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THE MANUFACTURE OF CENTRIFUGALLY CAST ALLOY FUEL SLUGS
(Mark-II Fuel Loading for EBR-I)

by

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THE MANUFACTURE OF CENTRIFUGALLY CAST ALLOY FUEL SLUGS
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ABSTRACT

This report describes the manufacture of the Mark-II fuel loading for EBR-I, fabricated at ANL during the period July through October, 1953. This fuel loading, consisting of a uranium-2 w/o zirconium alloy, replaced the initial loading of wrought and heat-treated unalloyed uranium. It represents the first recorded effort to fuel a fast reactor system entirely with fissile material in the as-cast condition.

Fuel slugs measuring 0.383 in. in diameter were centrifugally cast to size in massive copper molds at the rate of 16 slugs per melt. The resulting microstructure was characterized by a fine grain size and a completely random grain orientation not easily obtained in wrought fissile material of comparable composition, even after heat treatment. Reproducibility of the desirable as-cast structure and physical properties of the fuel slugs was automatic. On thermal cycling in NaK in the temperature range from 50 to 550°C, the resulting fuel slugs exhibited negligible growth, even after 570 cycles.

The gross weight of the 477 alloy fuel slugs produced in 31 productive melts was 67,199.6 grams. The overall process yield was 91.71 percent. These fuel slugs were loaded into 227 fuel rods for shipment to EBR-I.

Three copies each of Appendix A, Appendix B and Appendix C to this report exist as unissued volumes under separate cover. Appendix A contains detailed process data and material accountability data for the overall fuel fabricating operation. Appendix B is a chronological record of the loading of fuel slugs into fuel rods for shipment to EBR-I. Appendix C is a radiographic record of the internal soundness of the fuel slugs used in the loading, as well as a photographic record of their surface appearances. These data are mutually cross-referenced to permit the retracing of the metallurgical history of individual fuel slugs to the original reduction buttons from whence they came.

INTRODUCTION

Prior to July, 1950, the approximate starting date for the fabrication of the initial EBR-I fuel loading,[1] the only available information regarding irradiation-induced instability in fissile material pertained to unalloyed uranium. Accordingly, the fuel charge used in the inaugural startup of this reactor in 1951 consisted of highly enriched, unalloyed uranium in a wrought and heat-treated condition. The fabricating procedure began with cast uranium billets measuring $1\frac{1}{4}$ in. in diameter by $5\frac{1}{2}$ in. long. These were hot rolled at 300°C into rods of small diameter, using oil as the heating medium. Individual fuel slugs were machined to size from the rolled uranium rods after the latter had been given a "beta" heat treatment. This involved heating the rolled rods to a temperature slightly above the alpha-beta transformation point for unalloyed uranium (660°C) and rapidly quenching the material. Experimental results had indicated that the dimensional stability of wrought uranium was enhanced by such a treatment.[2]

Replacement of the initial fuel loading with the Mark-II loading, consisting of an as-cast uranium-2 w/o zirconium alloy, was a natural consequence of continued irradiation-damage experiments with uranium alloys. Statically cast sample fuel slugs of this composition were found to perform much better under irradiation than did wrought and heat treated unalloyed uranium. These alloy fuel slugs exhibited an inherently greater resistance to irradiation growth and irradiation-induced surface roughening than that commonly associated with beta-quenched uranium.[3,4]

The fabrication of the Mark-II fuel loading was begun in July, 1953, and completed in October, 1953. This is the first fast reactor loading to consist entirely of fuel slugs in the as-cast condition. Fabrication of the fuel blanket slugs for the Mark-II loading was completed during the same period. These latter slugs were machined from wrought and heat-treated uranium-2 w/o zirconium alloy rods in which the contained uranium was of the partially depleted variety.[5]

This report has as its purpose the description of equipment, fissile material, fuel slug specifications, and the procedural sequence used in the production of the Mark-II fuel loading. Along with this report there exist three unissued appendices, each under separate cover. Appendix A is primarily a fissile material accountability record covering the various steps utilized in the overall production operation. Appendix B is a chronological record of the loading of inspected fuel slugs into fuel rods for shipment to EBR-I. Appendix C is a collection of gamma radiographs which attest to the internal soundness of the cast fuel slugs used in the Mark-II fuel loading, and constitutes a complete photographic record of their general surface appearance.

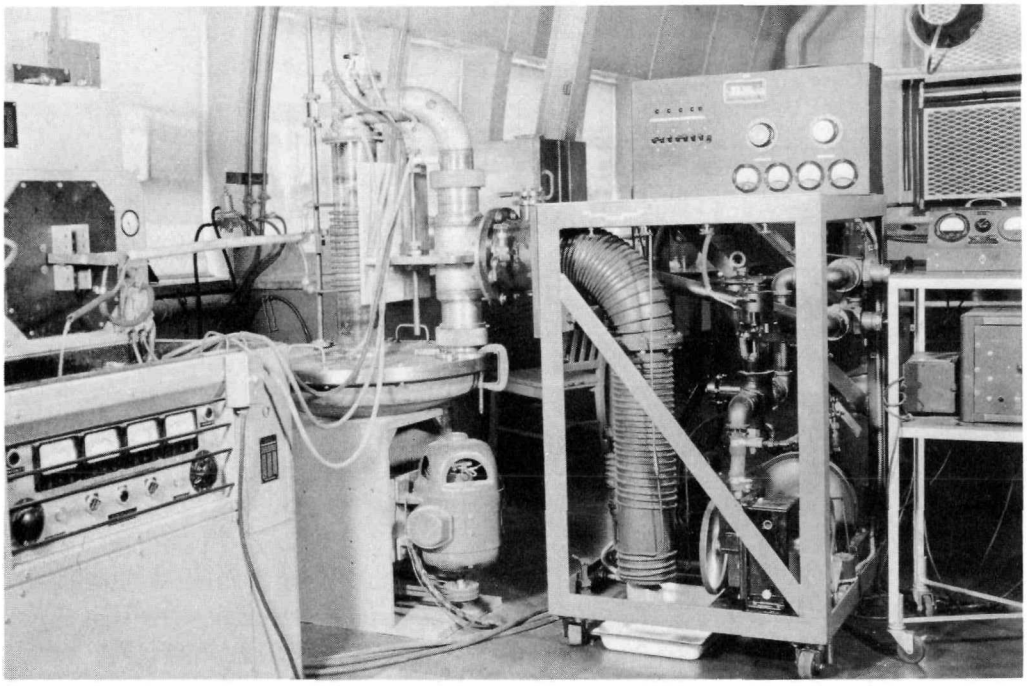
DESCRIPTION OF EQUIPMENT

Centrifugal Casting Furnace

The centrifugal casting technique was developed expressly for the Mark-II fuel loading and the equipment was designed and built at ANL. Being essentially a casting technique, it lends itself to the fabrication of a variety of fuel alloy compositions, especially those which are not readily fabricable by plastic deformation techniques. Since the equipment has been described in great detail elsewhere,[6] only a short and generalized description of its operation will be given here.

In principle, this machine consists of a conventional vertical-tube vacuum induction furnace mounted directly over a vacuum-housed centrifuge. A photograph of the assembled unit is shown in Figure 1, while a more detailed line drawing of this equipment appears in Figure 2.

Figure 1. Centrifugal Casting Machine Showing Accompanying Vacuum System and Power Source for Induction Melting



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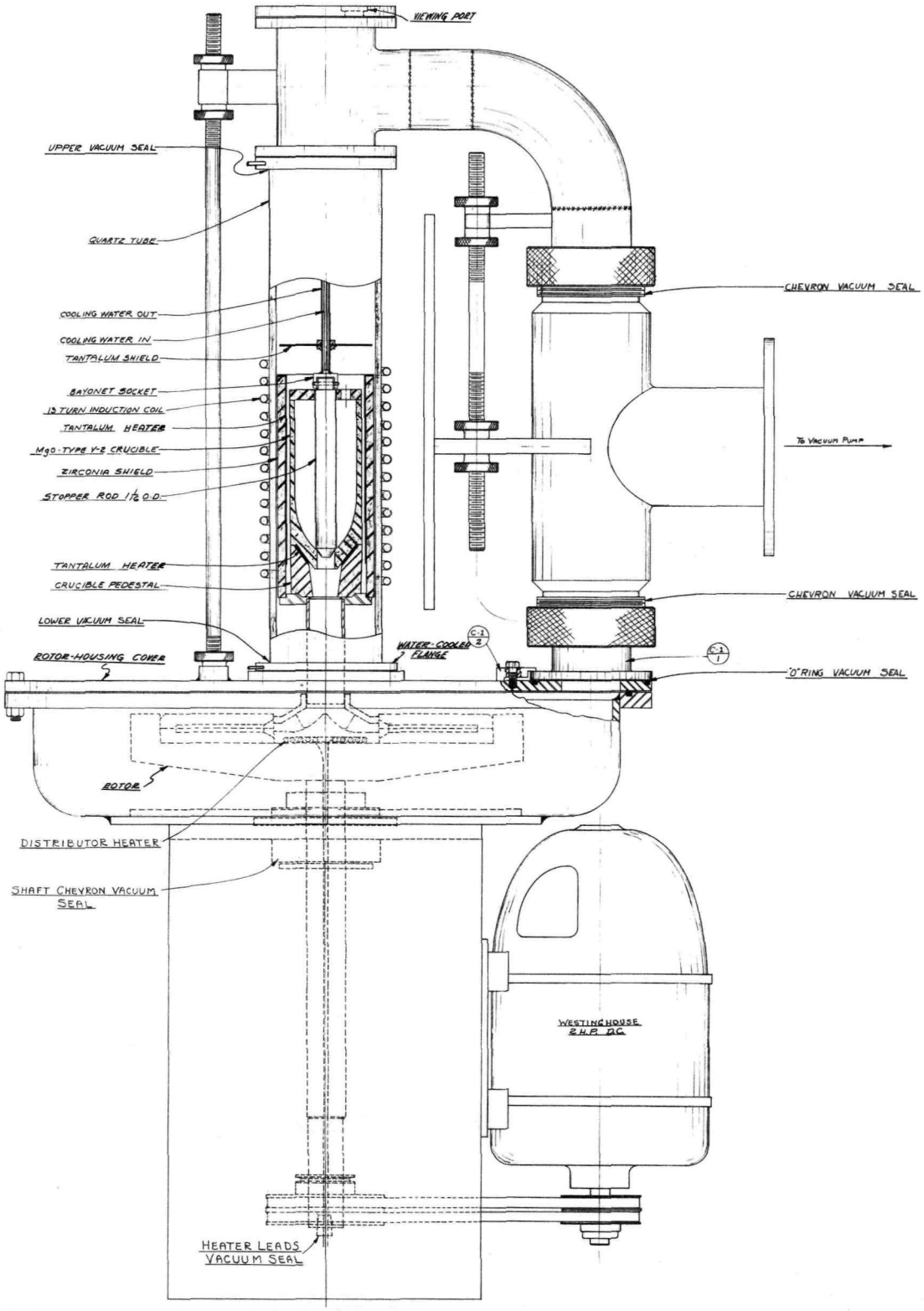
The melting charge is placed in a crucible of a suitable refractory material, which is located above the centrifuge, as shown in Figure 2. The charge is induction melted under vacuum and bottom poured into a graphite distributor located directly below the crucible in the lower centrifuge section.

Figure 2. Schematic Representation of the Centrifugal Casting Machine



The distributor diverts the molten stream to a horizontal direction and distributes it to massive copper molds arranged in a horizontal plane. The rotor containing the distributor and mold assembly is made to rotate in a clockwise direction before the molten charge is bottom poured. A constant gravitational force is maintained along the slug length by uniformly increasing the rotor speed during casting in an effort to achieve a maximum as-cast density.

After a cooling period of several hours under vacuum, the furnace system is filled with an inert gas and the machine is opened for removal of the cast fuel slugs. This is accomplished by lifting the upper curved portion of the furnace and rotating it 90 degrees in a clockwise direction. The pivot point is at the chevron vacuum seal (see Figure 2). When the Vycor (quartz) tube has been lifted off its lower water-cooled mount and the heater and ceramics have been removed, access to the centrifuge section is gained by removing the flange bolts and lifting off the metal cover.

In the Mark-II fuel loading, 16 fuel slugs were cast simultaneously. The massive copper molds were arranged symmetrically around the graphite distributor and inclined to it at a lag angle of approximately 44 degrees (see Figure 6).

Vacuum Pumping System

The vacuum pumping system shown with the centrifugal casting machine in Figure 1 was obtained commercially as a package unit. It consists of a 6-in. oil diffusion pump (Model MC-500-09) backed up by a 4-in. booster pump (Model MB-15-08) and two single-stage mechanical pumps. The $1\frac{1}{2}$-in. diameter vacuum piping within this system is so arranged as to permit the operation of one of the mechanical pumps independently of the high vacuum section. With this feature it is possible to pump out the furnace chamber through a bypass section while operating the high vacuum side of the pumping system. When the pressure within the furnace chamber has been reduced to 50-70 microns of Hg, the bypass line is closed and the 6-in. diameter vacuum valve connecting the high vacuum side to the furnace is opened. A vacuum of 4 microns of Hg or better was usually obtained within 15 minutes after opening the furnace chamber to the high vacuum pumping system.

Power Source

Power for induction melting was supplied by a "Tocco" motor-generator set of the type manufactured by the Ohio Crankshaft Corporation. This set was capable of delivering a maximum of 15 kilowatts of power at 10,000 cycles. Since the power source was located adjacent to the centrifugal casting machine, a short length of water-cooled bus bar was used to transport the power to the water-cooled copper induction coil which is external to the vacuum system (see Figure 1).

Distributor Design

The design of the distributor and the type of graphite used in its construction were found to have a profound influence on the useful service life, on the efficiency of the casting process, and finally on the surface appearance of the fuel slugs themselves.

The first workable distributor design is shown in Figure 3. This design, patterned along the lines of a centrifugal pump impeller, was used in the casting of approximately two-thirds of the Mark-II fuel loading. The center cone is located in a small circular hollow which serves as a reservoir for momentary containment of the molten pool to reduce splashing. From this reservoir the molten charge is guided to the copper molds by means of the curved vanes. Although this design was workable it proved to be too fragile. This fact is clearly illustrated in Figure 4, which shows a similar distributor which had been used in only three melts. In this complex design, metal which normally remains in the distributor bridges across the vanes and breaks them during the period of shrinkage after solidification.

Fine-grained, high-density graphite was found to be more suitable as a distributor material than the coarse-grained, less dense variety. The choice largely has to do with the ability of the high-density graphite to withstand repeated exposure to the abrasive action of molten metal without heat checking. Low-density graphite is very poor in this respect, and as a result the mechanical adhesion of solidified uranium-2 w/o zirconium alloy to its surface is noticeably greater.

A simplified distributor design for the EBR-I fuel slug size is shown on the left in Figure 5. It is coated with a sprayed-on protective layer of thoria. The complex, curved vanes of the original design (Figure 3) were replaced by short, straight vanes located at the base of a 45-degree cone. This design proved easier to machine, it exhibited a considerably longer service life, and it produced fuel slugs with a surface appearance as good or better than those produced with the more complicated distributor design of Figure 3. The 45-degree conical surface is a very rough approximation of the more desirable cycloid surface of the distributor shown on the right in Figure 5. A set of centrifugally cast fuel slugs typical of those produced with this simplified distributor design appear in Figure 6.

SPECIFICATIONS

Dimensional and physical specifications for the Mark-II fuel slugs were essentially those stipulated for the inaugural fuel loading. The single notable exception was the replacement of the wrought and heat-treated unalloyed uranium fuel with an as-cast uranium-2 w/o zirconium alloy fuel.

Figure 3. Graphite Distributor Design Used to Cast Two-thirds of the Mark-II Fuel Loading.

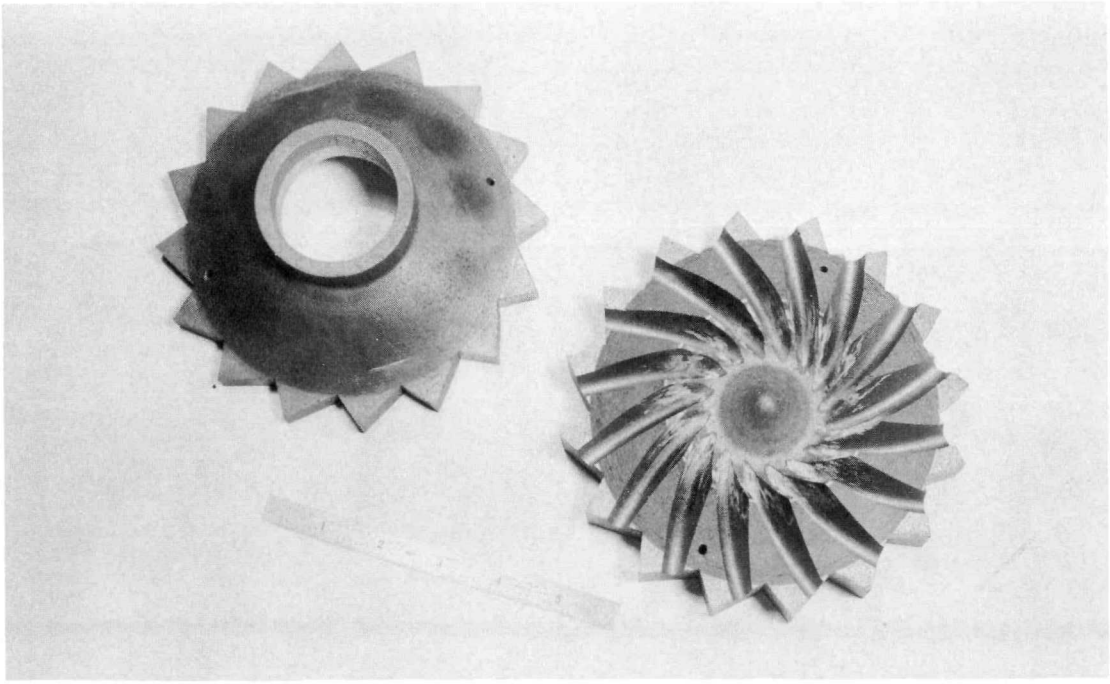


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Figure 4. Graphite Distributor Shown Above upon Completion of Three Melts.

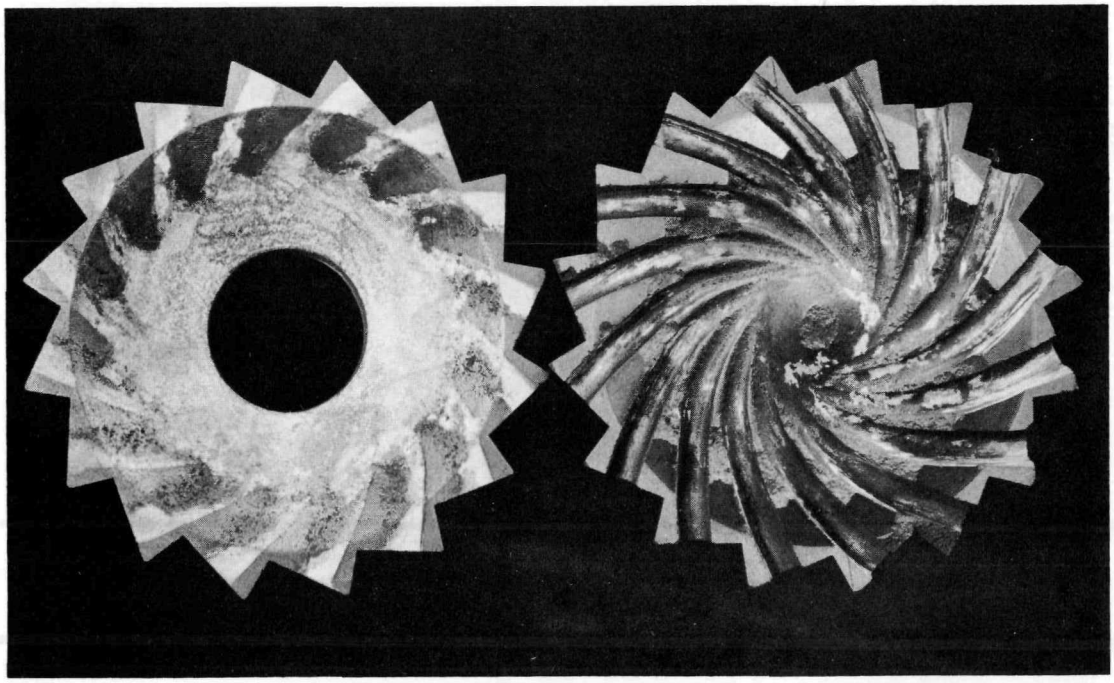

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Figure 5. (Left) Simplified Distributor Design for EBR-I Size Fuel Slugs. (Right) Distributor Design for Casting Small-diameter Fuel Pins.

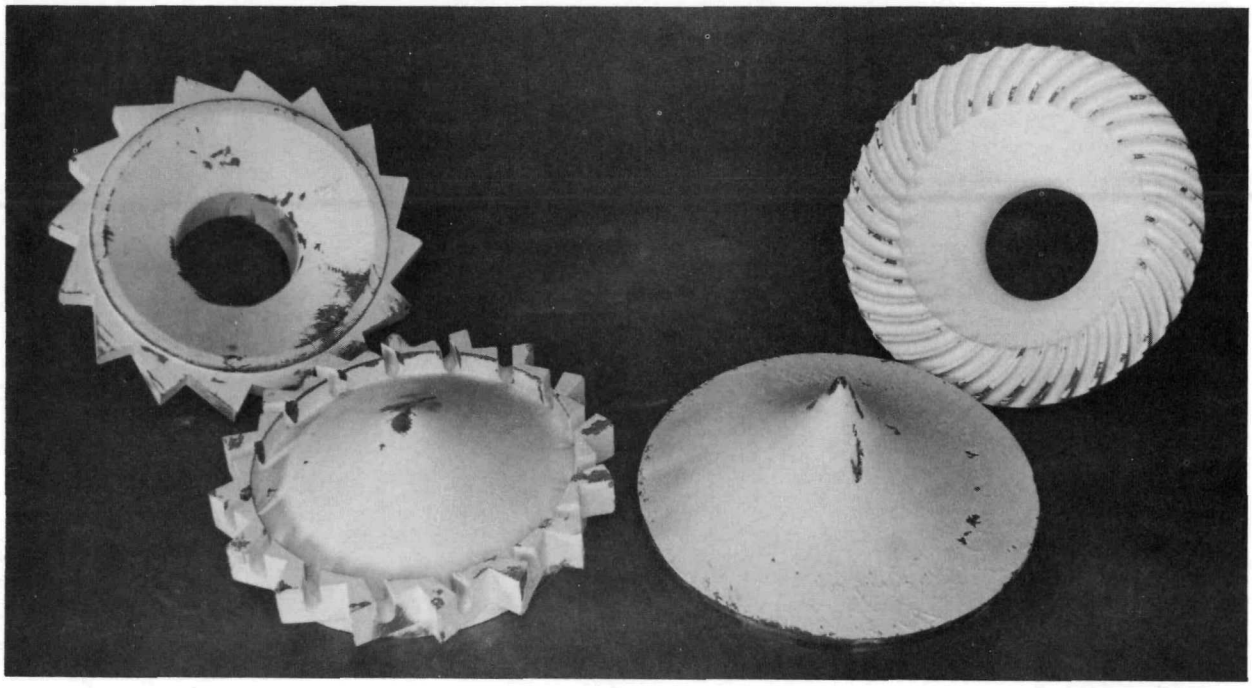

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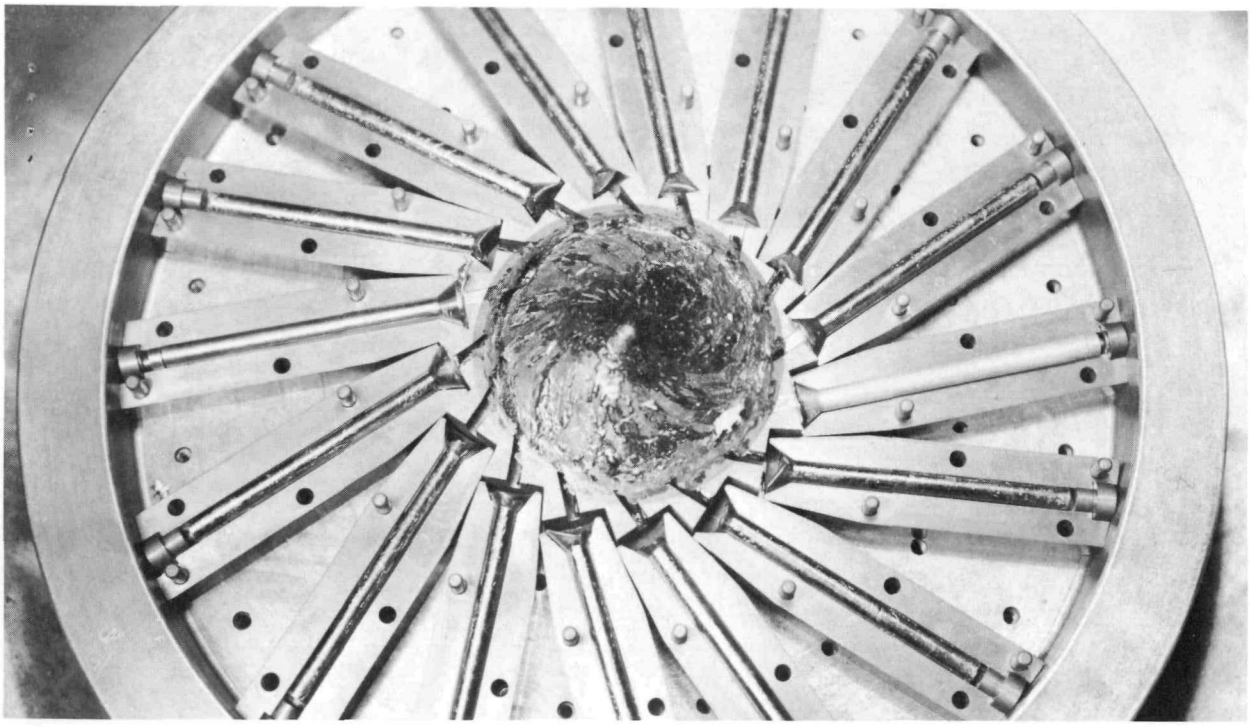
Figure 6. Fuel Slugs Centrifugally Cast with the Simplified Distributor Shown Above.



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Composition and Enrichment

Composition:	Uranium	97.85-98.03 w/o
	Zirconium	1.97- 2.15 w/o
Enrichment:	93.0-94.0 w/o	

Dimensional Tolerances

Diameter:	0.380-0.386 in.
Length:	4.247-4.253 in.

Maximum Impurities (ppm)

Al	5	Li	1	V	200
B	1	Mg	100	Cr	200
Be	0.1	Si	100	Co	200
Ca	100	Mn	200	Ni	200
Fe	200	Na	3	Cu	10

Although the maximum tolerable boron impurity is given above as 1 ppm, an exception was made in the case of the single melt CF-6 (SM Batch 62-729) with a reported 2 ppm of boron. A similar exception was made for melt 16F-19 (SM Batch 2-329) in the initial fuel loading,[1] which served as a precedent.

Density

The density requirement was indirectly specified by the dimensional tolerances placed on the individual fuel slugs, by the tolerances placed on the length of the fuel section in each fuel rod, and by the weight of enriched uranium to be contained in each fuel rod.

Fuel Loading

Length of Fuel Section per Fuel Rod	8.494-8.506 in.
Weight of U^{235} per Fuel Rod	264-270 grams

The above specifications pertaining to the loaded fuel rods were liberalized to the extent that any variation in the individual fuel slug length would be acceptable provided the "length of the fuel section" and the "weight of U^{235} per fuel rod" were preserved as stated. This interpretation permitted the use of short fuel slugs by pairing them with correspondingly longer ones, or by grouping them into suitably matched triads.

MATERIAL PROCESSES

Virgin U^{235} and Grade-I crystal bar zirconium were used as the feed materials, the zirconium being considered as an alloy addition to the enriched uranium.

All of the enriched uranium was obtained from Oak Ridge in the form of reduction buttons measuring 4 in. in diameter by $\frac{1}{2}$ in. thick at the center. A total of 31 whole buttons and two pieces of a 32nd button (SM Batch 62-747) were received at ANL. The individual buttons ranged in weight from 2183.3 grams to 2400.5 grams, while the two pieces of the 32nd button weighed approximately 1786.9 grams. The total weight of fissile material received was 73,659.9 grams, of which 71,756.0 grams were used in the production of fuel slugs. Approximately 1903.9 grams of the 31st button (SM Batch 62-746) were returned to the Special Materials vault as excess along with 7.7 grams of "history" samples and 4.6 grams of spectrochemical samples. The "history" samples consisted of a few small fragments of the button collected at the time it was broken into pieces for processing. Such samples serve as useful future references should the need arise to recheck the U^{235} content of a particular button as-received. Spectrochemical samples were taken at the same time to check on the purity of the fissile material being received.

The thirty-two enriched uranium reduction buttons are listed in Table I in the order received at ANL. All weights appearing in this table were determined at ANL preparatory to processing.

The Grade-I crystal bar zirconium used as an alloy addition to the enriched uranium was provided by the Special Materials and Services Division at ANL. This metal was originally received from Westinghouse in the form of bars measuring approximately $\frac{5}{8}$ in. in diameter by 20 in. long. These bars were cold worked, by rolling and swaging, into 0.100-in. diameter wire, then annealed in a salt bath at 800°C to permit coiling. The surface of the zirconium was etched bright in a heated nitric acid solution containing a few percent of hydrofluoric acid, after which the material was rinsed thoroughly with running tap water and air dried. A total of 1517.4 grams of zirconium was alloyed with virgin U^{235} during preparation of the fuel loading.

SEQUENCE OF FABRICATING OPERATIONS

The manufacturing sequence for the production of the Mark-II fuel loading is illustrated schematically in Figure 7. This routine was strictly adhered to in the interests of simplicity in handling and accounting for the fissile material. The only exceptions to this routine were four nonproductive

TABLE I.

Weights of U^{235} Reduction Buttons Received at ANL, before and after Breaking and Sampling

Button Number	ANL Batch Number	Received Weight (Grams)	Samples (Grams)		Processed Weight (Grams)	Breaking Loss (Grams)
			History***	Spectro Chemical		
1	62-619	2,183.310	0.516	0.147	2,182.487	-0.160
2	-620	2,184.036	0.260	0.143	2,183.741	+0.108
3	-621	2,382.748	0.455	0.135	2,382.089	-0.069
4	-622	2,181.411	0.191	0.120	2,181.079	-0.021
5	-623	2,381.577	0.224	0.150	2,381.173	-0.030
6	-624	2,182.263	0.200	0.158	2,181.871	-0.034
7	-715-1	2,372.248	0.242	0.154	2,371.833	-0.019
8	-715-2	2,400.494	0.214	0.143	2,400.139	+0.002
9	-715-3	2,398.197	0.280	0.157	2,397.752	-0.008
10	-715-4	2,394.675	0.240	0.127	2,394.307	-0.001
11	-717-1	2,396.884	0.149	0.141	2,396.571	-0.023
12	-717-2	2,364.411	0.164	0.176	2,364.070	-0.001
13	-717-3	2,403.651	0.157	0.114	2,403.366	-0.014
14	-717-4	2,391.862	0.225	0.237	2,391.399	-0.001
15	-718-1	2,398.336	0.179	0.115	2,398.042	0.000
16	-718-2	2,399.299	0.170	0.162	2,398.972	+0.005
17	-718-3	2,398.152	0.184	0.164	2,397.794	-0.010
18	-718-4	2,400.047	0.200	0.155	2,399.692	0.000
19	-734	2,393.356	0.208	0.141	2,393.009	+0.002
20	-735	2,368.010	0.242	0.182	2,367.573	-0.013
21	-736	2,393.009	0.273	0.146	2,392.584	-0.006
22	-737	2,399.038	0.201	0.227	2,398.606	-0.004
23	-738	2,392.517	0.314	0.113	2,392.108	+0.018
24	-739	2,194.575	0.225	0.155	2,194.206	+0.011
25	-740	2,179.900	0.294	0.136	2,179.460	-0.010
26	-741	2,381.118	0.308	0.182	2,380.620	-0.008
27	-742	2,179.020	0.237	0.138	2,178.644	-0.001
28	-743	2,180.800	0.331	0.110	2,180.347	-0.012
29	-744	2,183.836	0.302	0.128	2,183.373	-0.033
30	-745	2,188.750	0.247	0.123	2,188.380	0.000
31**	-746	2,225.563	0.257	0.118	321.245	-0.006
32*	-747	1,786.880	-	-	1,786.880	0.000
TOTALS		73,659.973	7.689	4.597	71,743.412	-0.338

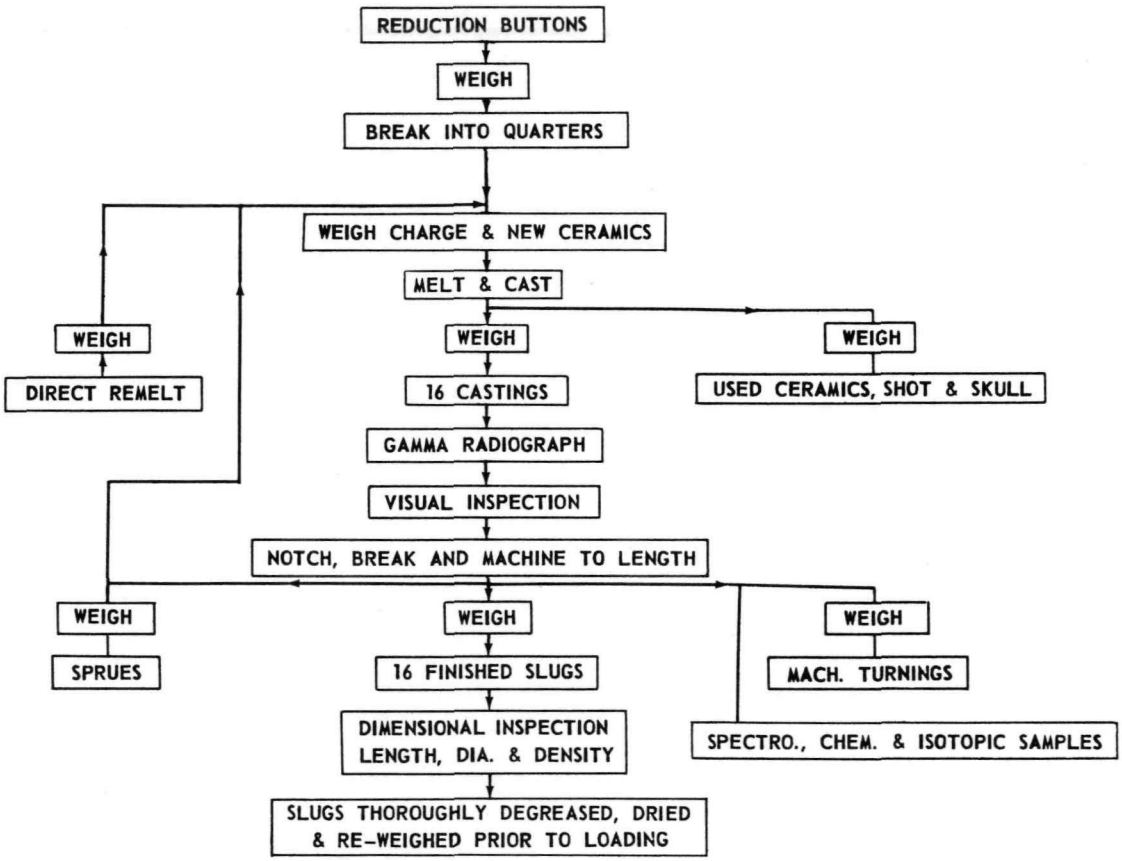
*Button received in 2 pieces already sampled.

**1,903.937 grams of broken button returned to the vault.

***Sample of original reduction button retained for possible future isotopic analysis check.

melts (CF-4, CF-5, CF-19 and CF-27) resulting from stopper-rod failures. In all four instances the molten charge was allowed to solidify in the crucible, then reused as the charge in subsequent melts (CF-6, CF-7, CF-24 and CF-30, respectively).

Figure 7. Sequence of Operations Used in the Manufacture of Centrifugally Cast EBR-I Fuel Slugs.



Fuel slugs were processed in batches of 16 as they came from the centrifugal casting machine. Each batch was contained in a white enamel-coated tray identified by a melt number. Operations such as machining, radiographing and so forth were performed on single batches. The issuing of a subsequent batch of fuel slugs was made dependent upon the return to the vault of a previous batch. This practice was applied to discourage that contempt for precaution which is usually bred by a sense of increased familiarity with the object.

Melting Charge Preparation

The melting charge was prepared from broken pieces of U^{235} button and 0.100-in. diameter zirconium wire. The weight varied somewhat from melt to melt, the lightest charge weighing 2952.2 grams and the heaviest

weighing 3199.7 grams. The minimum charge weight was fixed primarily by the weight of the sixteen cast fuel slugs and attached sprues, and to a lesser degree by the residues which are an inherent part of the casting method of fabrication. Wherever possible, the remelt scrap from one melt was used up completely in another melt to simplify material accountability and process records.

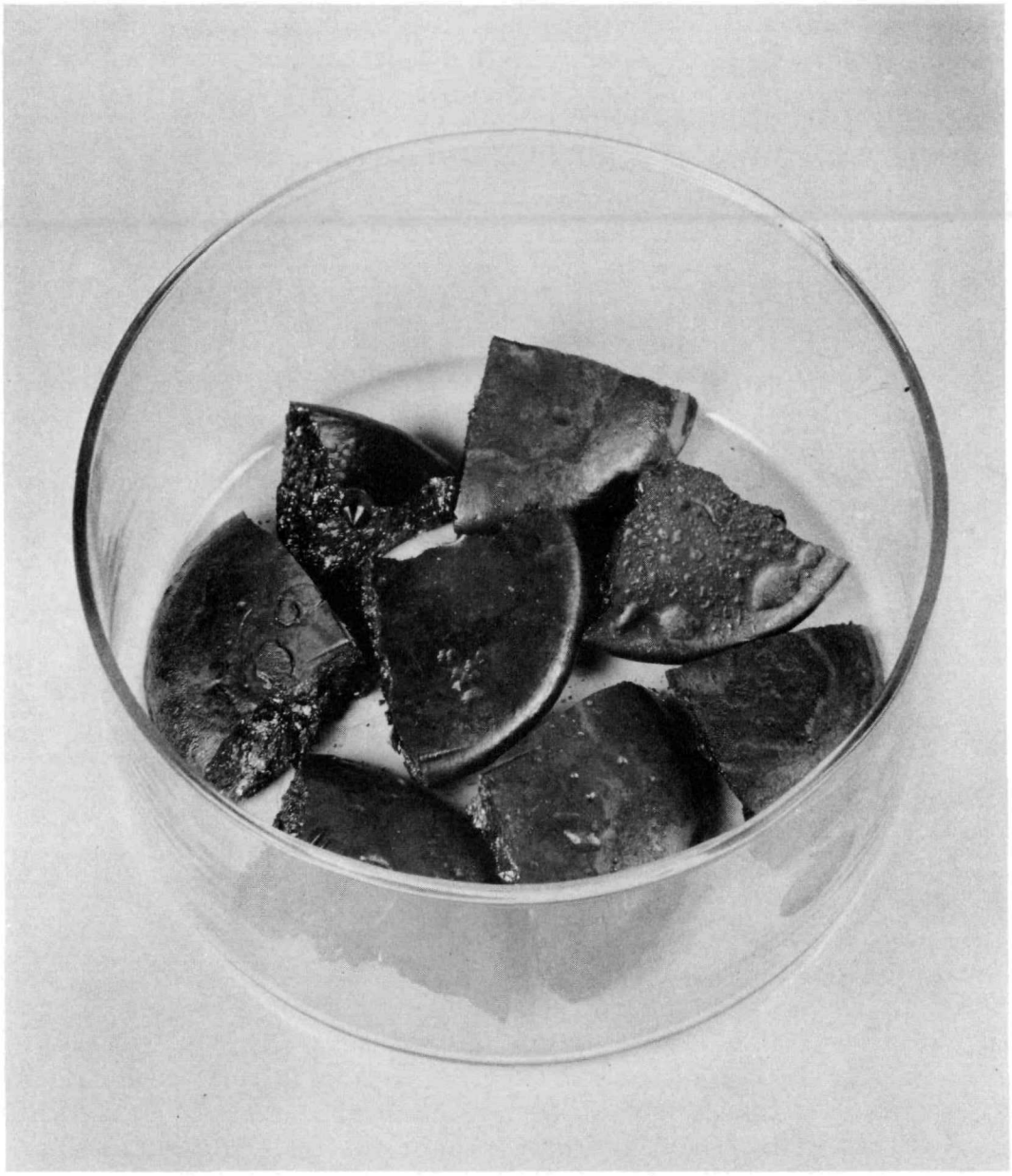
The melting charge took one of three forms: (a) virgin U^{235} and zirconium wire, (b) virgin U^{235}, uranium-zirconium alloy remelt scrap and zirconium wire, and (c) the uranium-zirconium alloy from nonproductive melts. Of the total of 35 melts, ten were charged with virgin U^{235} and zirconium wire; 21 with virgin U^{235}, zirconium wire and U^{235}-2 w/o zirconium remelt scrap; and four with the solidified U^{235}-2 w/o zirconium alloy charge from previous melts that could not be poured because of melting difficulties.

The reduction buttons were weighed individually to the nearest milligram as-received, before being broken into quarters. The button-breaking operation was performed on a hydraulic press equipped with a hooded platen. Liquid nitrogen was used to chill the buttons and thus promote a brittle fracture in an otherwise ductile material. Spectrochemical and "history" samples were collected from among the small fragments. The large pieces and remaining small fragments were dried and weighed for charging into melts as required. Table I is an accountability record of the button breaking operations. The size and shape of the broken pieces from a typical reduction button are shown in Figure 8.

Approximately one and one-half reduction buttons were used in the charge of virgin melts. Smaller quantities of reduction button were added to melts containing uranium-zirconium alloy remelt scrap, the weight of U^{235} charged depending upon the weight of remelt scrap used. Zirconium was added to all melts containing virgin U^{235} in sufficient amounts to yield a charge composition of 2 w/o zirconium. Calculated analyses were relied upon exclusively, since the results from analytical samples were not immediately available. Table II is a comparison of the calculated isotopic analyses with the reported analyses for the individual melts. A similar comparison regarding the zirconium content of the individual melts is given in Table III.

Data relating to the charge weight of individual melts and their makeup are summarized in Table IV. Complete charge calculations for each of the 35 melts are contained in Appendix A to this report, an unissued volume under separate cover.

Figure 8. Pieces of Broken U^{235} Reduction Button



Preparation of Ceramics

High-purity magnesia ceramics were used exclusively to reduce contamination of the fuel alloy during melting. A ceramic assembly consisted of a crucible, a crucible cover, a stopper rod and a pedestal. The crucible measured $3\frac{11}{16}$ in. I.D. by $7\frac{3}{8}$ in. deep and had a $\frac{1}{4}$-in. thick wall. The pouring hole at the bottom was enlarged from $\frac{3}{8}$ in. to $\frac{7}{8}$ in. in diameter.

TABLE II

A Comparison of the Calculated Isotopic Compositions with ANL-reported Values for a Series of U^{235} - 2 w/o Zr Alloy Melts

Melt Number	ANL Batch Number	Isotopic Composition (Per Cent)							
		U^{235}		U^{234}		U^{236}		U^{238}	
		Calc.	ANL	Calc.	ANL	Calc.	ANL	Calc.	ANL
CF- 1	62-720	93.24	93.25	1.00	1.01	-	-	5.76	5.73
- 2	-724	93.22	93.27	0.99	0.99	-	-	5.78	5.73
- 3	-725	93.20	93.23	0.99	1.00	-	-	5.81	5.76
- 4	-727	93.23	-	0.99	-	-	-	5.78	-
- 5	-728	93.18	-	1.14	-	0.12	-	5.55	-
- 6	-729	93.23	93.22	0.99	1.00	-	0.01	5.78	5.77
- 7	-730	93.18	93.21	1.14	1.13	0.12	0.12	5.56	5.54
- 8	-731	93.18	93.17	1.16	1.17	0.24	0.24	5.41	5.42
- 9	-732	93.18	93.14	1.19	1.19	0.28	0.29	5.35	5.38
-10	-733	93.22	93.24	1.18	1.18	0.29	0.30	5.30	5.28
-11	-743	93.16	93.18	1.18	1.19	0.28	0.28	5.38	5.35
-12	-749	93.23	93.23	1.18	1.19	0.28	0.29	5.30	5.29
-13	-750	93.16	93.20	1.16	1.16	0.25	0.25	5.42	5.39
-14	-751	93.22	93.24	1.15	1.15	0.22	0.22	5.42	5.39
-15	-752	93.23	93.23	1.14	1.14	0.21	0.21	5.41	5.42
-16	-753	93.21	93.26	1.16	1.16	0.21	0.21	5.42	5.37
-17	-758	93.21	93.16	1.19	1.20	0.27	0.26	5.33	5.38
-18	-759	93.15	93.21	1.19	1.19	0.21	0.21	5.45	5.39
-19	-760	93.17	-	1.19	-	0.30	-	5.34	-
-20	-761	93.16	93.19	1.19	1.19	0.30	0.29	5.35	5.33
-21	-762	93.21	93.21	1.19	1.20	0.30	0.29	5.31	5.30
-22	-763	93.17	93.17	1.19	1.20	0.29	0.28	5.35	5.35
-23	-764	93.19	93.22	1.19	1.18	0.28	0.28	5.33	5.32
-24	-769	93.17	93.19	1.19	1.19	0.30	0.30	5.34	5.32
-25	-774	93.20	93.19	1.19	1.17	0.23	0.23	5.38	5.41
-26	-781	93.21	93.25	1.18	1.18	0.26	0.26	5.35	5.31
-27	-782	93.24	-	1.20	-	0.26	-	5.30	-
-28	-783	93.17	93.18	1.20	1.17	0.30	0.30	5.32	5.35
-29	-784	93.16	93.26	1.18	1.18	0.29	0.29	5.37	5.27
-30	-785	93.24	93.26	1.20	1.18	0.26	0.25	5.30	5.31
-31	-786	93.20	93.17	1.15	1.15	0.23	0.22	5.42	5.46
-32	-787	93.20	93.22	1.19	1.18	0.29	0.28	5.31	5.32
-33	-790	93.20	93.19	1.17	1.16	0.26	0.26	5.38	5.39
-34	-791	93.19	93.16	1.18	1.18	0.28	0.28	5.35	5.38
-35	-792	93.20	93.23	1.18	1.17	0.26	0.26	5.36	5.34

TABLE III.

A Comparison of the Calculated Zirconium Composition with ANL-reported Values for Centrifugally Cast U^{235}-2 w/o Zr Melts

Melt Number	ANL Batch Number	Zr Content (w/o)			Melt Number	ANL Batch Number	Zr Content (w/o)		
		Calc. Value	ANL Value (Av.)				Calc. Value	ANL Value (Av.)	
			Top	Bottom				Top	Bottom
CF- 1	62-720	2.150	2.17 ± 0.06	2.11 ±0.06	CF-19	62-760	2.095	2.23 ±0.04	2.12 ±0.04
- 2	-724	2.149	2.26 ± 0.07	2.05 ±0.06	-20	-761	2.093	2.18 ±0.04	2.12 ±0.04
- 3	-725	2.149	2.21 ± 0.06	2.07 ±0.06	-21	-762	2.094	2.15 ±0.04	2.10 ±0.04
- 4	-727	2.149	2.12 ± 0.04	2.07 ±0.04	-22	-763	2.076	2.16 ±0.04	2.13 ±0.04
- 5	-728	2.150	2.17 ± 0.04	2.07 ±0.04	-23	-764	2.100	2.33 ±0.05	2.03 ±0.04
- 6	-729	2.149	2.12 ± 0.04	2.07 ±0.04	-24	-769	2.095	2.23 ±0.04	2.12 ±0.04
- 7	-730	2.150	2.17 ± 0.04	2.07 ±0.04	-25	-774	2.103	2.24 ±0.04	1.85 ±0.04
- 8	-731	2.150	2.13 ± 0.04	2.10 ±0.04	-26	-781	2.071	2.53 ±0.05	1.85 ±0.04
- 9	-732	2.150	2.25 ± 0.05	2.09 ±0.04	-27	-782	2.062	2.62 ±0.05	1.88 ±0.04
-10	-733	2.150	2.17 ± 0.04	2.07 ±0.04	-28	-783	2.060	2.56 ±0.05	1.76 ±0.04
-11	-748	2.150	2.15 ± 0.04	2.09 ±0.04	-29	-784	2.028	2.48 ±0.05	1.92 ±0.04
-12	-749	2.150	2.14 ± 0.04	2.12 ±0.04	-30	-785	2.062	2.62 ±0.05	1.88 ±0.04
-13	-750	2.150	2.17 ± 0.04	2.10 ±0.04	-31	-786	2.013	2.00 ±0.04	1.90 ±0.04
-14	-751	2.150	2.43 ± 0.05	2.43 ±0.05	-32	-787	1.964	2.08 ±0.04	1.92 ±0.04
-15	-752	2.150	2.20 ± 0.04	2.07 ±0.04	-33	-790	1.945	2.56 ±0.05	1.67 ±0.03
-16	-753	2.087	2.35 ± 0.05	1.99 ±0.04	-34	-791	1.853	2.39 ±0.05	1.63 ±0.03
-17	-758	2.087	2.35 ± 0.05	2.01 ±0.04	-35	-792	1.990	2.15 ±0.04	1.63 ±0.03
-18	-759	2.087	2.25 ± 0.04	2.02 ±0.04					

TABLE IV. Summary of The Metal Distribution in The Fabrication of EBR Fuel Slugs by The Centrifugal Casting Method

Casting Number	Weight of Furnace Charge (grams)	Remelt Stock to Charge (w/o)			Distribution of Furnace Charge after Casting and Machining												Finished Slugs + Remelt Stock (w/o)	Average Density (gm/cc)	Processing Loss (By Difference) (grams)
		Sprues	Remelt Scraps	Reject Slugs and/or Frozen Melts	Finished Slugs		Sprues		Remelt Scrap		Melting Residue		Turnings		Samples				
					Weight (grams)	w/o	Weight (grams)	w/o	Weight (grams)	w/o	Weight (grams)	w/o	Weight (grams)	w/o	Weight (grams)	w/o			
CF -1*	3068.515	none	none	none	1892.017	61.66	570.175	18.58	307.225	10.01	210.101	6.85	80.919	2.64	7.934	0.26	90.25	18.03	-0.144
-2*	3086.292	none	none	none	2181.533	70.68	427.660	13.86	362.504	11.74	52.873	1.71	54.894	1.78	7.140	0.23	96.28	18.05	+0.312
-3*	3175.226	none	none	none	2295.959	72.31	559.414	17.62	243.122	7.66	40.432	1.27	28.248	0.89	8.069	0.25	97.58	18.07	+0.018
-4	3169.174	none	none	none	none	-----	none	-----	2978.861	93.99	53.439	1.69	136.874	4.32	none	----	93.99	-----	0.000
-5	3225.531	none	none	none	none	-----	none	-----	2998.391	92.96	99.879	3.10	127.261	3.94	none	----	92.96	-----	0.000
-6*	3163.325	5.83	none	94.17	2150.921	68.00	575.721	18.20	327.165	10.34	62.552	1.98	39.259	1.24	7.871	0.24	96.54	18.07	+0.164
-7*	3105.357	3.44	none	96.56	2190.669	70.54	471.713	15.19	301.451	9.71	90.748	2.92	41.403	1.33	9.136	0.30	95.44	18.06	-0.237
-8*	3434.012	none	none	none	2204.988	64.21	797.534	23.22	279.199	8.13	76.922	2.24	67.343	1.96	8.267	0.24	95.56	18.06	+0.241
-9*	3195.971	none	none	none	2261.513	70.76	655.785	20.52	196.787	6.16	36.862	1.15	36.840	1.15	8.167	0.26	97.44	18.08	-0.017
-10*	3162.470	none	none	none	2300.759	72.75	555.083	17.55	216.895	6.86	52.965	1.68	22.816	0.72	13.961	0.44	97.16	18.08	+0.009
-11*	3191.571	none	none	none	2258.780	70.77	609.733	19.11	246.758	7.73	49.933	1.56	17.858	0.56	8.483	0.27	97.61	18.06	-0.026
-12*	3158.421	none	none	none	2298.057	72.76	471.511	14.93	290.781	9.21	67.007	2.12	22.194	0.70	8.849	0.28	96.90	18.05	-0.022
-13*	2952.182	6.58	10.41	none	2091.914	70.86	459.411	15.56	255.344	8.65	95.240	3.23	41.542	1.41	8.717	0.29	95.07	18.06	-0.014
-14*	3146.664	10.57	11.52	none	2214.314	70.37	548.219	17.42	147.321	4.68	116.366	3.70	111.411	3.54	9.199	0.29	92.47	18.07	+0.166
-15	3158.909	14.73	7.70	none	2296.517	72.70	414.109	13.11	254.081	8.04	61.732	1.95	123.970	3.92	8.910	0.28	93.85	18.07	+0.410
-16*	3096.348	10.29	10.57	none	2151.555	69.48	509.726	16.46	280.417	9.06	67.134	2.16	79.793	2.57	8.459	0.27	95.00	18.07	+0.736
-17*	3143.553	9.54	12.73	none	2060.335	65.54	660.851	21.02	289.821	9.22	85.072	2.71	39.383	1.25	8.056	0.26	95.78	18.12	-0.035
-18*	3085.533	15.79	5.85	none	2185.873	70.84	544.310	17.64	228.178	7.40	78.957	2.56	38.949	1.26	9.334	0.30	95.88	18.10	+0.103
-19	3087.919	14.50	6.37	none	none	-----	none	-----	3057.804	99.02	30.115	0.98	none	----	none	----	99.02	-----	0.000
-20*	2997.557	11.04	7.24	none	1864.899	62.21	768.290	25.63	235.737	7.87	43.915	1.47	75.595	2.52	9.064	0.30	95.71	18.07	-0.057
-21*	3103.646	13.34	7.95	none	2078.174	66.96	675.387	21.76	214.120	6.90	74.257	2.39	53.435	1.72	8.303	0.27	95.62	18.07	+0.030
-22*	3065.687	17.44	9.48	none	2125.895	69.35	656.962	21.43	192.656	6.28	58.446	1.91	23.460	0.77	8.245	0.27	97.06	18.10	-0.023
-23*	3139.245	16.27	12.83	none	1854.933	59.09	898.608	28.62	226.845	7.23	89.392	2.85	60.367	1.92	9.256	0.29	94.94	18.10	+0.156
-24	3057.804	none	none	100.00	2338.815	76.49	353.036	11.54	235.489	7.70	65.185	2.13	57.306	1.87	9.343	0.30	95.73	18.10	+1.370
-25	3123.016	14.01	8.14	none	1489.907	47.71	1243.521	39.82	245.456	7.86	96.492	3.09	33.278	1.06	14.403	0.46	95.39	18.11	+0.041
-26	3015.530	16.94	9.30	none	2343.047	77.70	358.941	11.90	174.953	5.80	78.771	2.61	42.096	1.40	17.731	0.59	95.40	18.11	+0.009
-27	3199.713	14.24	16.11	none	none	-----	none	-----	3181.764	99.44	17.370	0.55	none	----	none	----	99.44	-----	-0.579
-28	3066.196	6.35	20.96	none	2341.604	76.37	329.890	10.76	206.984	6.75	98.366	3.21	81.206	2.64	8.144	0.27	93.88	18.11	-0.002
-29	3129.388	6.02	22.62	none	2342.660	74.86	407.050	13.01	229.793	7.34	83.235	2.66	56.364	1.80	10.268	0.33	95.21	18.13	-0.018
-30	3181.764	none	none	100.00	2340.994	73.57	474.943	14.93	183.869	5.78	130.900	4.11	43.382	1.37	7.620	0.24	94.28	18.13	-0.056
-31	3183.801	16.51	none	62.80	2338.330	73.44	409.686	12.87	250.989	7.88	118.668	3.73	58.492	1.84	7.644	0.24	94.19	18.10	+0.008
-32	3179.180	66.70	none	8.66	2343.083	73.70	512.831	16.13	173.347	5.45	95.746	3.01	46.367	1.46	7.790	0.25	95.28	18.12	-0.016
-33	3092.632	34.08	13.12	24.68	2182.203	70.56	446.161	14.43	224.508	7.26	183.608	5.94	46.575	1.50	9.610	0.31	92.25	18.15	+0.033
-34	3174.052	41.61	26.40	2.67	2118.381	66.74	509.184	16.04	297.603	9.38	183.883	5.79	54.547	1.72	10.447	0.33	92.16	18.19	-0.007
-35	3168.107	45.43	16.48	27.73	2061.012	65.05	455.282	14.37	300.886	9.50	201.495	6.36	137.691	4.35	11.844	0.37	88.92	18.15	+0.103

*Denotes castings in which one or more slugs were shortened to reduce longitudinal bow to 6 mils or less.

Note: The following slugs were remelted after thermal cycling: Group 1: CF-1-7, CF-6-13, CF-13-2, CF-17-10, CF-20-14 and CF-23-4.
Group 2: CF-25-1, CF-25-4, CF-25-7, CF-25-13, CF-25-15, and CF-25-16.

The accompanying stopper rod was $1\frac{1}{16}$ in. in diameter and 8 in. long. One end was ground to a 45-degree point and made to seat against the inner edge of the pouring hole. The entire ceramic assembly is shown in Figure 2 as it appeared during the melting operation.

All ceramics were heated for at least 12 hours in an oven at 250°C, desiccator cooled, and weighed prior to being put into service. Ceramics from the first melt were reused successfully in the second and third melts. This practice was abandoned when stopper-rod failures in the fourth and fifth melts (CF-4 and CF-5) made pouring of the molten charge impossible.

Loading the Melting Charge

The weighed charge was loaded into the crucible in a prescribed manner which proved to promote homogeneity in the resultant alloy. The 0.100-in. diameter zirconium wire was always introduced as a coil fitted snugly over the lower end of the stopper rod and slightly removed from the bottom of the crucible. With the stopper rod seated, the pieces of broken reduction button were packed around it. Remelt scrap was loaded last, being fitted on top of and between the pieces of the reduction button. Complete dissolution of the zirconium was achieved by preventing it from floating to the surface of the molten mass.

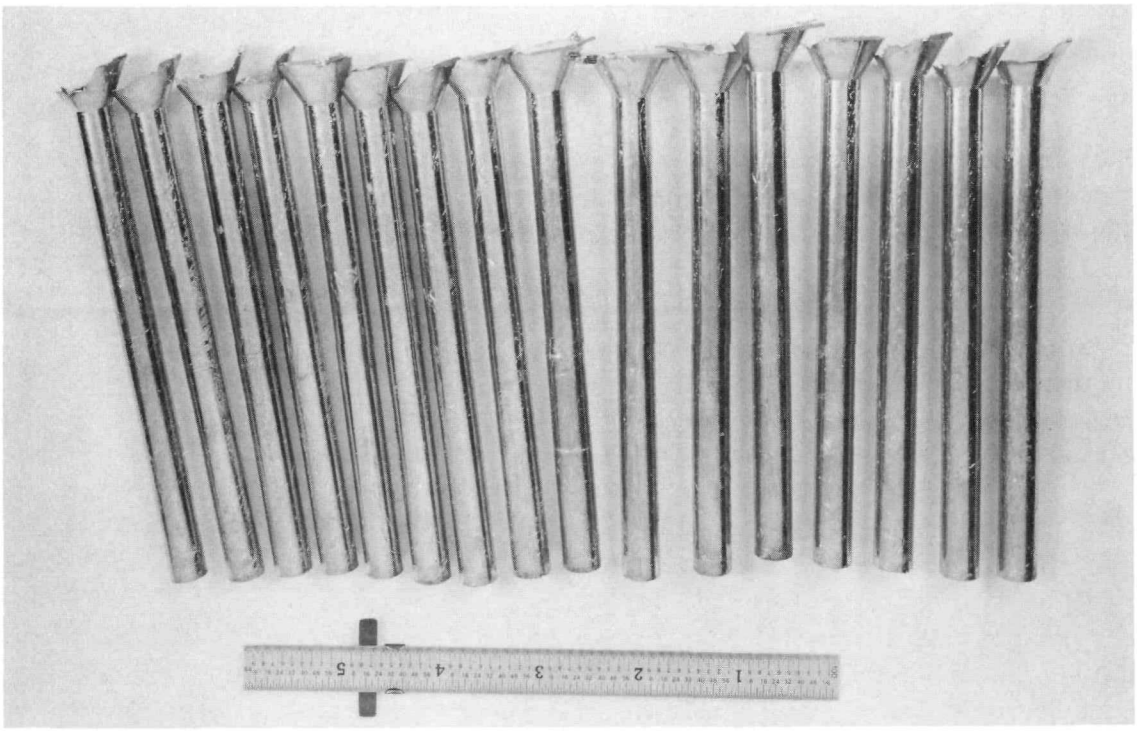
Melting and Casting

The melting charge was heated slowly to 1000°C, then at a more rapid rate to the final pouring temperature of 1400 to 1450°C. The slow initial heating rate was necessary to avoid the generation of cracks in the crucible and stopper rod. Temperature readings were obtained by sighting into the melt with an optical pyrometer. The melt was always held at temperature for 15 minutes to ensure complete dissolution of the zirconium and homogenization of the molten alloy. Vacuums of the order of 1×10^{-4} to 4×10^{-5} mm Hg were recorded prior to pouring. The optimum rotor speed at the time of pouring was found to be in the range 350-400 rpm and increasing at a uniform rate of approximately 80 rpm up to 600 rpm. The rotor speed was maintained at 600 rpm for three minutes after casting.

The castings and ceramics were cooled for 4 hours before the casting machine was disassembled. The ceramics and the melting residue removed from the crucible were weighed and returned to the Special Materials vault for shipment to Oak Ridge for recovery. Likewise, separate weights were obtained for the group of 16 cast fuel slugs and the remelt scrap removed from the distributor. An overall material balance was made as a check against unreasonable material losses during melting.

The as-cast appearance of sixteen fuel slugs upon removal from the centrifugal casting machine is shown in Figure 9. The casting length was $4\frac{3}{4}$ inches when measured to the bottom of the sprue and $5\frac{1}{4}$ inches when measured to the top of the sprue. Each fuel slug was identified with a casting number and a slug number upon removal from the casting machine. These identifying marks were electrically etched on the slug surface near the bottom end.

Figure 9. Appearance of As-cast EBR-I Fuel Slugs upon Removal from the Centrifugal Casting Machine



Final Machining

Each slug was notched with a sharp tool just below the sprue, chilled in liquid nitrogen, and parted at the notch in the same hooded press used to break the reduction buttons. The rough fuel slugs were then faced at both ends to the desired length in a hooded lathe. The sprues were collected, weighed and used in the charge of subsequent melts.

The majority of the fuel slugs in each casting batch were notched to finish within the specified 4.247 to 4.253-in. length. Those slugs that

were finished at a shorter length because of incomplete mold filling were paired with correspondingly longer slugs, and in a few instances with two other short slugs.

Analytical Samples

Chemical samples were taken from the "tops" and "bottoms" of slugs numbered 4, 8, 12 and 16 in each batch. These four slugs were arbitrarily chosen for chemical samples because each is located in one of the four quadrants of the circular mold assembly. Each of the samples consisted of machined turnings and weighed between 3 and 5 grams. A portion of one of these samples also served for the isotopic analysis. The reported isotopic and zirconium values are given in Table II and Table III, respectively.

The spectrochemical sample usually weighed between 85 and 265 milligrams and consisted of small pieces of the alloy selected arbitrarily from the accumulated turnings in the batch.

Carbon and nitrogen samples were submitted less frequently in deference to the other analyses requested. However, alloy samples were submitted for carbon and nitrogen analyses from two of the 35 melts made, namely, melt CF-7 and melt CF-26.

Typical analytical results for the fuel slugs produced by centrifugal casting are given in Table V.

TABLE V

Typical Analytical Results Reported for the Cast U^{235}-2 w/o Zr Fuel Alloy

Impurity	Amount (ppm)	Impurity	Amount (ppm)
Aluminum	L10	Silicon	50
Boron	1	Manganese	8
Beryllium	L0.05	Sodium	L2
Calcium	20	Chromium	2
Iron	80	Cobalt	L5
Lithium	L1	Nickel	50
Magnesium	7	Copper	30

Melt No.	SM Batch No.	Reported Values (ppm)	
		Carbon	Nitrogen
CF-7	62-730	15-98	25-67
CF-26	62-781	36-42	67-92

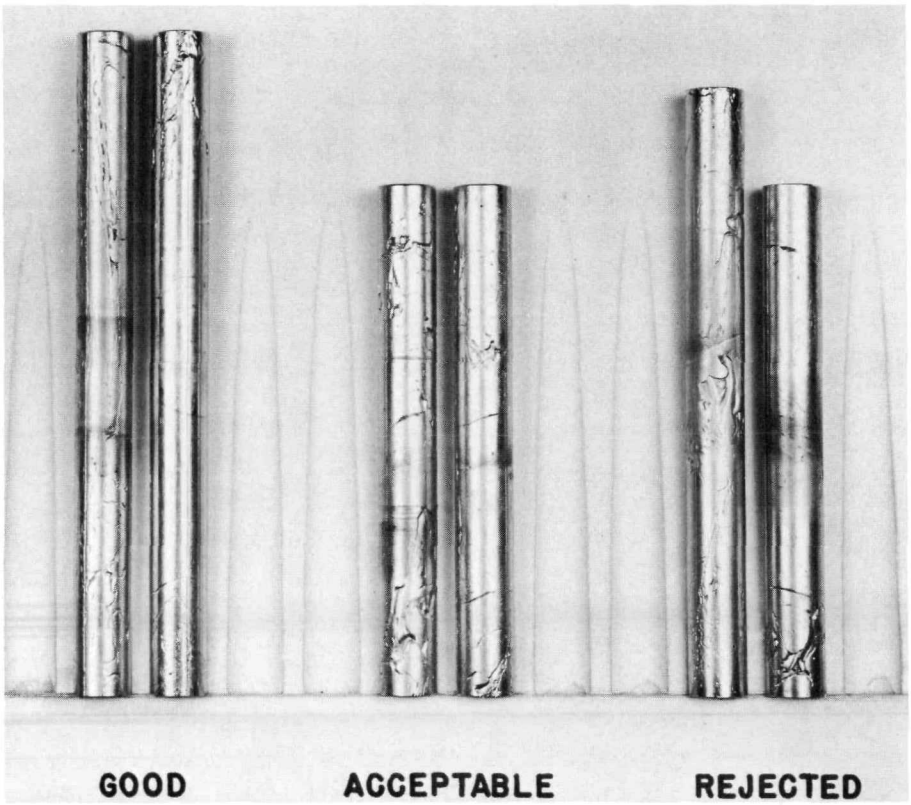
FUEL SLUG INSPECTION

Visual Inspection

Each batch of fuel slugs was inspected visually for such obvious defects as surface porosity, laps and cold-shuts which might be serious enough to be cause for rejection. This inspection actually preceded the final machining operation.

It was realized at the outset that complete elimination of surface markings on the fuel slugs would be impossible because of the very nature of the centrifugal casting process. Since a certain degree of surface imperfection would be accepted by the EBR-I Project Engineer, there remained need for agreement on a "standard" to be used for passing upon the acceptability of completed fuel slugs. Such a "standard" was agreed upon in the form of the six centrifugally cast natural uranium slugs shown in Figure 10. These six fuel slugs were inspected by the EBR-I Project Engineer and the indicated classifications were accepted by him.

Figure 10. Centrifugally Cast Uranium Fuel Slugs Used as Visual Acceptance Standards



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The observed surface markings are in reality very shallow recesses resulting from the immediate solidification of a thin layer of the molten alloy as it enters the copper molds. These markings appear most prominently along the lagging edge of each mold, which is precisely the edge along which the molten alloy flows into the mold in the absence of true centerline filling. The geometric character and extent of these surface markings vary between fuel slugs from the same casting batch, and are probably related to the turbulence in the molten alloy stream entering the individual molds.

To make the visual inspection a permanent and more descriptive record of surface appearance than can be set down in words, each batch of completed fuel slugs was photographed in a manner similar to that used in photographing the "standards." Four batches of finished fuel slugs are shown in Figures 11 through 14. All of the fuel slugs were photographed with the most prominently marked surface showing. These surface markings tend to be accentuated because of the usual difficulties in obtaining proper lighting for an accurate photographic reproduction of a light-reflecting surface.

Only two fuel slugs were rejected on the basis of the visual inspection. Both slugs, CF-1-2 and CF-20-11, were subsequently used as remelt scrap.

Radiographic Inspection

Gamma radiography was used in a 100 percent inspection of the fuel slugs for subsurface defects. With a 0.42-curie Co^{60} source and No-Screen type X-ray film the exposure time was 2 hours at a focal distance of 37 inches.

Practically all of the fuel slugs were found to be completely free of internal defects of any kind. The one exception, fuel slug CF-18-6, had a small internal defect at one end, and was subsequently shortened in length and matched with other short fuel slugs.

Prints of the gamma radiographs are included in an unissued Appendix C to this report.

Dimensional and Weight Measurements

Diameter and length measurements were made with micrometers capable of being read to one-tenth of one mil. Eight diameter measurements were made on each full-length fuel slug at four equally spaced points. Six diameter readings were taken on the shorter fuel slugs. Two diameter readings were made at each measuring point by rotating the slug 90 degrees.

Figure 11. Centrifugally Cast Uranium-2 w/o Zirconium Fuel Slugs. Melt CF-1

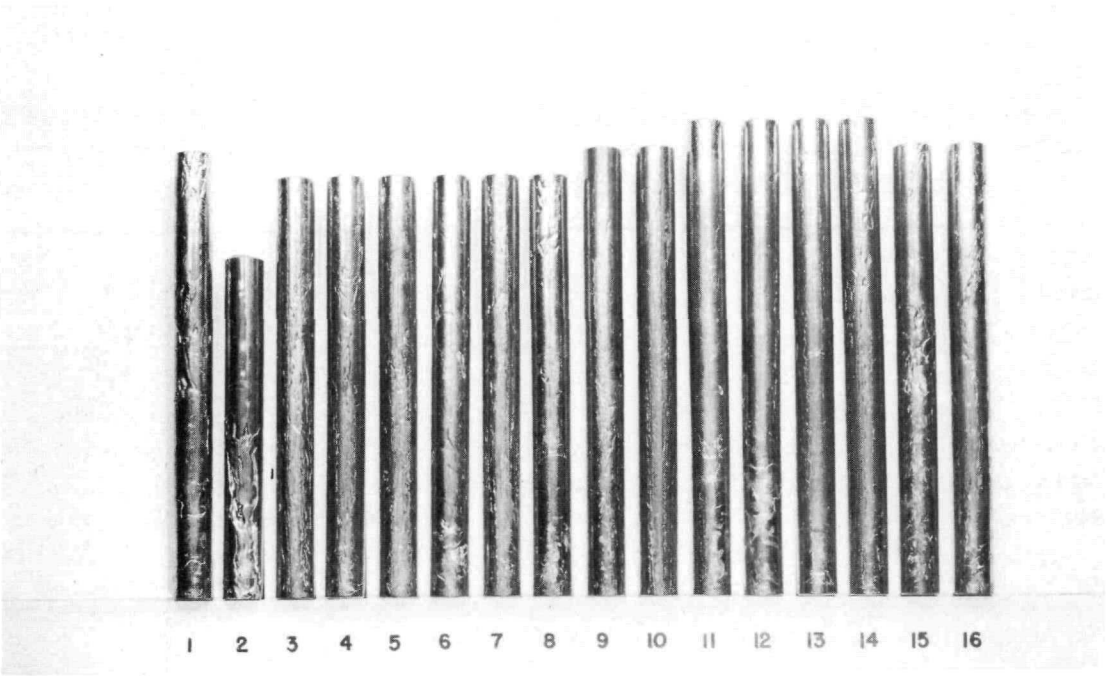


Figure 12. Centrifugally Cast Uranium-2 w/o Zirconium Fuel Slugs. Melt CF-2.

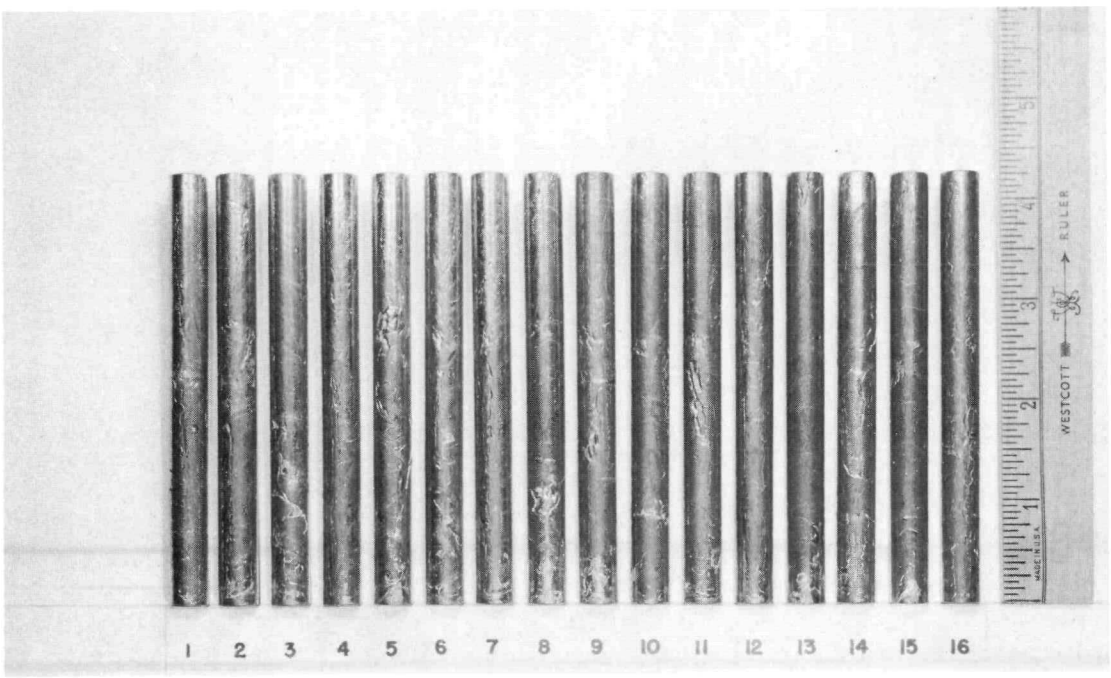


Figure 13. Centrifugally Cast Uranium-2 w/o Zirconium Fuel Slugs. Melt CF-33.

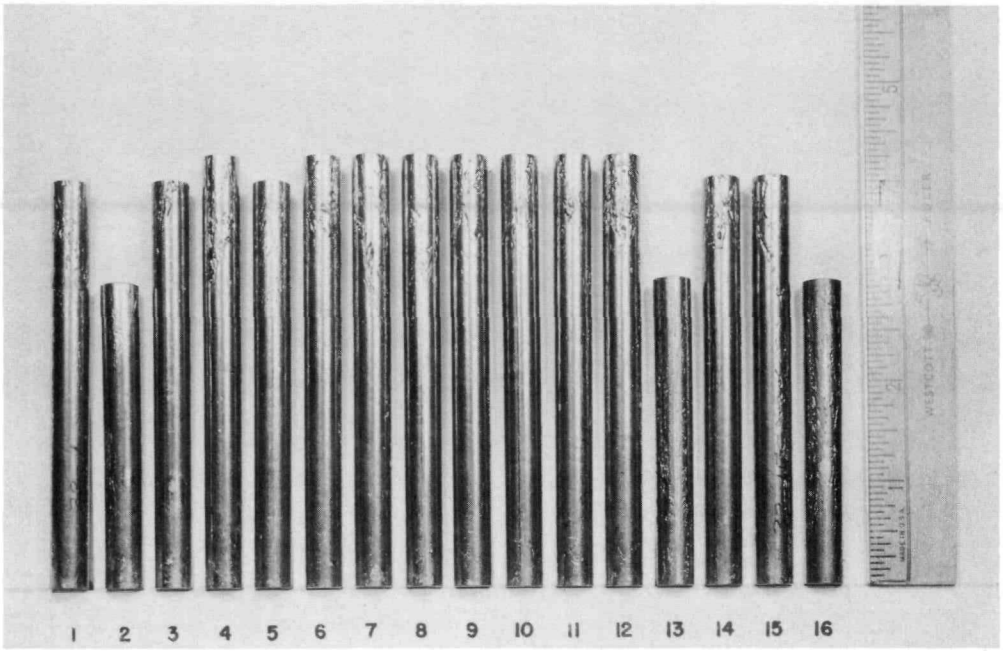
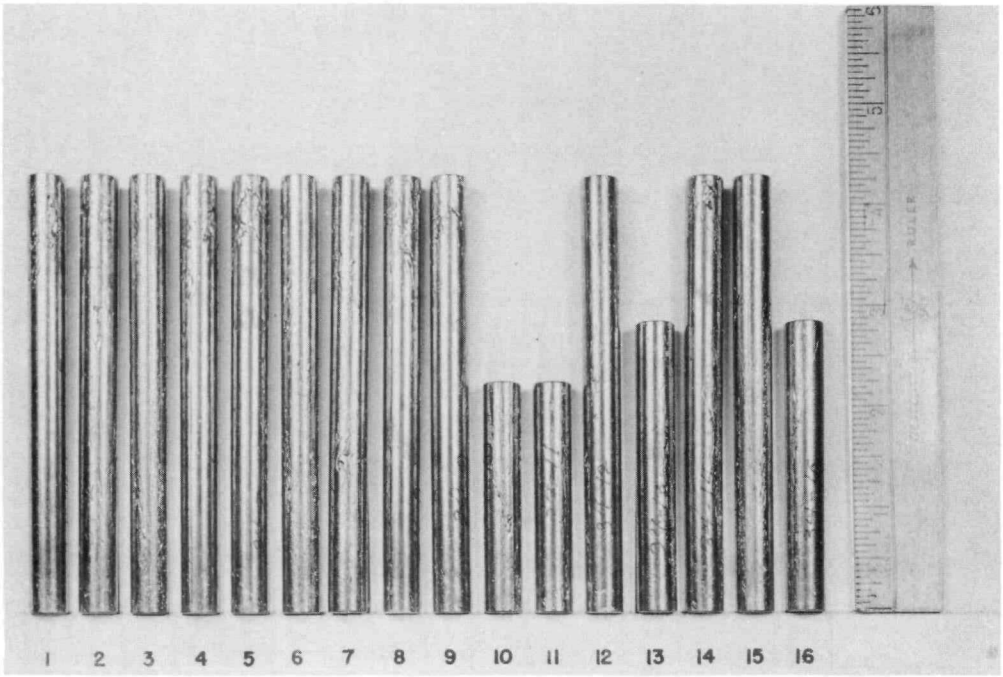


Figure 14. Centifigually Cast Uranium-2 w/o Zirconium Fuel Slugs. Melt CF-34.

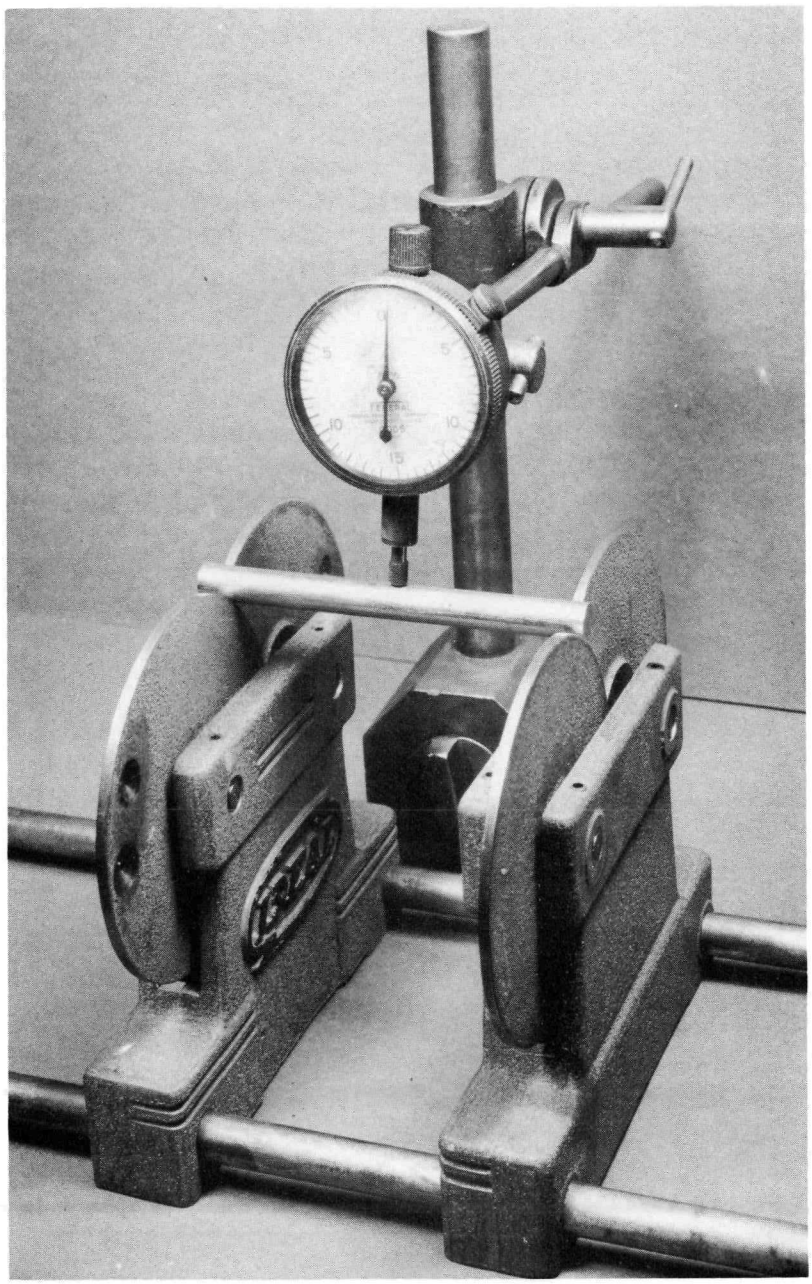


The diameters, lengths, and weights of the individual fuel slugs are recorded in Appendix A.

Inspection for Bow

The longitudinal bow inherent in the finished fuel slugs was checked with the apparatus shown in Figure 15. A 0.384-in. diameter by $4\frac{1}{2}$-in. long centerless ground aluminum slug was used to "zero" the dial indicator.

Figure 15. Equipment Setup for Measuring Longitudinal Bow in Finished Fuel Slug



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To check the longitudinal bow, the fuel slugs were rotated in the apparatus and the maximum positive and negative displacements of the dial indicator noted. An average value was obtained by dividing the sum of the positive and negative displacements by two. The value for the acceptable average bow was arbitrarily set at 6 mils.

Longitudinal bow values which are typical of those obtained for the centrifugally cast EBR-I fuel slugs are given in Table VI.

TABLE VI

Longitudinal Bow Observed in Centrifugally Cast EBR-I Fuel Slugs. Values Obtained from Fuel Slugs ($4\frac{1}{4}$-in. Length) of Melt CF-17

Fuel Slug No.	Maximum Displacement (mils)		Average Bow S/2 (mils)	Remarks
	Plus	Minus		
1	8	0	4	Accepted
2	5	3.5	4.3	Accepted
3	7	3.5	5.3	Accepted
4	8	2	5	Accepted
5	10	7	8.5	Rejected
6	7	3	5	Accepted
7	7	4	5.5	Accepted
8	10	4	7	Rejected
9	4	0	2	Accepted
10	Fuel Slug Thermal Cycled			
11	3	1	2	Accepted
12	11	9	10	Rejected
13	5	2	3.5	Accepted
14	6	4	5	Accepted
15	6	3.5	4.8	Accepted
16	5	3	4	Accepted

Density Determination

Density determinations were made in the conventional manner of liquid displacement. Carbon tetrachloride was used as the density-measuring medium because of its ability to dissolve light oil film such as might result from handling the fuel slugs with bare hands. Reproducibility of density values was achieved by submerging the fuel slugs for a minimum of 3 minutes before recording the submerged weight.

Detailed data relating to the density of individual fuel slugs are contained in Appendix A, an unissued volume under separate cover. The average density value obtained for each batch of fuel slugs is given in Table IV.

THERMAL CYCLING

The dimensional stability of these centrifugally cast U^{235}-2 w/o Zr fuel slugs was tested by thermal cycling two groups of six slugs each between 50 and 550°C. The thermal cycling equipment and the cycling procedure have been described in detail elsewhere.(7) Included in the first group were fuel slugs selected at random from six different melts and six different mold positions within these melts. The second group, on the other hand, consisted of six fuel slugs from the same melt, but not from consecutive mold positions.

The two groups of thermal-cycled fuel slugs are shown in Figures 16 and 17. All of the fuel slugs in the first group exhibited a negligible linear growth rate which ranged between zero and 13 microinches per inch per cycle after 475 cycles. Five of the fuel slugs in the second group also exhibited a negligible linear growth rate which ranged between zero and 9 microinches per inch per cycle after 570 cycles. One fuel slug in the second group, CF-25-1, exhibited a negligible shrinkage of 8 microinches per inch per cycle. None of the fuel slugs in either group exhibited the serious surface roughening associated with wrought and "beta" heat-treated unalloyed uranium after a similar thermal cycling treatment.

LOADING OF FUEL RODS

The accepted fuel slugs were thoroughly degreased in batches preparatory to loading into fuel rods, and thereafter were handled only with tongs or gloved hands. Two carbon tetrachloride baths and one absolute alcohol bath were used in the degreasing operation. The fuel slugs were allowed to soak for 5 minutes in the first carbon tetrachloride bath, and rinsed in the second carbon tetrachloride bath and the absolute alcohol bath in that order. After 10 minutes of air drying, the fuel slugs were placed on a stainless steel grid in an evacuated desiccator for 30 minutes for removal of minute traces of alcohol. The solvent in each bath was replaced frequently, usually after a throughput of approximately 64 fuel slugs (4 casting batches).

A detailed record of the loading of fuel slugs into fuel rods for shipment to EBR-I is contained in Appendix B, an unissued volume under separate cover. Loading data for three fuel rods are given in Table VII to illustrate the three methods used to match fuel slugs. Thus, the fuel

Figure 16. Centrifugally Cast Uranium-2 w/o Zirconium Fuel Slugs after 475 Thermal Cycles in NaK through the Temperature Range 50-550°C

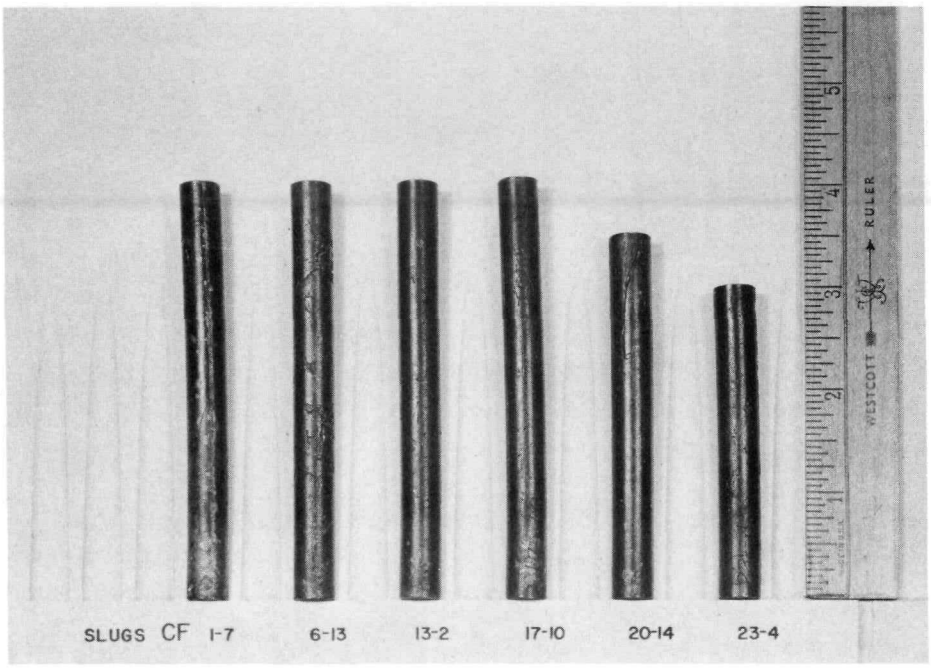

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Figure 17. Centrifugally Cast Uranium-2 w/o Zirconium Fuel Slugs after 570 Thermal Cycles in NaK through the Temperature Range 50-550°C

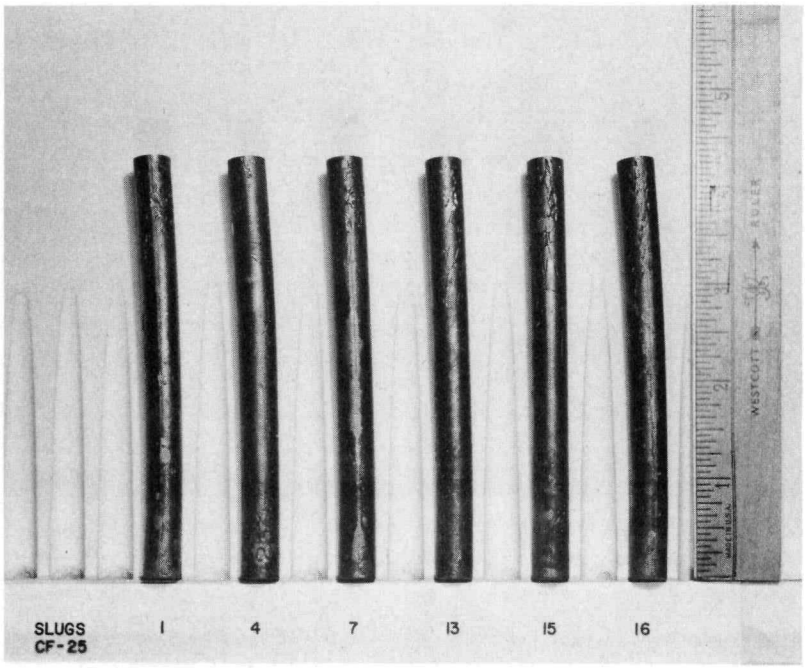

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TABLE VII

Fuel Rod Loading Data Illustrating Three Methods
Used in Matching Fuel Slugs

Rod Number CF-62-754-69 — Date Loaded 11-4-53

Position	Slug No.	S.M. Batch No.	Normal Uranium		Enriched Uranium					Zirconium		Slug Dimensions		
			Net Wt. (grams)	SF Wt. (grams)	Net Wt. (grams)	SF (w/o)	SF Wt. (grams)	U^{235} (w/o)	U^{235} (grams)	(w/o)	(grams)	Length (inches)	Dia. (inches) Max.	Dia. (inches) Min.
1	401		138.784	136.008										
2	CF-12-15	62-749-20			145.478	97.85	142.351	93.50	132.717	2.15	3.127	4.2489	0.3827	0.3848
3	CF-12-16	62-749-2P			145.632	97.85	142.501	93.50	132.857	2.15	3.131	4.2501	0.3815	0.3851
4	367 399		122.869 122.854	120.412 120.397										
Totals			384.507	376.817	291.110		284.852		265.574		6.258	8.4990		

Rod Number CF-62-754-73 — Date Loaded 11-4-53

1	355		138.540	135.769										
2	CF-13- 8	62-750-2H			137.443	97.85	134.488	93.50	125.296	2.15		4.0009	0.3835	0.3869
3	CF-13-11	62-750-2K			154.106	97.85	150.793	93.50	140.486	2.15		4.5002	0.3830	0.3855
4	393 400		122.681 122.847	120.227 120.390										
Totals			384.068	376.386	291.549		285.281		265.782			8.5011		

Rod Number CF-62-754-74 — Date Loaded 12-18-53

1	342		138.654	135.881										
2	CF-13- 7	62-750-2G			137.031	97.85	134.085	93.50	124.920	2.15		4.0006	0.3822	0.3854
3	CF-13-12	62-750-2L			76.593	97.85	74.946	93.50	69.824	2.15		2.2495	0.3828	0.3860
4	CF-14-12	62-751-2L			77.074	97.85	75.417	93.50	70.303	2.15		2.2492	0.3824	0.3854
5	386 394		122.743 122.673	120.288 120.220										
Totals			384.070	376.389	290.698		284.448		265.047			8.4993		

Note: Data taken from Appendix B to this report issued under separate cover.

section in fuel rods CF-62-754-69 and CF-62-754-73 consisted of matched pairs of fuel slugs of equal and unequal lengths, respectively. However, the fuel section in fuel rod CF-62-754-74 consisted of a triad of matched fuel slugs of unequal lengths. Although the individual fuel slugs used in these three fuel rods varied in length, the specifications relating to the "length of the fuel section" and the "weight of U^{235} per fuel rod" were properly satisfied.

Of the 227 loaded fuel rods shipped to the EBR-I, 162 rods contained a pair of fuel slugs of equal length; 46 rods contained a pair of fuel slugs of unequal length; and 19 rods contained a triad of fuel slugs of unequal length. Companion fuel slugs did not always come from the same melt, nor was this a requirement.

FABRICATION YIELD

The completed fuel fabricating operation is summarized in Table IV in terms of its individual melts. Material losses during processing are given in the last column. These losses were kept very low by making a weight balance around each step in the fabricating operation in which a division of the material occurred.

The fuel slug yield on an individual melt basis is given in Table VIII On the average, slightly less than 70 percent of the charge weight resulted in completed fuel slugs acceptable for loading, while slightly more than 25 percent of the charge weight was recirculating remelt stock. The balance of the material charged took the form of analytical samples and recoverable residues not suitable for melting.

TABLE VIII

Fuel Slug Yield Per Melt

Material Fraction	Percent of Charge Wt. (Average Value)
Accepted Fuel Slugs	69.29
Remeltable Stock	25.71
Sprues	(17.85)
Remelt Scrap	(7.86)
Recoverable Melting Residue	2.78
Turnings	1.92
Analytical Samples	0.30
Total	100.00 w/o

The overall fuel slug yield based upon the total amount of material processed (73,273.409 grams of U^{235} and zirconium) was 91.71 percent. On completion of the Mark-II fuel loading, the only remelt stock on hand consisted of remelt scrap and casting sprues produced in the final melt. Data pertaining to the overall fuel slug yield for the process are given in Table IX.

TABLE IX

Overall Fuel Slug Yield for Centrifugal Casting Method of Fabrication

Material Fraction	w/o of Material Processed (73,272.909 g)
Accepted Fuel Slugs	91.71
Remeltable Stock	
Sprues from CF-35	0.61
Remelt Scrap from CF-35	0.41
Recoverable Melting Residue	4.17
Turnings	2.71
Analytical Samples	0.39
Total	100.00 w/o

SUMMARY

The centrifugal casting method of fuel fabrication proved to be very well suited for the Mark-II loading for EBR-I. Some of its more important advantages over the hot-rolling technique used in the fabrication of the initial loading are:

(a) It simplifies the overall fuel slug manufacturing process by having fewer operations.

(b) By casting the fuel slugs to size, diameterwise, it produces fewer residues and ones that are easily reclaimed.

(c) Being essentially a casting technique, it is capable of handling alloys that do not lend themselves readily to fabrication by plastic deformation techniques.

(d) In the case of the uranium-2 w/o zirconium fuel alloy, it is capable of producing fuel slugs that exhibit very good resistance to irradiation damage by present standards.

(e) It permits an automatic reproducibility of microstructure which is not always possible in wrought and heat treated material of similar composition.

(f) It is capable of substantially high yield production.

Although experimental attempts at casting thinner fuel pins (0.165 in. in diameter by $9\frac{1}{2}$ in. long) by the centrifugal casting technique have been somewhat successful, this technique is not especially recommended for casting specimens with diameters smaller than that of the EBR-I fuel slug. As might be expected, the centrifugal casting parameters are appreciably more difficult to establish for the smaller diameter pins.

ACKNOWLEDGEMENT

The subject fabrication was accomplished with the cooperation of several persons whose assistance is gratefully acknowledged. The author is indebted to W. H. Morris and D. L. Hoffman of the Metallurgy Division for the operation of the equipment and processing of the fuel slugs, to S. T. Zegler of the Metallurgy Division for the thermal cycling data, and to B. J. Mikolajeski of Central Shops for machining and inspection of the completed fuel slugs. Special credit is due J. Patterson, formerly of the Special Materials Analytical Group, who provided the chemical and isotopic analyses.

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