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DEVELOPMENT AND MANUFACTURE OF FUEL,
BLANKET, AND THERMOCOUPLE RODS FOR THE
EXPERIMENTAL BREEDER REACTOR I, CORE IV

by

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DEVELOPMENT AND MANUFACTURE OF FUEL, BLANKET, AND THERMOCOUPLE RODS FOR THE EXPERIMENTAL BREEDER REACTOR I, CORE IV

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ABSTRACT

This report describes the development and manufacture of Core IV for the Experimental Breeder Reactor I (EBR-I). A total of 420 rods and 10 thermocouple fuel rods containing plutonium-1.25 w/o aluminum fuel slugs were made. In addition, 120 blanket rods and 5 thermocouple rods were assembled with depleted uranium slugs. Both the fissile and fertile slugs were NaK bonded in Zircaloy-2 jacket tubes.

The fuel alloy was made by induction melting plutonium and aluminum. The centrifugal casting technique developed for EBR-I, Core-II was tried without success with this alloy. The gas pressure injection casting method developed for the EBR-II fuel cycle was used to cast the Core-IV rods. These were parted into rough slugs which were rolled and coined to final shape. After coining, the slugs were heat-treated and inspected.

A loading technique was developed to protect the outside of the jacket tube and the weld zone from plutonium contamination. A connector fitting, with an integral tube for NaK filling, was welded to the top of the jacket tube. A measured quantity of NaK was injected through the fill opening by a hypodermic needle and syringe. The filling tube was then welded closed by the capacitor-discharge technique. The rods were then heat treated, leak detected, eddy-current bond inspected, X-rayed for NaK level, and gaged. All rods were surveyed for alpha contamination of the external surfaces and were shipped in approved birdcages to the reactor site.

INTRODUCTION

The development and manufacture of Core-IV for EBR-I was carried out under Programs 7.2.20 and 7.2.21 of the Metallurgy Division. The

purpose of Program 7.2.20 was to develop a suitable fuel and practical fabrication technique for a metallic plutonium loading for EBR-I. Program 7.2.21 was established for the purpose of manufacturing Core-IV rods and components. Since the methods of fabrication were greatly modified during production, both programs are covered in this report.

A total of 420 fuel rods containing slugs of plutonium alloy and slugs of depleted uranium were fabricated. Ten of these fuel rods contained wells for thermocouples and are known as "thermocouple-fuel rods." In addition to the fuel, 120 blanket rods and 5 blanket thermocouple rods, both types containing only depleted uranium, were assembled. The fuel and blanket rods were similar except for the composition and sizes of the internal slugs.

The fuel rod is shown in Figure 1. The Zircaloy-2 jacket has a nominal outside diameter of 0.299 in. and a wall of 0.021 in. Three equispaced, 0.049-in.-high, Zircaloy-3 spacer ribs were welded longitudinally along the active portion of the rod.

The fuel consists of four, 0.232-in.-diameter by 2.121-in.-long, plutonium-1.25 w/o aluminum alloy slugs. Four, 0.007-in.-high, equispaced ribs on the slugs serve to approximately center them within the jacket. Two, 0.325-in.-diameter, depleted uranium slugs, measuring 7.745 and 3.552 in. in length, are located above and below the fuel section.

The annulus between the slugs and the jacket wall is filled with NaK to serve as the heat transfer medium. An Inconel-X spring and a Zircaloy spacer above the upper blanket slug are used to keep the fuel in position. A helium-filled gas reservoir above the upper blanket slug accommodates thermal expansion and gaseous fission products. An 85-in.-long, Type 304 stainless steel extension rod is screwed to the threaded Zircaloy-2 top connector for manual manipulation and additional radiation shielding. The triangular-shaped Zircaloy-2 tip is used to orient and position the fuel rod in its hexagonal fuel element assembly. All of the Core-III blanket rods contained in the outer 12 hexagonal assemblies will remain in the Core-IV loading. Special Core-IV-type blanket rods are required to fill out the region between the plutonium core and the Core-III blanket. These rods were made identical with the fuel rods except that two depleted uranium slugs replaced the four plutonium slugs.

The fuel and blanket thermocouple rods were used for monitoring the temperatures in the core. These rods are identical to the Core-IV fuel and blanket rods with the exception that a 0.086-in.-diameter axial hole was drilled through the upper blanket slug and two top fuel slugs to the core center. A 0.080-in.-outside-diameter by 0.015-in.-wall Zircaloy-2 thermocouple well was installed in each thermocouple rod.

Fig. 1. EBR-I Core-IV Fuel Rod
(All dimensions in inches)

The flow diagram for the manufacture of the Core-IV fuel rods is shown in Figure 2. The fabrication of blanket and thermocouple rods was basically the same as that shown for the fuel rods with minor modifications required to accommodate the differing components.

This report covers the development of fabrication techniques, the manufacture of the plutonium alloy slugs, and the assembly of the various types of rods. Procurement and processing of Zircaloy-2 hardware was done by the Foundry and Fabrication Group and is covered in Report ANL-6621.(1)

Fig. 2. EBR-I - Core-IV Fuel Rod Manufacture

PRODUCTION OF PLUTONIUM ALLOY FUEL SLUGS

Centrifugal Casting Tests

The technique of centrifugal casting⁽²⁾ was perfected and used for producing the 0.383-in.-diameter by 4.25-in.-long uranium-2 w/o zirconium slugs for EBR-I Core II.⁽³⁾ In the hope of minimizing development and fabrication time and of reducing the process scrap generated, the initial melting and casting tests were performed by the centrifugal casting technique.

The centrifugal casting machines were of the vertical spindle type with the metal centrifuged into off-axis molds. The metal was melted in the upper chamber of the furnace and dropped through a hollow crucible pedestal into a 16-vane centrifugal distributor. It was thrown radially into copper molds from the distributor. The 16 molds and graphite distributor were carried on a 29-in.-diameter rotor table mounted on a vertical spindle. The spindle passed through a synthetic-rubber V-packing seal in the bottom of the rotor chamber and was driven by a 5-hp, dc, variable-speed motor.

The furnace and rotor chambers were of the bell-jar type. The rotor chamber sealed to a 39-in.-diameter vacuum plate by means of an O-ring flange. The furnace chamber sealed to a flange on the top of the rotor chamber. Each of these chambers could be elevated independently by a pair of motor-driven lift screws. A solid copper high-frequency induction coil was attached to the furnace chamber. The crucible, crucible spacer, and tantalum heater were supported on a hollow pedestal attached to the top of the rotor chamber.

Power, supplied by a 30-kw, 10,000-cps motor generator, was introduced into the furnace chamber through a one-million-circular mil coaxial feed-through fitting insulated with compressed magnesia. The alloy was melted in a bottom-pour magnesium oxide crucible. A stopper rod attached to a water-cooled extension and passed through the furnace bell allowed the metal to be poured from the crucible into the graphite distributor. The exterior of the furnace chamber and rotor chamber was cooled by chilled water pumped at subatmospheric pressure through copper tubing brazed to the chamber. The furnace was evacuated by a 700-liter/sec diffusion pumping system.

Adaptation of the centrifugal casting technique to casting 0.236-in.-diameter by $9\frac{1}{2}$ -in.-long, plutonium-1.25 w/o aluminum alloy rods was singularly unsuccessful. The following variables were adjusted in the attempt to make full-length castings: (1) pouring temperature, (2) distributor design, (3) distributor and mold temperature, and (4) rotor speed.

Between 300 and 500°C superheat was required to make the alloy flow freely through the distributor. At these temperatures the magnesium oxide crucibles were rapidly attacked by the molten plutonium. A heavy coating of evaporated magnesium was deposited on the distributor and cold parts of the furnace. The magnesium in the distributor caused pouring difficulty. In addition, the stopper rod became tightly fused to the pour hole by a solid slag. The use of yttrium oxide as a protective coating on the internal crucible surface and stopper rod did not solve this problem although it reduced the degree to which the molten alloy attacked the crucible. A tantalum cap was tried over the end of the stopper rod. This eliminated sticking, but the tantalum-tipped stopper rods did not satisfactorily seat. This caused the metal to drip past the stopper rod prior to pouring.

The distributor requirements were as follows:

1. that the metal drop vertically upon the raised center of the distributor converting the flow from a vertical direction to a uniform horizontal radial direction;
2. that approximately equal quantities of metal be delivered to all 16 molds in an unbroken flow;
3. that the horizontal flow of metal be directed in the direction of the mold axis without excessive impingement on the mold walls and turbulence.

Three different designs of distributors of graphite, illustrated in Figure 3, were tried. The distributor rested upon a copper disc containing 9 cartridge-type electrical resistance heaters. These enabled the distributor to be heated to approximately 550°C. Each succeeding design reduced the length of the feed vanes, increased the cross-sectional areas of the vane gates, and sharpened the flow-cutting points on the vanes.

The molds were clamped to the rotor table with their open ends abutting the distributor vane gates. They were preheated by conduction from the distributor. At the maximum distributor temperature of approximately 550°C the mold temperature averaged not greater than 150°C. With the distributor temperature at 400°C, a mold temperature of 75°C was measured.

Ten developmental melts were made by the centrifugal casting method and cast into the copper molds. In no case did the length of acceptable cast material equal the full mold length of 9 in. Excessive flow marks characterized the best sections of these castings, while the extreme ends exhibited an irregular cold shut condition. A photograph of the rotor table with 16 centrifugal castings is shown in Figure 4. This represents one of the better casts of this material. Table I is a compilation of results showing

Fig. 3. Variations in Graphite Distributor Design

Fig. 4. Centrifugal Castings in Lower Halves of Molds on Rotor Table

Table I
CENTRIFUGAL CASTING PARAMETERS AND RESULTS

Melt Number	Pouring Temp, °C	Distributor Temp, °C	Speed of Rotation, rpm	Distributor Design ⁽²⁾	Resultant Usable Casting Length, in. ⁽¹⁾		
					Maximum	Minimum	Average
R-9	1100	340	250 ⁽³⁾	Type 2	5	0	$2\frac{3}{8}$
R-11	1100	395	175 ⁽³⁾	Type 2	$5\frac{3}{8}$	$1\frac{1}{2}$	$3\frac{3}{8}$
R-12	1150	475	175 ⁽³⁾	Type 2	$6\frac{1}{8}$	0	$4\frac{1}{2}$
P-1	1140	420	200	Type 1	$4\frac{3}{4}$	0	$1\frac{5}{8}$
P-5	1160	480	300	Type 3 ⁽⁴⁾	4	2	$3\frac{1}{4}$
P-7	1160	560	100	Type 3	$8\frac{3}{4}$	$2\frac{1}{4}$	$5\frac{3}{8}$

(1) Maximum possible cast length is 9 in.

(2) Refer to Figure 3.

(3) Rotational speed gradually increased to 600 rpm after pouring.

(4) Distributor coated with yttrium oxide.

the dependence of acceptable material on the various casting parameters. As a result of the poor success of the centrifugal casting, the method was abandoned for the Core-IV alloy.

Injection Casting

Injection casting is a method by which molten metal is forced into evacuated impermeable mold tubes by gas pressure.^(4,5)

The injection casting machine in which this is accomplished is shown schematically in Figure 5. The machine consists of two sections. The lower section houses the induction heating coil in which the fuel alloy is melted. The crucible rests upon the ram of a vertical actuator cylinder. Stops are set to control the distance of cylinder travel. The molds are suspended vertically over the crucible in the mold pallet which is supported on the pallet stand. The upper chamber of the furnace is movable and contains four resistance elements for preheating the molds. This chamber may be raised and lowered to allow access for loading and unloading the mold pallet, for charging the crucible, and for servicing the induction coil. Both the upper and lower furnace sections are of heavy stainless steel and are sealed together by means of an O-ring gasket. Bolts secure the sections together so that the system may be either pressurized or evacuated. A safety valve on the lower furnace section prevents overpressurization of the chamber. The induction coil consists of a solid copper coil surrounding a lava cylinder and spaced by means of lava spacer plugs. Three thin, split, molybdenum cylinders inside the lava insulators serve as reflectors to keep the temperature of the copper coil and outer furnace shell at a reasonable level.

Fig. 5. Injection Casting Machine

Ten-thousand-cycle power is brought into the furnace chamber by means of a one-million-circular mil, coaxial feed-through fitting insulated with compressed magnesium. This power is supplied by a 30-kw, 10,000-cps motor generator. The exterior of the furnace chamber, piston housing, and the central conductor of the feed-through fitting are cooled by chilled water from the subatmospheric pressure pumping system. As there are no water-cooled lines within the furnace chamber, the possibility of internal flooding is minimized. The high-vacuum pumping system attached to the furnace is identical with that used on the centrifugal casting machine. It consists of

a three-stage fractionating diffusion pump, booster diffusion pump, and a rotary-piston mechanical roughing pump.

Controls on the pressurizing valve and accumulator tank allow variation in the rate of furnace pressurization and final furnace pressure.

In operation, 0.236-in.-ID by 18-in.-long Vycor glass molds, which were closed at one end and open at the other, were suspended open end down above the crucible. The crucible was charged with plutonium and aluminum in accurately weighed proportions. The casting machine was evacuated and power was applied to the induction melting coil to melt the metal charge. At the same time, power was applied to resistance heaters to bring the molds to the correct temperature. When the molten metal was ready to be cast, the piston was actuated, raising the crucible to a height sufficient to submerge the open ends of the molds. This "trapped" a vacuum within the molds. The chamber was then pressurized with helium gas, and the pressure differential between the inside and the outside of the molds forced the molten metal up into the molds where it solidified.

Preparation of Furnace Charge

The charge material used in producing the plutonium-1.25 w/o aluminum fuel alloy consisted of plutonium metal ingots and reagent-grade aluminum wire. A typical analysis of the charge material is given in Table II. On the basis of charge calculations, the fuel alloy was carefully proportioned to produce the following composition: 98.60 w/o plutonium, 1.25 w/o aluminum, and 0.15 w/o impurities. This was equivalent to 90 a/o plutonium and 10 a/o aluminum. The alloy of this composition had an approximate density of 15.05 gm/cc. Two grades of plutonium were available. The nominal composition of the first was 95.1% plutonium-239, 4.5% plutonium-240, 0.44% plutonium-241, and traces of plutonium-242. The second grade of plutonium had the following nominal analysis: 93.2% plutonium-239, 6.2% plutonium-240, 0.55% plutonium-241 and traces of plutonium-242.

The first material was received in the form of reduction buttons weighing approximately 2000 g. The buttons were rather heavily oxidized and required cleaning prior to sectioning into smaller pieces for charging into the crucible. The loose oxide was removed from the reduction buttons by wire brushing. This was carried out in a vinyl tent inside a helium-filled hood to control the spread of the finely divided oxide in the hood. Recovered oxide was sealed in a metal can, removed from the system, and stored for later recovery.

The second batch of material was received as sections of a rolled slab. This material was received in 2000-g containers. The pieces were somewhat irregular in shape. This material was very clean and did not require wire brushing prior to sectioning.

Table II

TYPICAL ANALYSES FOR MINOR ELEMENTS IN
CHARGE MATERIALS AND ALLOYED METAL

Impurity	Analyses		
	Charge Materials		Alloyed Metal Melt P-34(2,3)
	Pu Ingot Metal(1,3)	Al Wire(2,4)	
Ag	<10	<0.01	<5
Al	112	Balance	1.20(4)
As	<100	<0.1	NR
B	0.5	0.007	<10
Ba	<1	<0.005	<5
Be	<0.1	<0.001	<0.02
Bi	<10	<0.01	<5
Ca	20	<0.002	<10
Cd	<10	<0.01	NR
Co	NR	<0.01	<5
Cr	168	<0.005	15
Cu	<2	0.2	110
Fe	90	0.4	50
Ga	50	0.02	60
K	2	<0.01	<5
Li	NR	<0.01	<0.05
La	<50	NR	<1
Mg	20	<0.01	<5
Mn	20	<0.005	2
Mo	<10	<0.005	6
Na	NR	<0.005	<5
Ni	475	<0.001	150
P	<100	<0.1	NR
Pb	<10	<0.01	<5
Pd	<10	<0.005	NR
Rh	NR	NR	<10
Ru	NR	NR	<10
Sb	<10	<0.01	<50
Si	25	0.1	NR
Sn	<10	<0.01	<20
Sr	<20	<0.001	<0.05
Ta	<1000	NR	NR
Te	<20	NR	NR
Ti	20	<0.002	<5
V	<10	<0.005	<5
W	NR	NR	<20
Y	NR	NR	7
Zn	<10	<0.01	<20
Zr	<100	<0.01	<5

(1) Analysis received from supplier.

(2) Analysis performed at Argonne National Laboratory.

(3) Analysis reported as ppm.

(4) Reported as weight per cent.

NR Analysis not reported.

Sectioning was accomplished by heating the pieces to approximately 350°C on a hotplate with a transite cover for heat retention. This converted the unalloyed plutonium from its brittle alpha-phase structure at room temperature to a soft delta-phase structure above 319°C. The heated billet was transferred by hand tongs to V-wedge cutting dies

mounted on a 50-ton hydraulic press. The billets were cut by closing the cutting dies. The upper and lower die assemblies were aligned by guide pins, and loose or flying fragments were retained by enclosing the cutting dies in a telescoping shield.

Large sections of plutonium-1.25 w/o aluminum fuel alloy, generated in casting or metal recovery operations, could be cut into smaller pieces without preheating to 350°C. The aluminum alloying addition resulted in the alloy retaining the soft delta phase at room temperature. This was sufficiently soft to section without preheating. The sectioned plutonium was packaged in 500- and 1000-g lot sizes for ease in assembling charges. An amount of reagent-grade aluminum wire, sufficient to correspond to a 1.25 w/o aluminum alloy, was added to each lot of plutonium metal.

Normally a 1,500-g charge of new metal together with the heel from a previous melt, weighing approximately 900 g, resulted in an average charge weight of about 2,400 g. Not more than three charges were made up at a time and stored in the hood system, thus reducing problems associated with criticality control. Other charges were made up and placed in individual tin cans together with containers of "Drierite" desiccant. These were removed from the glove box system in sealed plastic bags. They were stored in the vaults for ready access for future melting.

Fig. 6. Crucible Containing Heel of Ejected Material

Material from three heats showed an abnormally high nickel content. This material, which was too brittle for the rolling operation, was fed into subsequent melts in small additions which kept the nickel below the embrittling range.

After a number of casts had been made, it was found that certain melts were characterized by excessive frothing and spitting of the molten metal. The results from one melt of this type are shown in Figure 6. It was found that this was the result of using excessively oxidized plutonium metal. Recleaning of the oxidized metal by wire brushing just prior to charging reduced this problem.

Each furnace melt was sampled for analyses of aluminum and minor elements. Plutonium isotopic analyses were performed with six random melts. A summary of the calculated melt composition and sample analysis is shown in Table III.

Table III
CALCULATED MELT COMPOSITION AND ANALYSIS

Melt No.		Pu, w/o	Pu ²³⁹ , % of Pu	Pu ²⁴⁰ , % of Pu	Pu ²⁴¹ , % of Pu	Pu ²⁴² , % of Pu	Al, w/o	Imp. w/o	Cr - 120	Cs - <100	Cu - 200	Minor Impurities (100 or more ppm)	Ga - 300	Ni - 300
1	Calculated Analyzed	98.60	95.06	4.49	0.45	-	1.24 1.23	0.16	Cr - 120	Cs - <100	Cu - 200	Fe - 300	Ga - 300	Ni - 300
2	Calculated Analyzed	98.60	95.06	4.49	0.45	-	1.24 1.30	0.16	Cr - 120	Cs - <100	Cu - 200	Fe - 300	Ga - 1000	Ni - 300
3	Calculated Analyzed	98.64	95.04	4.50	0.46	-	1.20 1.26	0.16	Cr - 140	Cu - 150	Fe - 600	Ga - 400	Ni - 400	
4	Calculated Analyzed	98.68	93.23	6.20	0.55	0.02	1.24 1.17	0.08	Ca - 500	Cu - 300	Fe - 450	Mg - 100	Ni - 100	
5	Calculated Analyzed	98.68	93.71	5.74	0.53	0.02	1.22 1.66	0.10	Cu - 150	Fe - 150	Ga - 100	Ni - 150		
6	Calculated Analyzed	98.69	93.31	6.14	0.53	0.02	1.23	0.08						
7	Calculated Analyzed	98.65	93.23	6.22	0.54	0.01	1.23 1.15	0.12	Cu - 150	Fe - 200				
8	Calculated Analyzed	98.68	93.30 93.52	6.17 5.98	0.53 0.482	- 0.018	1.23 1.09	0.09	Cu - 150	Fe - 200	Ni - 150	Y - 100		
9	Calculated Analyzed	98.67	93.27	6.19	0.53	0.01	1.23 1.21	0.10	Fe - 150					
10	Calculated Analyzed	98.66	93.29	6.16	0.54	0.01	1.23 1.06	0.11	Fe - 200	Ni - 150				
11	Calculated Analyzed	98.68	93.23	6.20	0.55	0.02	1.24 1.33	0.08	Fe - 300	Ni - 100				
12	Calculated Analyzed	98.67	93.18 93.40	6.25 6.08	0.55 0.492	0.02 0.020	1.24 1.13	0.09	Cu - 100	Fe - 300				
13	Calculated Analyzed	98.61	93.06	6.36	0.56	0.02	1.27 1.17	0.12	Cu - 400	Fe - 300	Ni - 5000			
14	Calculated Analyzed	98.62	93.06	6.37	0.55	0.02	1.26 1.12	0.12	Fe - 150	Ni - 1500	Pb - 100			
15	Calculated Analyzed	98.60	95.16	4.47	0.37	-	1.24 1.12	0.16	Fe - 220	Ga - 150	Ni - 300			
16	Calculated Analyzed	98.61	95.07	4.49	0.44	-	1.23 0.98	0.16	Fe - 200	Ga - 150	Ni - 250			
17	Calculated Analyzed	98.61	95.09	4.49	0.42	-	1.23 1.29	0.16	Fe - 200	Ga - 200	Ni - 200			
18	Calculated Analyzed	98.62	95.16 95.00	4.48 4.53	0.36 0.448	- 0.017	1.22 1.33	0.16	Fe - 150	Ga - 150	Ni - 200			
19	Calculated Analyzed	98.61	94.93	4.60	0.47	-	1.23 1.22	0.16	Cs - <150	Cu - 220	Fe - 150	Ga - 150	Ni - 350	
20	Calculated Analyzed	98.61	94.96	4.58	0.46	-	1.23 1.22	0.16	Cs - <150	Cu - 150	Fe - 150	Ga - 150	Ni - 400	
21	Calculated Analyzed	98.61	94.98	4.57	0.45	-	1.23 1.07	0.16	Cu - 150	Fe - 150	Ni - 300			
22	Calculated Analyzed	98.61	95.03	4.53	0.44	-	1.23 1.37	0.16	Cu - 150	Fe - 200	Ga - 100	Ni - 300		
23	Calculated Analyzed	98.61	94.70	4.81	0.48	0.01	1.23 1.39	0.16	Cu - 150	Fe - 150	Ga - 100	Ni - 300		
24	Calculated Analyzed	98.61	94.89	4.66	0.45	-	1.23 1.26	0.16	Cu - 250	Fe - 200	Ga - 200	Ni - 300		
25	Calculated Analyzed	98.61	95.06	4.56	0.38	-	1.23 1.29	0.16	Cu - 250	Fe - 300	Ga - 200	Ni - 400		
26	Calculated Analyzed	98.60	95.14	4.50	0.36	-	1.23 1.18	0.17	Cu - 250	Fe - 200	Ga - 200	Ni - 300		
27	Calculated Analyzed	98.60	94.83	4.74	0.43	-	1.24 1.23	0.16	Cu - 150	Fe - 150	Ga - 150	Ni - 170		
28	Calculated Analyzed	98.60	94.82	4.73	0.45	-	1.24 1.30	0.16	Cu - 200	Fe - 110	Ga - 110	Ni - 150		
29	Calculated Analyzed	98.63	93.04	6.39	0.55	0.02	1.25 1.60	0.12	Cu - 180	Ni - 200				
30	Calculated Analyzed	98.65	93.15 93.1	6.28 6.4	0.55 0.49	0.02 0.021	1.24 1.22	0.11	Cu - 120	Ni - 250				
31	Calculated Analyzed	98.63	93.10	6.33	0.55	0.02	1.26 1.11	0.11	Cu - 160	Ni - 1200				

Table III (Contd.)

Melt No.		Pu, w/o	Pu ²³⁹ , % of Pu	Pu ²⁴⁰ , % of Pu	Pu ²⁴¹ , % of Pu	Pu ²⁴² , % of Pu	Al, w/o	Imp, w/o	Minor Impurities (100 or more ppm)			
32	Calculated Analyzed	98.61	94.82	4.70	0.48	-	1.24	0.15				
33	Calculated Analyzed	98.61	94.82	4.70	0.48	-	1.24	0.15				
34	Calculated Analyzed	98.61	94.90	4.64	0.46	-	1.23	0.16				
35	Calculated Analyzed	98.61	94.93	4.62	0.45	-	1.23	0.16				
36	Calculated Analyzed	98.61	94.93	4.62	0.45	-	1.23	0.16				
37	Calculated Analyzed	98.61	94.96	4.55	0.48	0.01	1.24	0.15				
38	Calculated Analyzed	98.61	94.97	4.59	0.44	0.018	1.08	0.16				
39	Calculated Analyzed	98.61	94.85	4.65	0.50	-	1.24	0.15				
40	Calculated Analyzed	98.61	94.60	4.88	0.52	-	1.84	0.14				
41	Calculated Analyzed	98.60	94.77	4.74	0.49	-	1.25	0.15				
42	Calculated Analyzed	98.60	94.79	4.73	0.48	-	1.49	0.15				
43	Calculated Analyzed	98.60	94.84	4.66	0.50	-	1.25	0.15				
44	Calculated Analyzed	98.60	94.84	4.66	0.50	-	1.25	0.15				
45	Calculated Analyzed	98.60	94.93	4.62	0.434	0.018	1.67	0.15				
46	Calculated Analyzed	98.60	94.82	4.68	0.50	-	1.25	0.15				
							1.30	0.15				
							1.46	0.15				

Average

Calculated	High Isotopic	93.22	6.21	0.02	1.24	0.14						
Analyzed	Low Isotopic	94.93	4.62	0.01								
	High Isotopic	93.34	6.15	0.488	1.30							
	Low Isotopic	94.98	4.56	0.018								

Remarks: The analytical accuracy of the above is as follows:

1. Aluminum, $\pm 10\%$
2. Isotopic, varies with sample
3. Minor Elements, factor of 2

Molds and Crucibles

The molds used for casting the fuel material were of precision-bore, high-silica glass. The inside diameter of these molds was held to 0.236 ± 0.001 in. The wall thickness was nominally 0.060 in., and the internal mold length was 18 in. One end of the mold was plugged and fused shut, forming a tab by which the mold was suspended in the pallet. The open end of the mold was cut at 45° to permit the mold more easily to penetrate the layer of slag over the molten metal. The angle-cut end also prevented flow restriction should the mold approach or contact the crucible bottom. It also formed a drip tip that eliminated formation of a knob on the bottom of the casting.

Approved criticality-control procedure limited the charge weight to a maximum of 2600 g of plutonium-aluminum alloy. This allowed casting of a maximum of nine Vycor molds per melt. These molds were supported in a mold pallet or holder on a 1.75-in.-diameter circle. Provision was made for the inclusion of a graphite thermocouple-protection tube; a platinum-10 per cent platinum-rhodium thermocouple was used on early melts to check the readings obtained by optical pyrometer.

The first tests were made in uncoated Vycor molds. This resulted in a very smooth, glass-like surface finish and formed a hard, brittle shell on the surface of the cast metal, which was not amenable to cold working. Colloidal graphite and yttrium oxide (Y_2O_3) were both tried and found successful. Yttrium oxide was chosen for production use. Minus six-micron yttrium oxide was applied as a slurry with ethyl alcohol as a carrier. This was followed by flame drying with a propane torch. The coated tubes were used immediately after coating. It was found that a 24-hr delay before use reduced the effectiveness of the coating and adhesion to the Vycor.

The thickness of mold coating was critical. When the coatings were too heavy, casting surface quality was poor. When the coatings were too thin, the cast metal adhered to the mold surface.

As a result of the poor success with magnesium oxide crucibles, graphite crucibles were tried. These were first coated with yttrium oxide and with yttrium oxide over a magnesium zirconate ceramic coating. In neither case would the coating adhere sufficiently well to the crucible to prevent attack. A tantalum liner was then tried. This worked extremely well, but the heel remaining was fused to the liner and could not be conveniently removed. After 10 or 12 melts, sufficient dross accumulated in the crucible heel to reduce the effective length of cast pins. Then the residual heel and slag were removed from the liner in a recovery operation described later.

The graphite crucible was fabricated from reactor-grade, high-density graphite. The crucible dimensions were 4 in. OD, 3 in. ID, $4\frac{5}{8}$ in. outside height, and 4 in. internal depth.

The liner was fabricated from 30- to 50-mil-thick tantalum sheet. This was done by welding a rolled and seam-welded cylinder to a drawn bottom. The graphite crucible was coated internally with yttrium oxide to prevent the tantalum liner from becoming carburized by direct contact. The graphite crucible and tantalum liner are shown in Figure 7.

Fig. 7. Graphite Crucible and Tantalum Liner

Melting and Casting Cycle

Melting and casting were accomplished in the following cycle. The tantalum-lined crucible was charged with plutonium ingot sections, aluminum wire, and remeltable alloy from previous castings or fabrication alloys. The charging weights ranged from 2200 to 2575 g. After closing the furnace, the mechanical vacuum pump was turned on and the furnace evacuated to a pressure of $50\ \mu$. At this point the diffusion and booster pumps were turned on. When the furnace chamber reached a vacuum of less than 10^{-3} Torr, power was applied to the induction coil. At the same time power was applied to the mold heaters. The charge was heated slowly. Approximately $1\frac{1}{2}$ hr were required to melt the metal without splattering and to promote homogeneity of the alloy.

At the conclusion of the melting and homogenizing stage, the crucible was raised by the air-operated cylinder. This submerged the open ends of the molds to within $\frac{1}{8}$ in. of the crucible bottom (as measured with a cold crucible and molds). After a 3-sec time delay to allow the agitated metal to become quiet, the furnace was pressurized. After pressurizing, the molds were held submerged for a minimum of 15 sec prior to crucible retraction to allow the cast metal to solidify in the molds.

Mold preheat temperature at the time of casting proved critical. Too high a temperature resulted in adhesion of the glass to the casting, while too low a temperature resulted in an incomplete filling of the molds. A mold temperature of approximately 250°C yielded the best results. The metal temperatures were determined by an optical pyrometer from radiation through a quartz window in the furnace top. Mold temperatures were read and controlled by a chromel-alumel thermocouple and pyrometer controller. Table IV is the operational log of a typical melt and casting cycle.

Table IV

LOG OF TYPICAL FURNACE OPERATION

Fuel Fabrication Facility
Furnace Operation Data

Melt No. P-25
Batch No. 423-694
Date: 5-19-62

Time	PF-Line #9		Furnace #2		Furnace Type		Inj		Mech. Pumps		On		Diff. Pumps		On		Remarks
	Volts	Amps	MG Readings		% kvar	Furnace Pressure mm Hg	Temps °C		Metal*	Molds*	Power on - out-gassing	Melt quiet - slight slag	Melt quiet - heavy slag	Melt quiet			
			kw														
1300	84	-	3		+2	7×10^{-4}	-	30	-								
1340	108	-	4.5		+3	1	700	190	700								
1355	108	-	4.5		+3	1	790	200	790								
1410	119	-	5.4		+5	1	825	190	825								
1432	125	54	6.3		+6	7×10^{-4}	900	215	900								
1443	134	57	7.2		+7	6×10^{-4}	945	210	945								
1455	134	57	7.2		+7	7×10^{-4}	995	275	995								
1510	134	57	7.2		+7	3×10^{-4}	1015	265	1015								
1520	134	57	7.2		+7	3×10^{-4}	1025	225	1025								
1527	Cast						1030	260	1030								

*Temperatures measured by optical pyrometer, and chromel-alumel thermocouple respectively.

Crucible: Graphite with tantalum liner.

Molds: Nine glass molds, Y_2O_3 coating.

Tank Pressure: 255 psig before cast; 9.5 psig after cast.

Furnace Pressure: 3×10^{-4} mm, Hg, before cast; 9.25 psig after cast.

Time Delay: Three seconds immersion before pressurization; fifteen seconds after pressurization before retraction.

Mold temperature: 260°C at cast; 340°C peak temperature during cast.

Results: Nine full-length castings; surface quality excellent.

After the furnace and castings had cooled sufficiently to allow handling, the furnace was opened and the glass molds containing the cast metal were removed. The glass molds were broken away from the castings by pliers or a hammer. The castings were then cleaned by wiping with an acetone-moistened tissue to remove residual yttrium oxide from the surfaces. Any areas with glass adhesion were cut out of the castings. These parts were cleaned to bare metal by filing or scraping and recharged to subsequent melts. A series of eight castings from a typical melt are shown in Figure 8.

Fig. 8. Plutonium - 1.25 w/o Aluminum Injection Castings

Fabrication of Fuel Slug

The original design assumptions for the EBR-I, Core-IV fuel slugs were as follows:

- (a) Alloy composition: 1.0 w/o (8.2 a/o) aluminum
- (b) Plutonium-239: 92% of alloy
- (c) Plutonium-240: 6 to 8%
- (d) Density of fuel: 15.5 to 15.7 g/cc
- (e) Thermal conductivity 0.02 cal/(cm)(sec)(°C).

The original slug diameter was 0.234 to 0.236 in. This slug was expected to weigh 23 to 24 g and to contain 20.8 to 22.8 g of plutonium-239. Both the Vycor glass and the centrifugal casting molds were manufactured to produce the 0.235-in. nominal-diameter slugs. Plutonium was ordered for this fabrication.

The plutonium came in two isotopic ranges. The bulk of the material contained 95.0 to 95.3 per cent plutonium-239. About 30 kg were 93.0 to 93.3 per cent plutonium-239. Thus, for the main part, the plutonium-239 content was higher than that assumed in the original computations.

At this time, new information on the plutonium-aluminum phase diagram became available. This information indicated the need for 1.25 w/o aluminum instead of 1.0 w/o to achieve the highest degree of delta-phase stability. The increase in aluminum content reduced the slug density from 15.7 to 15.0 g/cc. This partly compensated for the increase in plutonium-239 content.

The 0.235-in.-diameter slugs in the original design were centered by star-shaped spring clips inserted between the slugs. These had originally been used in Core I and presented some loading difficulty. With the smaller Core-IV slugs and jackets, the spring clips were found to be even more difficult to load. The spacers were nearly impossible to handle in the gloveboxes and could not be loaded through the fittings designed to protect the jacket weld zone from contamination. As a result of these difficulties, the fuel slugs were redesigned to make them self-centering.

Two designs were tried. One incorporated four raised bumps on the cylindrical surface at each end of the slug. These were raised by striking the end of the slug with a four-pointed staking tool while the slug was held in a clamping die. Some distortion of the end of the slug was experienced, and it was necessary to machine the slug end square before loading. The possibility of the slugs warping and contacting the side wall of the jacket during reactor operation was also considered undesirable.

The second method employed four equispaced ribs. These were formed by upsetting the slug in a double-plunger, split, coining die at 185,000 to 200,000 psi pressure. The ends of the slugs remained flat and parallel. The lengths were somewhat irregular. The slugs increased in hardness and density as shown in Table V.

Table V
TABULATION OF STATISTICAL DATA ON PROPERTIES OF PU-1.25 w/o Al
EBR-I CORE-IV FUEL SLUGS AT VARIOUS STAGES OF FABRICATION

Factor	Melt 17 - 12 Pins			Melt 18 - 13 Pins		
	As-cast	As-upset	As-annealed	As-cast	As-upset	As-annealed
a) Density (gm/cc):						
Average	15.01	15.03	15.01	15.03	15.06	15.03
Std Deviation	0.0060	0.035	0.0060	0.0052	0.040	0.0115
Range	15.00/15.01	15.00/15.09	15.00/15.02	15.03/15.04	15.02/15.15	15.00/15.04
b) Body Diameter (in.):						
Average	0.2341	0.2378	0.2385	0.2342	0.2375	0.2379
Std Deviation	0.00028	0.0010	0.00064	0.00023	0.0002	0.0004
Range	0.2337/0.2346	0.2374/0.2385	0.2375/0.2395	0.2340/0.2349	0.2372/0.2378	0.2375/0.2388
c) Rib Diameter (in.):						
Average	-	0.2496	0.2494	-	0.2490	0.2491
Std Deviation	-	0.0021	0.0013	-	0.0007	0.0008
Range	-	0.2485/0.2507	0.2471/0.2512	-	0.2479/0.2500	0.2477/0.2502
d) Length (in.):						
Average	2.285(1)	2.187	2.190	2.279(1)	2.177	2.180
Std Deviation	0.0098	0.0149	0.0139	0.0089	0.0146	0.0131
Range	2.266/2.297	2.166/2.211	2.169/2.208	2.266/2.297	2.146/2.201	2.157/2.204
e) Volume (cc):						
Average	1.6062	1.6033	1.6058	1.5971	1.5945	1.5977
Std Deviation	0.0105	0.0109	0.0113	0.0061	0.0078	0.0061
Range	1.5963/1.6344	1.5845/1.6255	1.5941/1.6162	1.5884/1.6090	1.5813/1.6094	1.5887/1.6093
f) Hardness (R _f)						
1) 1/2 in. from top						
Average	53	63	60	49	61	60
Std Deviation	5.1	5.6	4.9	5.7	3.3	2.6
Range	44/58	53/70	55/67	43/57	57/67	55/63
2) Middle						
Average	54	62	63	50	62	59
Std Deviation	4.5	5.4	3.3	5.3	3.5	3.4
Range	46/59	53/66	58/67	42/57	55/65	54/63

(1) Rough cut slugs measured to nearest 1/64 in. and converted to decimals.

Annealing brought back the original density, but the slugs retained the high hardness after annealing. The composition, gross weight, and calculated plutonium and plutonium-239 contents of upset and annealed slugs from two batches were as shown in Table VI.

This information was submitted to the EBR-I Design Group. Their computations showed that the amount of plutonium-239 in these slugs would make the core smaller than desirable. Based upon the density and composition of these slugs, a new nominal slug diameter of 0.232 in. was specified.

Diameter Reduction Since about 40 per cent of the required slugs had been rough cut from cast pins that were 0.234 to 0.237 in. in diameter, a method for reducing the diameter of these rough cut slugs was necessary.

It was also desirable to use the costly 0.237-in.-ID Vycor glass molds which had been procured for casting. Cold rolling was evaluated for reducing slug diameter. The delta-phase alloy proved very malleable and easily cold worked. The slugs were rolled to an octagonal shape through a modified gothic roll pass. The reduction in cross-sectional area was approximately ten per cent. This produced a desired maximum cross-sectional dimension of 0.227 in. A later coining operation was expected to increase the diameter to the specified value.

Table VI

TABULATION OF STATISTICAL DATA ON Pu AND Pu²³⁹ CONTENTS AND GROSS WEIGHTS OF Pu-1.25 w/o Al, EBR-I Core-IV FUEL SLUGS

	Melt 17 - 12 Pins	Melt 18 - 12 Pins	Melts 17 and 18 Com- bined - 24 Pins
Compositions:			
w/o Pu(1)	98.61	98.62	98.61(2)
w/o Al	1.23	1.22	1.22(2)
w/o Impurities	0.16	0.16	0.16(2)
% Pu ²³⁹	95.09	95.16	95.12(2)
% Pu ²⁴⁰	4.49	4.48	4.49(2)
% Pu ²⁴¹	0.42	0.36	0.39(2)
Gross Slug Wt., g			
Average	23.34	23.34	23.34
Std Deviation	0.076	0.084	0.079
Range	23.19/23.45	23.17/23.53	23.17/23.53
Slug Pu Content, g			
Average	23.01	23.02	23.01
Std Deviation	0.073	0.079	0.077
Range	22.87/23.12	22.85/23.21	22.85/23.21
Slug Pu ²³⁹ Content, g			
Average	21.88	21.90	21.89
Std Deviation	0.071	0.077	0.076
Range	21.75/21.98	21.74/22.09	21.74/22.09
Specified Slug Pu ²³⁹ Content, g ⁽³⁾			
Average			21.59
Range			20.81/22.81

(1)w/o Pu = 100.00 - w/o Al - w/o Impurities

(2)Average of Melts 17 and 18

(3)See Specification PF-1403, Section 1, Para. C1, in Appendix I.

About ten per cent of the slugs were rejected, after rolling, for poor surface quality or casting defects. Three melts resulted in severe radial cracking. It was later discovered that these melts contained a nickel content greater than 1200 ppm. All reject rolled slugs were reclaimed by remelting in subsequent heats. The reject material with high nickel content was divided into small batches and remelted with relatively large quantities of fresh material. This prevented building up the nickel content in the total charge to the point where embrittlement would again result.

Coining

New dies and coining punches were made. They upset each slug to a body diameter of 0.232 in. and formed the required four 0.007-in.-high ribs. The dies, container, and die pins are shown in Figure 9. The die cavity and tapered surfaces were sprayed with colloidal graphite lubricant to reduce friction in upsetting and to facilitate release of the split die from the container. After inserting the rolled fuel slug in the die, the die

Fig. 9. Split Coining Die Used to Upset Fuel Slugs

was seated in the container under a $1\frac{1}{2}$ -ton load. The pins were inserted and a load of $4\frac{1}{2}$ tons was applied to upset the slug. The container was then inverted and pressure was applied to release the die. The upset slug was removed and cleaned with an acetone-moistened cloth to remove adhering graphite. The slugs were inspected. In a few cases the ribs were improperly formed and were rejected. All reject slugs were reclaimed in subsequent melts.

Heat Treating

Concurrently with development of fuel-slug-manufacturing techniques, a series of hot deformation studies were being run by the Applied Physical Metallurgy Group⁽⁶⁾ to determine the slumping characteristics of the 1.25 per cent aluminum fuel alloy under various loads at temperatures ranging from 400 to 600°C. Tests by the same group also indicated that a homogenization heat treatment of 145 hr at 450°C greatly enhanced the load-carrying ability of the alloy. Under a 20-psi load the initial slumping temperature was raised from 400 to over 500°C. Further tests showed that a heat treatment of 3 hr at 550°C produced similar benefits in slump resistance. This heat treatment was practical for fuel fabrication and was incorporated in the fuel-slug-processing sequence following the rib-upsetting operation.

The heat treatment was carried out in a resistance-heated vacuum annealing furnace. The slugs were placed on strips of corrugated tantalum sheet. The vacuum during heat treatment was held to less than 10^{-3} Torr.

During one heat treatment, the rear-zone temperature controller failed to maintain the temperature of 550°C. A resulting temperature of approximately 760°C was reached before the condition was corrected. Examination of the slugs after cooling revealed that eight showed areas of localized melting and subsequent reaction with the stainless steel backup plate. The slugs located in the middle and front furnace zones were not affected.

Machining

A slight excess of metal was deliberately allowed on the length of slugs parted from the castings. After coining and heat treating, 0.040 to 0.100 in. was faced from the length of the slugs in a modified Hardinge lathe located in a helium-atmosphere glovebox. This lathe operation is shown in Figure 10. A closed Lucite box surrounding the cutting tool and collet provided a means for collecting the chips and turnings. The tool was held in a boring bar through a seal in this box. The tool bits were AISI Class T9 (18.5 per cent tungsten, 4 per cent vanadium, and 4 per cent chromium). The alloy was found to be gummy in nature and required an exaggerated top rake to aid chip formation. Best results were attained with a speed of 700 to 800 rpm.

Fig. 10. Fuel-slug-facing Operation

The thermocouple elements required a 0.086-in.-diameter hole through the center of the top blanket slug and through the two top fuel slugs to allow passage of a Zircaloy-2 thermocouple-protection tube. Passage of a drill through the length of a 2.121-in.-long plutonium-aluminum slug was found to be extremely difficult. The gummy chips tended to weld to the drill causing it to break. In the thermocouple fuel elements the two 2.121-in.-long fuel slugs were replaced by four 1.060-in.-long fuel slugs. The shorter slugs were drilled from each end. Mineral oil lightly applied to the drills aided in chip removal. After drilling, the slugs were washed in acetone and ethyl alcohol to remove the adhering oil.

Inspection of Fuel Slug

Inspection of the fuel slugs consisted of length and diameter measurements, rib-height measurements, go/no-go test for straightness, visual inspection for cracks, pits, and fullness of ribs, and weighing. Body diameter and rib diameter were the averages of four dimensions taken at each end of the slug and at 90° rotation. Rib diameters were taken $\frac{1}{2}$ in. from the ends of the slugs. The go/no-go straightness gage was a tube with an inside diameter of 0.251 in. The slugs were required to slide

through this tube by their own weight. Approximately 15 per cent of the finished slugs were rejected in dimensional inspection for undersized body or insufficient rib height. Rejected slugs were recovered by remelting.

Scrap Recycle

The injection casting technique produced a residual heel in the tantalum liner. This heel, weighing about 600 to 700 g, was carried from melt to melt. Sufficient charge material was added to bring the charge weight up to approximately 2400 g. After ten heats were made in this manner, sufficient dross accumulated in the crucible liner to hinder further injection casting.

To recover this material and to salvage the tantalum liner, the liner containing the heel and dross was inverted in a magnesia crucible with a bottom pour hole. The crucible was placed over a $\frac{3}{4}$ -in.-ID copper mold. The assembly was placed in the induction heating coil and heated to about 1000°C. This resulted in the casting of the molten plutonium-aluminum alloy into the copper mold while the more viscous slag was retained in the magnesia crucible.

The total weight of drossy metal heels remelted was 4.13 kg. The quantity of recovered and recycled alloy was 3.09 kg. Approximately 1.0 kg of dross was reserved for future chemical recovery.

Lathe turnings and chips were not oxidized in the protective helium atmosphere. They were recovered by pressing in a split, 1-in.-diameter die at 4 to 4½ tons. The resulting briquet was approximately one-half inch thick by one inch in diameter. These briquets were charged into a bottom-pour magnesia crucible with a stopper rod and heated to about 1025°C. The stopper rod was pulled to allow the metal to flow into a graphite mold. Three reclamation melts were made from turnings.

Results of Fuel Slug Production

Fuel slugs were produced from 46 melts. The developmental work was carried out simultaneously with production. At least some of these melts should be considered developmental. Four melts did not yield acceptable cast metal because of furnace malfunction. A total of 45.42 kg of virgin materials went into the melts. From these, 38.44 kg of acceptable slugs were generated. Table VII is a mass materials balance that shows the disposition of the other materials.

A total of 2327 slugs were cut from the castings. Table VIII shows the disposition of these rough-cut slugs. Reject slugs were remelted during process. Acceptable slugs totaled 1747. After final inspection, the acceptable slugs were identified and weighed individually for calculation of plutonium content in the fuel element. The average weight of a fuel slug was 22.30 g, with a standard deviation of 0.23 g and a range of 21.04 to 22.94 g.

Table VII

MASS BALANCE IN FUEL SLUG PRODUCTION

Material	Weight, g	Per Cent of Virgin Material
Acceptable Slugs	38,443.95	84.6
Analytical Samples	51.43	0.1
Research Samples	740.41	1.6
Available Remelt Stock	1,755.25	3.9
Scrap*	<u>4,424.94*</u>	<u>9.7*</u>
Virgin Charge Materials	45,415.98	100.00

*Of the total scrap generated, 1,805.65 g were materials scrapped because of a high nickel content. This is 4.0% of virgin charge materials, leaving only 5.7% as nonusable scrap generated in manufacture.

Table VIII

DISPOSITION OF ROUGH-CUT SLUGS

	Number of Slugs	Per Cent of Cut Slugs
Total Rough-cut Slugs	2,327	100
Slugs for Property Studies	31	1.3
Slugs Rejected in:		
Rolling	229	9.8
Upsetting and Heat Treating	24	1.0
Inspection	<u>296</u>	<u>12.7</u>
Total Slugs Rejected (to remelt)	549	23.6
Total Slugs Rejected or Used for Property Studies	580	24.9
Acceptable Fuel Slugs	1,747	75.1

ASSEMBLY OF CORE-IV RODS

The following conditions were imposed upon the assembly, welding, and bonding of EBR-I, Core-IV fuel rods:

- (1) The completed fuel rods should show not more than 200-dpm alpha contamination. No loose alpha contamination should appear on wipes.
- (2) All fuel slugs loaded should be identified as to position, weight, batch number, and composition; a complete loading record on each rod keyed to the rod number should be maintained.
- (3) Not more than 24 fuel rods (or 96 fuel slugs corresponding to 2136 g) should be handled at a time in any process zone. In practice the batches were limited to 16 rods, 64 slugs, and 1424 g of plutonium.
- (4) Open rods with exposed plutonium and NaK should be handled only in gloveboxes having an inert protective atmosphere.
- (5) NaK-filled and welded rods should be transported to the counting hood in sealed vinyl pouches. After counting and acceptance, these can be handled in air without glovebox protection.
- (6) All interzone transfers must be in approved birdcages and supervised by the staff man assigned to nuclear hazard control.

The 120 blanket rods, which contained only depleted uranium slugs, were assembled first. This allowed loading, welding, and bonding techniques to be developed on a less critical and dangerous material than plutonium.

Component Inspection

The components used in assembling EBR-I, Core-IV fuel and blanket rods are shown in Table IX. The procurement of adequate quality Zircaloy-2 jacket components caused major delays in the program. This phase of the program was under the Foundry and Fabrication Group and is reported in ANL-6621.(1)

The hardware components were inspected for general dimensional conformity just before loading. The packet tubes were inspected visually for dents or defects which might have slipped by the manufacturing inspection. The tubes were inspected for straightness, depth of cavity, and fit between the connector and jacket.

After all of the blanket rods and 300 of the fuel rods were loaded, a serious weld cratering condition, hidden beneath the fuel tube rib wires, was noticed. Two rods sprung leaks while loading. Rib wires were stripped from some of the jackets already loaded, and it was determined that the defect occurred in a small percentage of the fuel rods. This defect is

described in detail in ANL-6621. The defect consisted of a small-diameter steep-wall crater where the resistance weld nugget had been ejected. The defect was covered by the wire and could only occasionally be visually detected.

Table IX

FUEL AND BLANKET ROD COMPONENTS

Components	Material	Number Required	Number Received
Fuel Slugs	Pu-1.25 w/o Al	1680	1687
Upper Blanket Slugs	0.22% depleted U	540	728
Center Blanket Slugs	0.22% depleted U	240	358
Lower Blanket Slugs	0.22% depleted U	540	740
Jacket Tubes	Zircaloy-2 with Zircaloy-3 ribs	540	760
Upper Connectors	Zircaloy-2	540	840
NaK-level Spacers	Zircaloy-2	540	758
Compression Springs	Inconel X	540	844
Filler Tube Caps	Zircaloy-2	540	906

After several weeks of experimentation, an X-ray technique was evolved which resolved these defects. Each fuel rod or jacket tube was X-rayed six times in batches of 10 to 14 on a 14 x 17-in. film. It was necessary to support the loaded rods in the vertical position to preserve the NaK bond. Mild-steel-antiscatter shields were made to fit the contour of the rod and were grooved for the rib wire. Internal scattering was not a problem with the loaded fuel rods. A close-fitting stainless steel rod was inserted in each fuel tube which had not been loaded to prevent internal scatter. The optimum conditions for defect resolution were found to be as shown in Table X.

Processing was in standard Eastman liquid X-ray film developer for 8 min at 20°C. Two standards were used on each film. The first was a naturally occurring conical defect about 0.008 in. deep and with a base diameter of approximately 0.012 in. The second standard was a fuel tube with machined U-grooves, approximately 0.002 in., 0.004 in., 0.006 in., 0.008 in. and 0.010 in. deep, and three 0.014-in.-diameter holes drilled to a depth of 0.007 in. and 0.013 in. and through the 20-mil-wall tube. A rib wire was attached above these defects to simulate the condition occurring in the fuel jacket. Processing was maintained so that the 0.004-in. groove and the shallower of the drilled holes were always detectable.

Table X
X-RAY MACHINE SETTINGS

	For Rib-weld Inspection	For NaK Level and Connector Weld Inspection
Film Focal Distance, in.	33	36
Films	Gevaert D-2 and Eastman Type M	Eastman Type M
Lead Screens, in.	Front: 0.005 Back: 0.010	Front: 0.005 Back: 0.010
Tube Voltage, v	130,000	130,000
Current, ma	14	10
D-2 Film Exposure, min	5.6	-
M Film Exposure, min	2.6	2.5

The films were read by means of a 7X loupe and a 7X measuring magnifier to estimate the depth of defect. Because of eye strain, the amount of time which any person would inspect rods was scheduled and two persons examined each film. Suspicious areas were X-rayed again. It was possible to see pits as small as 0.003 in. in depth. Any pits deeper than 0.005 in. were cause for rejection of the tube. Eccentricity of the counterbore in the lower end of the tube and poor penetration of the tip weld also showed up in these X rays and were cause for the rejection of a small number of the tubes. The results of fuel tube inspections are as shown in Table XI. The finished tubes which were found defective upon X-ray examination were opened. The internal slugs and hardware were removed and cleaned of NaK by reacting in butyl alcohol. The slugs were reloaded into X-ray-inspected jackets.

Table XI
JACKET TUBE INSPECTION

Inspection	Number Rejected
(a) Visual or dimensional inspection of tubes	24
(b) X-ray inspection of 216 tubes for crater	26
(c) X-ray inspection of 300 finished fuel rods	39
(d) X-ray inspection of 132 finished blanket rods	12
Total of Rejected Tubes:	<u>101</u>

Loading

After investigation of a number of loading methods, it became apparent that the jacket wall should be made a part of the glovebox barrier. The jacket inner space was thus filled with the inert atmosphere while the outside of the jacket was in the uncontaminated room atmosphere. The problem was to protect the weld zone from exposure to contamination. A vinyl plastic fitting was designed such that the open end of the jacket tube could be inserted and tightly sealed to the soft vinyl plastic by means of hose clamps. The other end of this fitting was a re-entrant cone. A 0.004-in.-thick polyethylene funnel was cemented into the cone. The neck of the funnel extended $\frac{1}{4}$ in. into the jacket tube when in the loading position. This extension prevented the fuel slugs from contacting the edge of the tube and leaving particles which would contaminate the girth weld between the tube and connector. This fitting was dielectrically sealed to a 3-in.-diameter by 5-in.-long vinyl sleeve. A photograph of the fitting, vinyl sleeve and funnel, and the jacket tube is shown in Figure 11.

Fig. 11. Fuel Jacket Loading Pouch

Sixteen of these sleeves and fittings were attached to a standard 22-in.-diameter vinyl change pouch without cutting through the bottom of the change pouch. This maintained a vinyl membrane between the tubulation and the glovebox atmosphere. The change pouch was attached to a pouch ring on the end of the loading glovebox, as shown in Figure 12. It was possible to replace pouches one over the other in the same manner as used for glove changes.

Fig. 12. Equipment Used for Loading Fuel Rods

The cumulative tolerances on fuel and blanket slugs, spacer sleeve, and spring would not allow the specified gap of 0.055 in. between the spring and spacer. In order to achieve this specified gap, the assembly of slugs and internal hardware was placed in a dial-indicator comparator and the combined length measured. The internal depth of the tube was measured and the upper connector was faced to the length required to give the specified gap of 0.055 in. The assembled pieces were then cleaned with methyl alcohol, dried, and placed in numbered blocks to assure the proper matching of tubes and fuel slug assemblies. The tube jackets were washed, dried in an oven, and flushed with tank helium to remove solid particles.

The sleeve to which the tube was to be attached was squeezed to remove as much air as possible, and the jacket inserted and seated in the

vinyl fitting. Care was taken that the funnel entered the jacket. Three spring-type hose clamps were attached to provide a helium-tight seal between the jacket and the fitting. The jacket was supported in the holding fixture as shown in Figure 12.

An edge-sharpened "cookie cutter" was used to cut a hole in the inner membrane. Cylinder-tip tweezers were used to insert the slugs through the loading funnel into the jacket, as shown in Figure 13. The identification number of each slug and its position in the fuel rod were recorded on the loading sheet. When all internal components had been loaded into the jacket, the vinyl sleeve was dielectrically sealed, as shown in Figure 14, and cut from the loading pouch. This provided a small envelope of inert atmosphere over the plutonium slugs while they were being transferred to the welding hood line.

Fig. 13. Loading a Core-IV Rod as Viewed from Glovebox Window

Fig. 14. Dielectrically Sealing the Vinyl Sleeve for Removal of the Loaded Fuel Rod from the Pouch

Connector Welding

Fuel rods were closed by means of two welds (see Figure 15). The connector was attached to the tube by means of a girth weld. The NaK filler tube was finally closed by a capacitor-discharge weld. The tungsten-electrode, inert-gas-shielded (TIG) welding method was used to produce sound and uniform girth welds. Power was supplied by a modified magnetic-amplifier controlled, 200-amp, DC arc welder. High frequency was employed to start the arc. A 0.040-in.-diameter thoriated-tungsten electrode was held in a Linde HW-18 torch. Water cooling was not required because of the low amperages used. Power and welding shield gas were supplied from outside of the hood through a feed-through fitting in the glovebox wall. A mixture of helium and argon gas was supplied to the torch.

Fig. 15. Fuel Tube with Upper Connector and Closure Plug

A welding lathe constructed in Building 350 was used. This consisted of a base plate, a universal dividing head equipped with a collet chuck driven by a $\frac{1}{6}$ -hp variable-speed dc motor. A ball-bearing live center was designed to thread onto the connector and provide alignment during welding. The assembly was mounted on a cast iron bed plate. A special shielding gas chamber was designed to enclose the weld zone and the tip of the torch. The chamber contained stops which allowed the various parts to be accurately positioned. The torch was supported by a rugged positioner of commercial design. The welding operation is shown in Figure 16.

A sequence control was designed and constructed to automatically control and sequence the following functions: (1) the preweld gas purge, (2) the high-frequency arc start, (3) chuck rotation, (4) weld start current, (5) high-frequency cutoff, (6) weld current, (7) weld taper current, (8) arc extinction, and (9) post-weld gas purge and motor-drive cutoff. An optimized welding sequence is shown in Table XII.

Fig. 16. Welding the Connector to the Loaded Fuel Tube

Table XII

TYPICAL CONNECTOR WELDING CYCLE

Time (sec)	Condition	Amount
0	Cycle start; gas flow on	19 cfh He, 8 cfh A
10*	High frequency on; arc initiation	2500-v, high-frequency, 36-amp starting current
10.3	Drive on	18 rpm
10.5	Change to weld current	28 amp
10.5	High frequency off	
13.5	Change to taper current	12 amp
15	Taper current off	
30	Drive off; gas flow off	

*Slight delays were sometimes experienced in arc starting. The remaining steps of the cycle were controlled from this step.

In production, a batch of 16 loaded rods was transported from the loading glovebox to the welding glovebox and introduced through a vacuum purge chamber. The vinyl pouch and fitting were carefully removed and placed in a covered dry active waste can to prevent spread of contamination. The connector, which had been previously custom machined to provide a

0.055-in. gap, was inserted into the open end of the tube. The assembly was then placed into the welding lathe for girth welding. Care was required in all handling operations to prevent contamination of the welding area.

After completion of the girth weld, the tail stock was removed and a 3-in. gage extension was threaded onto the connector. The assembly was then rotated while runout was measured at a distance of $1\frac{3}{4}$ in. from the weld by means of a dial indicator. Maximum allowable runout was 0.015 in. A visual inspection of the girth weld was made by the operator using a magnifying glass. The welds were later radiographed during final inspection. Periodic specimen welds were made for metallographic inspection. A photomicrograph of a girth weld is shown in Figure 17.

Micro 34895 B.F. ~40X

Fig. 17. Typical Section of a Girth Weld Joining a Fuel Tube to an Upper Connector

NaK Filling

A rather elaborate chamber to fill a fuel rod with NaK was designed and constructed. It was fitted with a rotary magazine to index eight fuel rods beneath a precision burette. Provision was made alternately to evacuate and pressurize this chamber. In glovebox operation, this equipment was found to be too complicated for the limited number of fuel rods available for early experiments, and alternative equipment was developed which was much more simple and equally as fast.

Glass tubes were substituted for the stainless steel fuel tubes in preliminary experiments. When these were statically supported and gravity filled with NaK, large unbonded areas and smaller gas bubbles

appeared in the annulus. When vibration or impacts were applied to the bottom of the tube while filling, the void areas were reduced but were not eliminated. Much better filling resulted when the fuel tube was evacuated while filling, followed by pressurization to collapse the void areas. Still further improvement occurred when the NaK and the fuel tube were heated to 150°C while filling. Handling hot NaK and heating the fuel rod complicated and slowed the process, however, and this modification was abandoned.

A portable NaK filling fixture of plastic and brass was developed for the production rods. This fixture consisted of a small chamber fitted with tubulation for evacuating and pressurizing. The fuel rod was attached by a vinyl fitting of the type originally used on the loading pouch. A top cover was sealed to the fixture by means of an O-ring and brass clamp ring. A vaccine-bottle stopper was secured in a tapered hole in this cover by means of a brass hold-down ring.

NaK was handled by the hypodermic syringe and vaccine bottle technique. Six-inch-long, 18-gage hypodermic needles fitted with ball shut-off cocks were used. These were affixed to a 10-cc hypodermic syringe. NaK was transferred from a 10-lb stainless steel shipping container to a 250-ml Erlenmeyer flask. Helium was used to effect this transfer in order to prevent oxidation. The flask was plugged with a vaccine-bottle stopper.

NaK was transferred to the syringe by inserting the needle through the rubber stopper, and retracting the plunger. The ball valve was then closed, and the needle withdrawn from the flask and inserted through the stopper in the filler chamber into the fuel rod. Care was necessary to prevent NaK from contaminating the weld zone.

The filling chamber and fuel rod were then evacuated with a mechanical pump to a pressure of less than one torr. A 60-cps vibrator supplied axial vibration to the fuel rod. The ball valve was opened and NaK was drawn into the fuel rod from the hypodermic syringe. The calibrated barrel of the syringe provided a convenient measure of the NaK delivered. Each fuel rod was deliberately overfilled and the level corrected in subsequent operations. The filling operation is shown in Figure 18.

After filling, the rod was brought to glovebox pressure, removed from the chamber, and placed upon a vibratory stand. An 18-gage hypodermic needle on a syringe was inserted and NaK was withdrawn into the syringe to establish an exact level about $\frac{3}{8}$ in. above the upper blanket slug. An adjustable collar on the needle served as a depth gage. Experience showed that in subsequent bonding operations the NaK level would fall within the prescribed $\frac{7}{32}$ to $\frac{2}{16}$ in. above the top slug. Care again was required to prevent contamination of the area to be subsequently welded. Since the NaK and fuel elements were handled entirely within the helium glovebox atmosphere, oxidation and moisture reactions were minimized.

Fig. 18. Filling a Fuel Rod with NaK

Closure Welding

The capacitor-discharge welding technique developed by Stone and Noland⁽⁷⁾ was employed to close the NaK filling tube. Power was supplied from a bank of nine 0.017-farad capacitors. These were charged by a rectified current from a variable transformer. Welding was done in the chamber shown in Figure 19. An electrode is supported over the fuel rod in a calibrated screw collet holder, which allows the gap to be adjusted by means of a hand wheel. A Zircaloy-2 plug with a discharge tip was placed in the fuel rod opening. The fuel rod was inserted into the bottom of the chamber through a spring-loaded, split copper chill block. The electrode was gapped. The chamber was closed and purged with helium gas. A high-frequency, 7000-v, low-current discharge was used to ionize the helium between the electrodes and the discharge tip. The capacitors were then discharged, the current fusing the plug and NaK filling tube into a hemispherical bead. The closure welds were made under the conditions shown in Table XIII.

Fig. 19. Closure Welding by Capacitor Discharge

Table XIII

CAPACITOR-DISCHARGE WELDER SETTINGS

	For NaK Filler Tube Closure	For Thermocouple Well Tube Closure
Capacitance, farad	0.153	0.017
Capacitor Voltage, v	125	120
Electrode	$\frac{1}{16}$ -in.-diameter 1% thoriated tungsten	Same
Electrode Gap, in.	0.050	0.020
Rheostat Setting	38 per cent	0 per cent
Helium Gas Flow, cu ft/hr	20	13
Energy Input, w-sec	1200	122

If small amounts of NaK remained in the filler tube, a darkened irregular bead was formed and molten metal was often violently expelled, causing a defective weld. Sound welds could be produced if the NaK filler tube was wiped with an alcohol-moistened cloth just before the plug was inserted. Figure 20 is a photomacrograph of typical weld cross sections made by this process. The proper placement of the chill blocks and the proper amount of energy were found important in maintaining weld bead uniformity and in reducing the heat-affected zone. Before removing the rods from the welding glovebox, the welds were inspected under magnification and wipes were made to determine possible contamination.

Macro 29834

8X

Fig. 20. Typical Sections of Capacitor-Discharge Closure
Welds on NaK Filler Tube of Fuel Rod

NaK Bonding

Two methods of NaK bonding were evaluated experimentally:

- (1) the fuel rods were heated at 425°C for varying periods of time, and
- (2) the fuel rods were vibrated and heated at 425°C. The NaK bonds were examined by the eddy-current technique. The simple heat treatment appeared to do as good a job as heating plus vibration. Therefore, a treatment cycle of heating the rods to 425°C for a period of 4½ hr followed by furnace cooling was established. This was done in a vertical tube-type furnace with the rods supported in a fixture inside of a stainless steel muffle. The muffle was evacuated to less than 0.05 Torr. The resistance heaters were turned on and the furnace heated to 425°C in about 45 min and held at this temperature for a minimum of 4½ hr. The power was turned off, and the rods were allowed to furnace cool.

Considerable outgassing was noted during the heat treatment, and the fuel rods came from the furnace with a deep-blue discoloration. The initial test of the blanket rods showed that extreme care was required to eliminate all volatile materials from the tubes. The use of cutting fluids in final machining operations was discouraged because such liquids were difficult to eliminate completely from the jackets. Alcohol swabbing of the completed jackets was discontinued when it was found to be a source of gas. A Zircaloy-2 sheet liner was used in the muffle to act as a getter. This appeared to reduce the oxidation of the rod surfaces.

Following the bonding heat treatment, the rods were transferred from the helium-filled glovebox system to an air-filled glovebox for contamination survey. The vinyl transfer pouch technique was used.

Rod Inspection

The following final inspections were made on the EBR-I Core-IV fuel rods:

- (1) alpha survey (less than 200 dpm fixed per rod);
- (2) NaK level and girth welds by radiograph;
- (3) leak detection of girth and closure welds;
- (4) bond inspection by the eddy-current technique;
- (5) dimensional inspection, gaging for straightness, length and weld diameter; and
- (6) visual inspection for dents, corroded areas, weld pits or other nonconformity.

Contamination Survey

The rods were surveyed in the vestibule box of glovebox line PF-18. After opening the plastic pouch, the rods were removed and passed, one at a time, between two Eberline Type PAC-1A proportional alpha counters spaced $\frac{3}{4}$ in. apart. The rods were rotated to insure monitoring the complete surface. Rods showing no contamination were removed to the room air and were resurveyed by means of an Eberline PAC-3G gas proportional counter. Contaminated rods were wiped with alcohol-moistened and dry tissues until clean. Rods which could not be decontaminated to 200 dpm were dejacketed and reloaded.

Radiography

The surveyed rods were radiographed for NaK level and weld penetration by means of a 250-kv X-ray machine. The settings shown in Table X produced satisfactory results. The print of a typical radiograph

is shown in Figure 21. NaK levels were measured from the top of the upper slug. The welds were inspected by examination of the same radiographs. Rods were rejected if the girth weld thickness was less than 0.12 in. as measured by a magnifying comparator. In some cases it was necessary to remove a small amount of metal from the capacitor-discharge welds. Rods were rejected when radiographs indicated that the edge of the bead was less than 0.015 in. thick.

Fig. 21. Print of a Radiograph Showing NaK Levels

Leak Detection

Pressure leak detection, as developed by A. P. Grunwald(8) for the EBR-II fuel rods, was employed in the leak detection of the EBR-I Core-IV fuel rods to check girth and closure welds simultaneously. This involved sealing the upper end of the rod into a close-fitting pressure chamber through a gas-tight collar gasket. The pressure chamber was filled by momentarily opening to a prefill chamber pressurized to 900 psi with helium gas. The initial pressure of the sensing chamber was about 600 psi. The rate of pressure decay was sensed by a piezoelectric pressure transducer and recorded on an oscillograph for 4 min. If no pressure

change occurred, the welds were assumed to be sound. A small leak resulted in a gradual reduction in chamber pressure, whereas a large leak equalized at a pressure below 600 psig.

The leak-detection equipment was calibrated and periodically checked with dummy rods having "standard leaks" by means of a helium mass spectrometer leak detector. The sensitivity of the pressure leak detector was found to be equivalent to the 10^{-10} -cc/sec sensitivity of the mass spectrometer leak detector. The equipment used in leak detecting the Core-IV rods is shown in Figure 22.

Bond Inspection

A fully bonded fuel rod was required, because voids in the NaK bond between the fuel slugs and jackets would result in localized hot spots which might lead to slug melting or cladding failure. The Nondestructive Testing Group developed a double-probe side-scan eddy-current device to detect voids in the Core-IV rods.⁽⁹⁾

The fuel rods were pulled through the sensing unit by means of a rack-and-pinion drive. A spring-loaded roller eliminated side motion. The double-coil probe, necessary to inspect the annular area between the two ribs, consisted of two $\frac{1}{8}$ -in.-diameter coils on a Lucite core. These coils were perpendicular

Fig. 22. Pressure Leak Detection Equipment

to the direction of rod travel. One probe was located centrally between the two ribs while the second was positioned adjacent to the rib. Three passes, with the rod rotated 120° between passes, were necessary for each rod. The eddy-current signal was recorded on a strip chart recorder which was synchronized to the rod speed, which allowed the defect to be accurately located.

Two blanket-type rods with artificial defects were assembled and filled with NaK as standards. A series of 0.005-in. thick vinyl tape patches ranging from $\frac{1}{32}$ to $\frac{1}{2}$ in. diameter were cemented to the uranium

slugs in these standards before NaK filling in order to simulate voids in the NaK annulus. Voids $\frac{1}{8}$ in. in diameter produced strong and recognizable signals. Voids $\frac{1}{16}$ in. in diameter were detectable when between the ribs. A somewhat less reliable indication was received when $\frac{1}{16}$ -in.-diameter voids lay directly beneath the jacket rib.

A number of production rods showing voids were frozen in liquid nitrogen and the jackets stripped away to confirm the information obtained from the standards.(9) The correlation was good. Spurious indications were at times traced to eccentrically positioned slugs and to variation in slug rib height. The operators learned to interpret these indications. Spinning the rods causing the internal components to shift often aided in interpretation of questionable indications.

Dimensional Inspection

Rods in which the connector showed an indicator runout greater than 0.015, as described in the girth welding section of this report, were straightened to less than 0.10 indicator runout. Straightness was gaged between the ribs by means of a steel straight edge and feeler gages. The rods were somewhat soft and easily bent. Since the rods will become bent in handling and shipping, it is suggested that they be gaged immediately before insertion in the reactor loading units and hand straightened if required.

Visual Inspection

A visual inspection was made of each rod for surface defects. Several rods were rejected because of defects in the tube wall. Some rods with dents less than 0.005 in. deep in the tube wall were radiographed to determine whether there was a reduction in tube wall. No reduction in thickness was evidenced by radiography.

Reclaiming of Reject Rods

Reject rods were divided into two groups: those which could be repaired without de jacketing, and those which required de jacketing, cleaning of the internal components, and reassembly.

Approximately 20 per cent of the fuel rods and a number of the blanket rods showed NaK levels outside of the specified range. A rod with a high or low NaK level was reclaimed by cutting the NaK filler tube, just below the closure weld, with a standard tubing cutter. The NaK level was readjusted by adding or removing NaK by means of a hypodermic syringe. A new plug was inserted in the filler tube. The rod was rewelded in the capacitor-discharge equipment and returned to the inspection stream.

Rods showing NaK-bond defects were recycled through the bonding heat treatment. If the voids disappeared on subsequent eddy-current testing, the rods were accepted. Other rods were reclaimed by cutting the

NaK filler tube below the closure weld, re-evacuating by means of the portable vacuum chamber, and applying vibration to the rods while under vacuum. The NaK level was then readjusted, the closure weld made, and the rods re-inspected as previously described.

Defective welds or welds showing poor penetration of bead by X-ray examination were rewelded with considerable success.

It was necessary to disassemble a total of 77 fuel rods: 9 because of nonreparable girth weld defects, 22 because of alpha contamination of welds, 3 because of irreparable bond defects, 39 because of rib weld craters, and 4 because of other defects. These rods were opened just above the spacer ribs by means of a tubing cutter. The internal components were removed by tilting the open tube and sliding the components into a copper trough. The parts were immersed in butyl alcohol to react the clinging NaK. They were then brushed, cleaned in ethyl alcohol, and dried prior to reloading. The cleaned scrap tubes were placed in a dry active waste pouch. The butyl alcohol-NaK butylate residue was absorbed on vermiculite in polyethylene bottles and consigned to the dry active waste.

Identification of Rods

A rod identification number was electro-etched on the jacket of each rod just above the spacer ribs. The numbering system for the various rods was as shown in Table XIV. A complete loading record sheet was kept for each rod which provided the identification of the fuel slug and calculated plutonium, plutonium-239, -240, -241, aluminum, and impurity percentages. The weight of each fuel slug was shown, as well as the calculated contents of plutonium and plutonium isotopes. A limited number of copies of the complete EBR-I Core-IV loading record is available; a sample page is shown in Appendix II.

Table XIV

NUMBERING OF EBR-I CORE-IV FUEL RODS

Rod Type	Numbers
Fuel Rod	P-100 through P-618
Blanket Rod	700 through 859
Fuel Thermocouple Rod	PT-650 through PT-661
Blanket Thermocouple Rod	T-900 through T-908

Packaging for Shipment

The fuel and thermocouple rods were shipped in birdcages. The fuel rods were packed in $\frac{1}{2}$ -in.-diameter paper mailing tubes. A maximum of 16 fuel rods were placed in each birdcage, which was designed to hold

the rods vertically to prevent NaK displacement. The birdcages were reviewed and approved by the ANL Criticality Committee and by the appropriate authorities for interstate shipment.

Results of Rod Manufacture

A total of 420 fuel rods were produced. The average weight of plutonium alloy fuel slugs in each rod was 89.21 g. The fuel slugs ranged in weight from 87.96 to 90.95 g, the standard deviation being 0.72 g.

Since two distinct alloy compositions were used, the range of plutonium content is broad. The material of higher plutonium-239 content was used in 303 rods. The calculated average plutonium content in these rods was 83.43 g; the range was from 81.69 to 85.13 g, with a standard deviation of 0.45 g. The balance of the rods had a lower percentage of plutonium-239. The calculated plutonium content in these rods was 82.23 g; the range was from 80.72 to 83.45 g and the standard deviation 0.36 g.

A total of 497 fuel rod assemblies were processed to yield 420 acceptable fuel rods. A total of 159 blanket rod assemblies were processed to yield 120 acceptable blanket rods. The blanket rods were assembled first, and their higher percentage of rejects reflects the inexperience with NaK bonding and welding procedures in the early production. Eleven of the 120 accepted blanket rods contained radiographic evidence of oxide in the NaK. These rods were accepted because it was not felt that the service would be severe enough to affect the performance in the reactor. All fuel rods showing any uncertainty in the quality of the NaK bond, structural soundness, or dimensional tolerances were rejected because of the more severe service in the fuel section of the reactor.

Only 22 rods were rejected because of measurable fixed alpha contamination in the girth weld. This number was unexpectedly low when considering the high alpha activity of plutonium.

Table XV shows the distribution of acceptable and reject rods, and the number of fuel and blanket rods rejected for various reasons during assembly, welding, processing, and final inspection.

Table XV

DISTRIBUTION OF ACCEPTABLE AND REJECT FUEL AND BLANKET RODS

	Fuel Rods		Blanket Rods	
	Number	Per Cent	Number	Per Cent
Acceptable Rods	420	84.5	120	75.5
Reject Rods:				
Fixed alpha contamination in upper girth weld (by radiation survey)	22	4.4	-	-
Defective upper girth weld (by X ray)	9	1.8	4	2.5
Defects in NaK bond (by eddy current)	3	0.6	18	11.3
Thin tube wall under ribs (by X ray)	38	7.7	13	8.2
Dents in tube wall (visual)	2	0.4	1	0.6
Closure weld leak (leak detection)	1	0.2	-	-
Bowed blanket slugs (by X ray)	1	0.2	-	-
Missing spring component (by X ray)	-	-	3	1.9
Improper identity	1	0.2	-	-
Total Rejected Rods	77	15.5	39	24.5
Total Rods Processed	497	100.0	159	100.0

ASSEMBLY OF THERMOCOUPLE RODS

The thermocouple rod is shown in Figure 23. The assembly procedure for fuel and blanket thermocouple rods was modified to allow insertion of a thermocouple well to the center of the fuel section. The Zircaloy-2 thermocouple well tubes measured 0.080 in. in outside diameter, 0.015 in. in wall thickness, and 19 in. in length. They were sealed at one end by capacitor-discharge welding. The weld end of each tube was faced off in a lathe and cleaned with acetone and alcohol. No end plug was used. The end of the tube was inserted into the welding chamber and the weld made under the conditions shown in Table XIII. The arc discharge fused the end of the tube into a spherical bead as shown in cross section in Figure 24. The welds were inspected and radiographed for soundness; those found to be defective or questionable were removed and the tubes rewelded.

A $1\frac{1}{4}$ -in.-long, shouldered, Zircaloy-2 sleeve was fitted onto each tube. A $\frac{1}{2}$ -mil annular gap was provided in the upper $\frac{1}{2}$ in. of the sleeve while the lower $\frac{3}{4}$ in. was drilled with a 0.086-in. drill. A tapered counter-bore at the top of the sleeve was provided as a reservoir to hold the brazing powder. The composition of the brazing powder was 8% chromium, 8% nickel, and 84% zirconium. The components were positioned in a helium-filled Vycor glass tube and the pieces to be joined were heated by high-frequency induction.

The end weld and brazed joint were leak detected by means of a standard mass spectrometer leak detection procedure. After passing the leak detection test, the subassemblies were finish machined. The thermocouple occupied the hole in the final assembly which was previously used for adjusting the NaK level.

It was necessary to calculate the required NaK from the volume of the jacket tubes and the displacement of the fuel slugs, blanket slugs, and thermocouple well. The volumetric calculations showed that the adjusted NaK level before insertion of the thermocouple well should be $2\frac{15}{16}$ in. below the top of the upper blanket slug. The NaK level was adjusted by inserting an 18-gage hypodermic needle until the operator could feel the top edge of the slug. The gage collar was then adjusted $2\frac{15}{16}$ in. above the top of the NaK filler tube. The needle was then inserted into the center hole of the upper blanket slug and the excess NaK was drawn off to the desired level. The NaK filler tube was then wiped clean and the thermocouple well assembly was inserted. A $\frac{3}{16}$ -in. gap was allowed between the bottom of the thermocouple well and the bottom of the drilled hole in the slug to allow for differential expansion.

The final closure weld was a girth weld similar to that between the jacket and connector. It was necessary to make this weld with the rod in

Fig. 23. EBR-I Core IV Fuel Thermocouple Rod

the vertical position because of the NaK filling. This was accomplished by using the motor-driven indexing head and collet chuck, described earlier, in the vertical position. A chill block was installed to prevent the welding heat from melting the brazing material. The completed welds were inspected under a magnifying glass, and the thermocouple rods were heat-treated for bonding in the same manner as the fuel rods.

Micro 35176

B.F.

50X

Fig. 24. Typical Section of a Capacitor-Discharge Closure Weld on Zircaloy-2 Thermocouple Well Tube

The pressure leak detection could not be used to test the thermocouple rods. The upper ends of these rods were inserted in an evacuation chamber attached to a mass spectrometer leak detector. Upon evacuation of the chamber, defective rods were detected by escape of helium gas from the inside of the rod. The thermocouple welds were inspected for constrictions or obstructions by insertion of a 0.047-in.-diameter wire to the bottom of the well.

A total of 13 thermocouple tubes were available. One was rejected because of a dent in the tube wall. Another rod was rejected because of

an unacceptable upper girth weld. Three of the fuel thermocouple rods had NaK levels slightly above the normal acceptable range. The rods were considered acceptable by the EBR-I group as no additional thermocouple well subassemblies were available.

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APPENDIX I

Specification PF-1403 (Rev. A) EBR-I Core-IV Fuel Rods, Plutonium-1.25 w/o Aluminum Fuel Slugs

Section I - Fuel Slugs

A. Scope

This specification shall govern the manufacture and inspection of EBR-I Core-IV fuel slugs. The fuel slugs shall be right cylinders measuring 2.121 ± 0.002 in. long by 0.232 ± 0.001 in. in diameter. Spacing ribs, as shown in Drawing EB-5511-B, shall be formed on the cylindrical surface to provide a controlled annulus for NaK filling.

B. Chemical and Isotopic Composition

1. The nominal aluminum content shall be 1.25 w/o with a maximum variation of ± 0.10 from the nominal aluminum content.
2. Because the isotopic and impurity contents of the plutonium received are not within the control of the fabricator, it is hereby agreed that, if the desired analysis cannot be met, the Idaho Division representative shall be consulted prior to loading slugs of deviant composition into fuel elements. The desired isotopic content is as follows:

Table I

Pu^{239}	$95.18 \pm 0.3\%$
Pu^{240}	$4.50 \pm 0.3\%$
Pu^{241}	$0.31 \pm 0.1\%$
Pu^{242}	$0.01 \pm 0.1\%$

(The above isotopic content is based on specified isotopic content of plutonium to be received and isotopic analyses made by ANL of similar material. Should actual analysis fall outside the above limits, calculated Pu^{239} content shown in Part C1 will be invalidated and new calculations must be made.)

3. It is desired that impurities be less than 0.3 w/o as determined by spectrochemical analysis. (Normal spectrographic analytical techniques yield results on the following elements: Ag, Am, B, Ba, Be, Bi, Ca, Cd, Cr, Cs, Cu, Fe, Ga, Hf, K, La, Li, Mg, Mn, Mo, Na, Ni, Pb, Pd, Re, Rh, Ru, Sb, Sn, Sr, Th, Ti, U, V, W, Zn, and Zr.)

4. Sampling Procedures

- a. A minimum of one sample from each melt from which acceptable slugs are fabricated shall be analyzed by spectrographic technique for aluminum content and minor elements.

b. One $\frac{1}{2}$ -g-sample from each casting shall be retained in storage for a period of not less than six months after shipment of the fuel elements as an umpire sample.

c. One melt in every eight shall be sampled and the sample submitted for isotopic analysis as a check upon charge calculations.

5. Recorded Compositions and Calculations of Plutonium Control

Compositional data shall be maintained on the basis of calculated charge weights and compositional data on the originally charged material. Analytical data shall be shown for comparison but not for adjustment of the recorded composition. The record will show all weight on the basis of the original calculated composition.

C. Plutonium-239 Content

1. The maximum and minimum values for plutonium content were calculated from compositional and density variations imposed by variation in isotopic, aluminum, and impurity contents within the desired limits listed above.* Plutonium-239 content per slug shall be between the limits of 20.00 and 21.3 g. Slugs which fall outside these limits may be loaded with heavier slugs.

D. Dimensions

The fuel slugs shall be fabricated to meet the tolerances shown in Drawing No. EB-5511-B.

E. Surface Quality

Any surface condition such as laps, seams, or inclusions which might interfere with sodium bonding will be cause for slug rejection.

F. Inspection

1. All fuel slugs shall be inspected for length, body diameter, rib diameter, straightness, and weight. Values shall be recorded to the nearest 0.001 in. and 0.01 g.

2. Periodically and as deemed necessary, slugs may be inspected by radiographic means for internal quality, for microstructure, and for density.

*Calculation of plutonium-239 content shown in Computations section.

G. Identification and Records

1. Each slug shall be identified as to position in specific fuel rods and this identification correlated to the record of length diameter, rib diameter, weight, and calculated plutonium-239 content.
2. In addition, melting and fabricating records shall be maintained so that a complete metallurgical history is available from each casting batch, and the individual slugs shall be identifiable from the record as to their casting batch.
3. Individual marking of slugs will be done only where future identification of special samples may be desired.

H. Thermocouple Rod Slugs

Thermocouple rod slugs will be identical with the fuel slugs except for the required drilled hole and decreased weight.

Section II - Blanket Slugs

A. Chemical and Isotopic Composition

1. Blanket slugs shall be fabricated from depleted, unalloyed uranium. Table II gives the specification for content of uranium-235 and minor elements. As rod stock for fabricating the blanket slugs has been analyzed, the analytical results are shown in the same table.

Table II

Element	Specification	Ingot Analyses, ppm		
		High	Low	Average
U ²³⁵	0.22 ± 0.02%	0.2201	0.2087	0.2130
B	1 ppm max	1	-	0.5
Cd	1 ppm max	0.7	-	0.7
C	750 ppm max	740	60	298
Cr	100 ppm max	20	-	20
Cu	100 ppm max	70	-	13
Fe and Ni	300 ppm max	290	90	171
Mg	25 ppm max	10	-	7
Mn	150 ppm max	140	30	58
N ₂	100 ppm max	58	10	24
Si	150 ppm max	160(2)	15	76
All others ⁽¹⁾	400 ppm max	400	20	87
Total Other than U	2077 ppm max			755

(1) Includes Al, Be, Co, P, Pb, Sn, V, and Zn.

(2) One ingot analyzed 160 ppm. All others were within specifications.

B. Density

The density of depleted, unalloyed uranium is 18.96 ± 0.04 g/cc.

C. Internal Structure

1. All material shall be beta heat treated followed by a water quench prior to finish machining in order to produce a randomly oriented structure.
2. The average grain size of the beta-heat-treated uranium shall be between 0.05 and 0.15 mm as determined by the line-intercept method.
3. No surface or internal defects such as laps, seams, cracks, checks, voids, or inclusions greater than $\frac{1}{32}$ in. in any direction shall be permitted.

D. Dimensional Specifications

All blanket slugs shall be finished to dimensions shown in the Drawings EB-55 series. The slug surface shall have a centerless ground finish.

E. Inspection

1. All material for fabrication of finished blanket slugs shall be inspected for:
 - a. internal quality - cracks, inclusions, voids, etc.;
 - b. beta heat treatment;
 - c. grain size.
2. All completed blanket slugs shall be inspected for:
 - a. length;
 - b. diameter across body;
 - c. diameter across ribs;
 - d. straightness;
 - e. surface quality.

F. Identification

No identification of the blanket slugs will be maintained other than weights of individual blanket slugs to the nearest 0.01 kg.

Section III - Fuel and Thermocouple Rods

A. Hardware

1. All components used in assembling the fuel rods shall be within the tolerances shown on the Drawings and of the materials shown by the Bills of Materials.
2. Zircaloy-2 shall meet specifications MIL-Z-22124 (Bureau of Ships).
3. Jackets shall be visually inspected, tested for cracks, pits, and inclusions, and leak detected. No section of fuel element tubing shall be used having visible defects or defects shown by eddy-current traces to penetrate more than $\frac{1}{6}$ the nominal tube wall thickness.

B. Fuel Rod Assembly

1. The fuel rods shall contain fuel and blanket slugs in the arrangements shown on the applicable drawing.
2. The calculated plutonium-239 content per fuel rod shall be within the range from 80 to 85 g.
3. A data log shall be maintained for each fuel rod giving the following information: fuel slug position; Special Materials batch number; alloy content; calculated plutonium isotopic composition; blanket slug weight; gross weight of fuel slugs; calculated contents of Pu, Pu²³⁹, Pu²⁴⁰, and Pu²⁴¹; average body diameter of each slug; average rib diameter of each slug; and measured length.
4. Any deviation from standard fabrication procedures shall be indicated in the remarks section of the data log sheet.
5. The depth of each fuel rod shall be measured. The length of assembled components shall be adjusted by machining the connector extension to provide an internal gap of 0.055 ± 0.005 in.
6. The tungsten inert-gas shielded arc welding process shall be used to weld the connector to the jacket tube. This weld shall be free of cracks, discoloration, or other defects, and shall be of ample penetration as shown by X rays and visual inspection.
7. Care shall be taken in NaK filling to minimize oxidation. NaK filling shall be done under vibration and as otherwise required to achieve a completely filled annulus between fuel slugs and jackets.

8. NaK level shall be adjusted as shown by the Drawing, and shall be confirmed by X-ray examination after bonding.
9. The NaK bond shall be eddy-current inspected. No rod showing a defect greater than $\frac{1}{8}$ in. in any dimension shall be accepted.
10. Fuel rods shall not show alpha contamination as indicated by the count of paper wipes. Fixed alpha contamination shall be less than 200 dpm over the surface of the rod as surveyed by two parallel-spaced 61-sq cm proportional alpha counter probes between which the rod is passed.
11. Fuel rod bow shall be less than 0.040 in. total indicator reading. The runout of the upper connector shall be less than 0.015 in. total indicator reading as measured with an extension gage $1\frac{3}{4}$ in. above the girth weld.
12. The girth and seal weld shall be leak detected. The leak-detection method shall be capable of indicating a leak rate of 5×10^{-5} standard cc/sec or lower.

C. Assembly of Thermocouple Rods

The thermocouple rods shall in general meet the same specifications as the fuel rods with the following exceptions:

1. Plutonium-239 content shall be from 75 to 80 g.
2. The thermocouple wells shall be brazed to a Zircaloy-2 sleeve with an 8 w/o chromium-8 w/o nickel-balance zirconium brazing alloy.
3. A $\frac{3}{16}$ -in. gap shall be maintained between the end of the thermocouple well and the bottom of the drilled hole in the thermocouple slug.
4. The final seal weld shall be made by the tungsten inert gas shielded arc process.

D. Identification

Each fuel rod and each blanket rod shall be identified by a number electrically etched on the rod above the spacer ribs. The following number system shall be used for EBR-I Core IV:

Fuel Rods	P-100 through P-649
Fuel Thermocouple Rods	PT-650 through PT-675
Blanket Rods	700 through 899
Blanket Thermocouple Rods	T-900 through T-910

APPENDIX II

EBR-1 Core-IV Fuel Rod Loading Record

Appendix II consists of 430 pages giving material batch numbers, dimension, weights, and compositions of the contents of each fuel rod. A sample data sheet is shown below. Only twelve copies of the assembly record exist. These were given a limited internal distribution at Argonne National Laboratory.

EBR I CORE IV FUEL ELEMENT

SLUG NO.	A	B	C	D	E	F	TOTAL
SLUG TYPE	Blkt.	Fuel	Fuel	Fuel	Fuel	Blkt.	
SPM BATCH NO. for Pu: 423-701/	6-7	61	62	63	64	6-7	
SLUG MET NO.		M3-31	M3-32	M3-33	M3-34		
ALLOY CONTENT w/o	Pu	98.64	98.64	98.64	98.64		
	AL	1.20	1.20	1.20	1.20		
	Imp	0.16	0.16	0.16	0.16		
Pu ISOTOPIIC CONTENT %	Pu 239	95.04	95.04	95.04	95.04		
	Pu 240	4.50	4.50	4.50	4.50		
	Pu 241	0.46	0.46	0.46	0.46		
	Pu 242						
BLANKET SLUG WEIGHT, grams	GROSS	47.7				103.9	151.6
	U 235	0.10				0.23	0.33
FUEL SLUG WEIGHT, grams	GROSS		22.27	22.42	22.25	22.02	88.96
	Pu		21.97	22.12	21.95	21.72	87.76
	Pu 239		20.88	21.02	20.86	20.64	83.40
	Pu 240		0.99	0.99	0.99	0.98	3.95
	Pu 241		0.10	0.10	0.10	0.10	0.40
	Pu 242						
DIMENSIONS INCHES	AVG. BODY DIA.	Nominal 0.235	0.233	0.231	0.232	0.232	Nominal 0.235
	AVG. RIBBED DIA.	Nominal 0.245	0.247	0.245	0.245	0.246	Nominal 0.245
	LENGTH	Nominal 3.552	2.119	2.123	2.122	2.119	Nominal 7.745

REMARKS : 2. UPPER GIRTH WELD - welded twice because of initial separation.

Second bead appears sound on 3 radiographs.

7. ROD BOW - less than 0.020 in.

APPENDIX III EBR-I Core-IV Blanket Rod Slug Weights

Rod No.	Slug #1 Depleted U (g)	Slug #2 Depleted U (g)	Slug #3 Depleted U (g)	Slug #4 Depleted U (g)	Rod No.	Slug #1 Depleted U (g)	Slug #2 Depleted U (g)	Slug #3 Depleted U (g)	Slug #4 Depleted U (g)
701	104.0	57.1	57.0	47.6	792	103.5	56.9	56.9	47.5
703	103.9	57.0	56.9	47.8	793	103.9	56.9	56.8	47.5
704	104.3	57.0	57.0	47.8	794	104.0	56.9	56.9	47.9
706	104.3	57.0	57.0	47.5	795	104.0	56.8	57.0	47.8
708	103.6	57.0	57.0	47.8	796	103.4	56.9	56.8	47.8
713	104.0	56.9	56.9	47.3	797	104.0	57.0	56.9	47.8
720	104.0	57.0	56.9	47.5	798	104.0	56.8	56.9	47.7
721	103.8	57.0	56.8	47.7	799	103.8	56.9	57.0	47.9
726	103.9	56.8	57.1	47.8	800	103.9	56.8	57.0	47.8
728	103.9	57.0	56.9	47.5	801	103.9	56.9	57.0	47.5
730	103.5	57.0	56.9	47.8	802	103.5	56.8	56.7	47.8
731	103.5	57.0	56.8	47.7	803	103.6	57.0	56.9	47.8
732	103.9	57.0	57.0	47.4	804	104.0	56.8	56.9	47.8
734	103.7	57.0	56.9	47.6	805	104.0	56.8	56.9	47.8
735	103.8	57.0	56.9	47.7	806	103.3	56.8	56.9	47.7
738	103.4	57.0	56.9	47.7	807	103.7	56.9	57.0	47.8
740	103.8	57.0	56.9	47.9	808	103.9	56.9	57.0	47.7
741	103.9	56.9	56.9	47.5	809	104.1	56.9	56.9	47.8
742	104.0	56.9	57.0	47.8	810	104.0	56.9	56.9	47.7
744	103.9	57.0	56.8	47.8	811	104.1	56.8	56.9	47.5
745	103.9	56.9	57.0	47.8	812	104.0	56.8	57.0	47.3
746	103.8	56.9	57.0	47.5	813	104.0	57.0	56.8	47.7
747	103.3	56.4	56.9	47.8	814	103.9	56.8	57.0	47.7
750	103.9	56.9	57.0	47.5	815	103.9	56.9	56.8	47.7
751	104.0	56.8	56.9	47.8	817	104.0	56.8	56.9	47.7
752	103.9	56.9	57.0	47.4	819	104.0	56.8	56.9	47.6
753	103.8	56.9	57.0	47.6	820	103.9	56.9	56.9	47.5
754	103.8	56.9	56.9	47.7	821	103.9	56.8	57.0	47.6
755	103.3	56.9	57.0	47.8	822	103.9	56.9	56.9	47.4
756	103.4	56.9	57.0	47.8	823	103.5	56.9	56.9	47.8
757	103.9	57.0	57.1	47.7	824	104.0	56.9	56.7	47.7
758	103.8	56.9	56.8	47.8	825	104.0	56.5	56.6	47.7
760	104.0	56.6	56.9	47.8	826	104.0	57.0	56.9	47.7
761	103.8	57.0	56.9	47.8	827	104.0	56.5	56.9	47.8
762	103.7	57.0	56.9	47.8	828	103.4	57.0	56.9	47.8
763	103.7	56.9	57.0	47.7	829	104.0	57.0	56.8	47.6
765	103.8	56.8	56.8	47.3	830	103.9	56.8	56.9	47.5
766	103.8	56.8	56.8	47.5	831	103.9	56.8	56.8	47.8
767	103.9	57.0	56.9	47.7	833	103.9	56.7	56.9	47.8
768	104.4	56.9	56.9	47.8	834	103.9	56.9	56.8	47.5
769	103.8	57.0	56.9	47.5	835	103.6	56.9	56.6	48.0
770	104.0	56.8	57.0	47.8	837	103.9	56.9	56.9	47.8
771	103.9	56.8	56.9	47.5	838	104.1	56.8	56.9	47.8
772	103.5	56.9	57.0	47.8	839	103.9	56.8	56.9	47.4
773	103.9	56.9	57.0	47.8	840	103.9	56.9	57.0	47.8
774	103.5	56.9	56.8	47.7	841	103.8	56.4	56.8	47.8
775	103.9	57.0	57.0	47.4	842	103.5	56.9	56.9	47.8
776	103.8	56.9	56.9	47.5	843	103.8	57.0	56.8	47.5
777	104.0	57.0	57.0	48.0	844	104.1	56.7	56.9	47.8
779	103.8	56.7	56.8	47.8	845	104.0	56.7	56.4	47.5
780	103.3	56.6	56.9	47.8	846	104.0	56.8	56.3	47.4
781	104.0	56.8	56.9	47.8	847	104.1	56.9	57.0	47.8
783	103.9	56.9	57.0	47.8	848	103.9	56.9	57.0	47.7
784	103.8	57.0	56.9	47.9	849	103.9	56.8	56.9	47.9
785	104.1	57.0	56.9	47.5	851	104.0	56.9	56.9	47.8
786	103.8	56.9	57.0	47.4	852	103.7	56.7	57.0	47.8
787	103.4	56.8	56.7	47.8	853	103.9	56.7	56.8	47.6
789	103.7	57.0	56.9	47.8	855	104.1	56.8	57.0	47.8
790	104.0	56.9	56.7	47.5	857	103.9	56.9	56.8	47.5
791	103.9	56.8	56.8	47.8	858	103.3	57.0	56.9	47.8