediate objective of this work, namely, determination of the suitability of the centrifugal casting technique for the production of fuel pins of small diameter, has been achieved. However, the number and kind of manipulations inherent in this method of fuel manufacture, and the relatively low production potential per machine clearly preclude the use of this casting technique in high-production applications and/or applications requiring remote operation as in a high-level cave. On the basis of these latter considerations, the work reported herein was terminated in its present state in favor of the development of the more promising injection-casting technique proposed by A. B. Shuck of the ANL Metallurgy Division. The operating principle of this latter technique is illustrated in Figure 16, and the data on its performance have been reported in the open literature.(3)

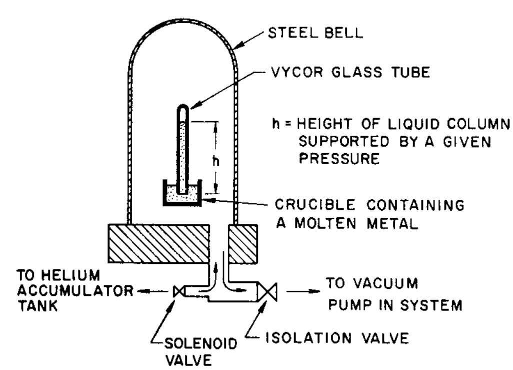


Figure 16

Principle of the Injection Casting Technique

ACKNOWLEDGEMENTS

The author is indebted to the Central Shops personnel for their cooperation in machining the distributors and molds used in these experiments, and to W. H. Morris of the Metallurgy Division for his assistance in conducting the casting experiments. An expression of gratitude is due A. B. Shuck of the Metallurgy Division for his interest and his suggestions.

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