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Argonne National Laboratory

DEVELOPMENT OF A PROCESS
FOR MANUFACTURING ZPR-III
U-Pu-Mo TEST FUEL ELEMENTS

by

A. B. Shuck, E. M. Pilarski,
A. G. Hins, and G. Burton, Jr.

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ABSTRACT

This report describes the work performed to determine the design and fabrication processes to manufacture uranium-plutonium alloy fuel elements for Zero Power Reactor III (ZPR-III) critical experiments. These fuel elements consist of vacuum-cast uranium-plutonium-molybdenum alloy fuel plates sealed in stainless steel jackets. Four areas were investigated: (1) fuel-plate casting, (2) jacket design and fabrication, (3) fuel-element-assembly techniques to produce fuel elements free from alpha contamination, and (4) jacket seal welding and weld-casting of bearing shoes. Sample fuel elements were manufactured as described to test the feasibility of the process.

INTRODUCTION

The design calculations of a new reactor are generally tested in a critical assembly or zero-power reactor, an assembly of small "building blocks" of reactor materials in various configurations approximating the proposed reactor structure. Neutron sources are introduced and neutron multiplication is measured as the zero-power reactor approaches criticality. The effects of fuel composition, core size and shape, structural materials, moderators, reflectors, and coolants are verified and optimized in the zero-power reactor.

Large numbers of stainless steel-jacketed uranium-plutonium alloy fuel plates are required for experimental verification of the Southwest Experimental Fast-Oxide Reactor (SEFOR) design in ZPR-III. Eventually these elements will be used in large power reactor critical experiments in the Zero Power Plutonium Reactor (ZPPR).

The following are required of the fuel elements:

1. The core plates should be fabricated from a depleted uranium-base alloy containing 17.9w/o($\text{Pu}^{239} + \text{Pu}^{241}$).

2. The fuel plates must have a large positive coefficient of thermal expansion, and any allotropic changes upon heating should cause an expansion.
3. The fuel plates must be sealed in close-fitting, leak-tight stainless steel jackets of sufficient ruggedness to maintain their integrity over several years of repeated handling.
4. The strength of the fuel plate should be sufficient to cause a net expansion of the element assembly against the constraining force of the jacket during a power excursion.
5. The assembled fuel element should be designed so that the lengthwise expansion of the individual elements causes a corresponding expansion of the reactor matrix assembly.
6. The fuel alloy should be oxidation-resistant and should not present a significant fire hazard if the jacket is accidentally ruptured in air.
7. The fuel elements should be fabricable by methods familiar to commercial suppliers, using commercially available equipment.
8. Because of a close time schedule, manufacture of the fuel elements should require a minimum of special equipment or tooling.

Previous Experience in Producing ZPR-III Fuel Elements

Previous metal fuel loadings in ZPR-III have been fabricated by rolling and machining rectangular cores from uranium and plutonium plate. The first loading was enriched uranium that was dip coated with a Teflon film.⁽¹⁾ A subsequent loading of plutonium plates was jacketed in loose-fitting stainless steel sleeves with a spring that held the core plate against one end of the jacket.⁽²⁾ This design did not produce the desired net core expansion. Further, close-fitting jackets were required for the SEFOR loading.

Alpha contamination is a serious problem in jacketing plutonium. Each microgram of plutonium emits 1.43×10^5 alpha particles per minute. The initial lot of plutonium fuel plates was carbonyl nickel coated before jacketing to control contamination, and a method was developed to protect the edge of the jacket by loading through funnels made from brass shim stock. Extremely careful handling techniques were employed to prevent transfer of plutonium contamination to the outside of the jackets by gloves and tools. These processing steps were lengthy and costly.

Fuel elements, jacketed, inspected, and accepted in Illinois, would not pass the width and flatness gages at the National Reactor Test Site (NRTS). This was the result of "aneroid" inflation of the jacket. The ambient barometric pressure at NRTS may drop to 840 millibars (12.3 psia) compared to the sea-level mean pressure of 1013.2 millibars (14.7 psia). Temperature is another factor that may cause inflation of the jackets. The internal pressure increases 23 percent with a 100°C temperature rise. Aneroid swelling was eliminated by jacketing at one-third to one-half of a standard atmosphere.

The sleeves used to jacket the previous plutonium loading were of 10-mil (0.25-mm) Type 304 stainless steel. The end plugs were made from 0.090 x 0.086 in. (2.29 x 2.18 mm) rectangular wire. Warpage occurred when the plugs were welded to the thin sleeves. This was corrected by pressing the fuel elements in a closed die that also flattened the weld. The ductile, delta-stabilized plutonium plate was not damaged during the straightening operations.

Fuel Alloy Development

The plutonium available for the SEFOR critical fuel elements contains about 8.5w/oPu²⁴⁰ and 91w/o(Pu²³⁹ + Pu²⁴¹). For a fuel alloy containing 17.9w/o(Pu²³⁹ + Pu²⁴¹), the total plutonium content will be 19.7w/oPu.

Both metallic and oxide fuel plates were initially considered. Metallic plates were preferred because of their higher thermal conductivity, greater density, and promise of greater strength. From the experimental standpoint, metallic plates allow greater flexibility in mocking up a variety of metallic and compound fuels. A metallic-core fuel element required less development work than one loaded with oxide.

Binary alloys of plutonium and uranium in this composition range contain an undesirable zeta phase.⁽³⁾ A typical 20w/oPu alloy containing zeta-phase structure displays an extensive pattern of microcracks. As a result, the alloy is brittle. It corrodes rapidly in air and is pyrophoric. Even in a fairly good helium atmosphere, containing about 35 ppm H₂O and 500 ppm O₂, the binary U-20w/oPu eventually oxidizes to a powder.

Ternary alloys of uranium and plutonium with iron, molybdenum, vanadium, and titanium were produced to improve the fuel alloy structure and characteristics. A U-20w/oPu-2.5w/oMo alloy was found to have acceptable physical and mechanical properties. The resistances of this alloy to air corrosion⁽³⁾ and to ignition⁽⁴⁾ were also found to be satisfactory.

Rolling Experiment

Rolling and multiple-mold gravity casting appeared to be the two most widely available methods for fabricating small plates. Facilities equipped to make plates by other methods, such as centrifugal casting, powder metallurgy, or press forging, are limited, and these methods were not investigated.

A short preliminary investigation was made of the rolling of U-20w/oPu-1.5w/oFe alloy. Rolling was attempted with 0.5-in. (1.3-cm) diameter billets at temperatures ranging from 25 to 600°C in a helium atmosphere. Although some improvement in ductility was observed at the higher temperature, the rolling characteristics of the alloy were not satisfactory. From 25 to 400°C, cracks appeared in the first five percent reduction. The billets fragmented in two to three five-percent passes.

An attempt was made to break down the cast structure by rolling plate in a heavy picture-frame jacket. The pieces rolled at 450°C broke up within the jacket at between 25 and 40 percent reduction in thickness.

A less complete series of three rolling tests were performed with the U-20w/oPu-2.5w/oMo alloy. This material also cracked when rolled. By this time the casting methods showed promise of producing fuel plates with little difficulty. The rolling experiments were discontinued.

FUEL PLATE FABRICATION

All plutonium alloy fuel processing was performed in inert-atmosphere gloveboxes. Although helium was used during development, the protective atmosphere could also have been argon or a vacuum. Nitrogen may be employed for operations not involving heat. The atmospheric impurities were closely controlled: water vapor was maintained below 35 ppm, oxygen below 500 ppm, and the total of other impurities was about 500 ppm.

Melting and Casting

Casting the molten alloy into reusable precision multiple molds appeared to be a practical method for plate fabrication, requiring a minimum of equipment. Previous work had indicated that, except for length, the required dimensional tolerances might be met without machining.

An electric induction-heated vacuum furnace was used to prepare the alloy and to cast the plates. All melting was done in yttria-washed bottom-pour graphite crucibles, each able to hold about $12\frac{1}{2}$ kg alloy.

Both graphite and copper molds were used. A typical graphite mold is shown in Figure 1. The mold dimensions are indicated in Table I. A protective coating was required to prevent carbon or copper contamination from the molds. The yttria wash was selected on the basis of favorable experience. Six-micron yttria, suspended in ethyl alcohol, was brushed on to the surface of the molds to form a very thin coating. The molds and crucibles were dried for one hour at 200°C after coating. A more adherent mold coating was achieved if the copper molds were acid-etched prior to coating. No surface preparation was required on the graphite molds.

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Figure 1. ZPR-III Multiple-cavity, Graphite Mold Assemblies for Casting 4.5 x 4.5-cm and 4.5 x 7.1-cm Fuel Plates

Table I
DEVELOPMENTAL PLUTONIUM ALLOY FUEL PLATE CASTING MELTS

Melt No.	Melt Temp, °C	Mold Temp, °C	Type Mold	Nominal Mold Sizes	Calculated Compositions (w/o)				Average Shrinkage (%)		
					U	Pu	Mo	Fe	L	W	T
R-152	1300	300	Cu	2 - 1.777 x 1.780 x 0.177 in. (4.514x4.521x0.450 cm) 2 - 1.777 x 2.780 x 0.177 in. (4.514x7.061x0.450 cm)	80.5	18.0	-	1 5	1.3	1.2	0.6
			G	3 - 1.777 x 1.780 x 0.177 in. (4.514x4.521x0.450 cm) 4 - 1.777 x 2.780 x 0.177 in. (4.514x7.061x0.450 cm)	80.5	18.0	-	1 5	1.3	1.2	0.6
R-153	1400	100	G	1 - 1.777 x 1.780 x 0.177 in. (4.514x4.521x0.450 cm) 3 - 1.777 x 2.780 x 0.177 in. (4.514x7.061x0.450 cm)	78.6	17.5	-	3 8	0.0	0.0	-
R-155	1300	550	G	2 - 1.777 x 1.780 x 0.177 in. (4.514x4.521x0.450 cm) 1 - 1.777 x 2.780 x 0.177 in. (4.514x7.061x0.450 cm)	78.6	17.5	-	3 8	0.0	0.0	-

Table I (Contd)

Melt No	Melt Temp °C	Mold Temp °C	Type Mold	Nominal Mold Sizes	Calculated Compositions (w/o)				Average Shrinkage (%)		
					U	Pu	Mo	Fe	L	W	T
R-162	1345	240	G	1 - 1 777 x 2 780 x 0 086 in (4 514 x 7 061 x 0 218 cm)	78 75	20 0	1 25	-	1 7	1 7	2 4
R-163	1240	170	G	1 - 1 777 x 1 780 x 0 250 in (4 514 x 4 521 x 0 635 cm)	78 13	20 0	1 87	-	1 8	1 8	2 9
R-164	1330	220	G	1 - 1 777 x 1 780 x 0 177 in (4 514 x 4 521 x 0 450 cm)	77 5	20 0	2 50	-	1 8	1 8	2 3
R-165	1275	290	G	2 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	78 67	20 0	(1 33 V)	-	1 7	1 7	2 1
R-166	1280	280	G	2 - 2 50 x 0 394 in dia (6 35 x 1 00 cm dia)	78 73	20 0	(1 35 Ti)	-	1 9	1 9	2 3
R-172	1300	-	G	2 - 1 75 x 7 00 x 0 22 in (4 45 x 17 78 x 0 559 cm)	77 5	20 0	2 50	-	1 8	1 7	2 2
R-176	1315	245	G	5 - 1 777 x 1 780 x 0 177 in (4 514 x 4 521 x 0 450 cm) 4 - 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	77 5	20 0	2 50	-	1 7	1 8	2 2
R-177	1250	575	G	4 - 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm) 3 1 777 x 1 780 x 0 177 in (4 514 x 4 521 x 0 450 cm)	77 5	20 0	2 50	-	-	1 5	2 7
R-179	1230	520	G	2 - 1 777 x 1 780 x 0 177 in (4 514 x 4 521 x 0 450 cm) 5 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	77 5	19 96	2 50	-	-	1 9	2 2
R-180	1245	560	G	3 1 777 x 1 780 x 0 177 in (4 514 x 4 521 x 0 450 cm)	77 5	19 94	2 50	-	-	1 9	2 2
R-183	1250	480	G	2 - 1 777 x 5 780 x 0 210 in (4 514 x 14 681 x 0 533 cm)	77 4	19 95	2 50	-	1 9	1 9	1 3
R-183A	1275	480	G	2 - 1 777 x 5 780 x 0 210 in (4 514 x 14 681 x 0 533 cm)	77 4	20 02	2 51	-	1 8	1 9	1 9
R-187	1245	540	G	2 1 777 x 2 780 x 0 210 in (4 514 x 7 061 x 0 533 cm)	72 5	15 0	2 50	-	-	-	-
R-190	1175	500	G	2 - 1 777 x 2 780 x 0 210 in (4 514 x 7 061 x 0 533 cm)	82 4	15 1	2 50	-	-	-	-
R-191	1075	640	G	2 - 1 777 x 2 780 x 0 210 in (4 514 x 7 061 x 0 533 cm)	92 0	25 1	2 49	-	-	-	-
R-204	1220	420	G	1 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	79 5	18 0	2 50	-	-	-	-
R-205	1175	410	G	1 - 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	78 5	19 0	2 50	-	-	-	-
R-206	1190	520	G	1 - 1 777 x 2 780 x 0 177 in (4 514 x 7 061 x 0 450 cm)	76 5	21 0	2 50	-	-	-	-

Note Cu - Copper
G - Graphite (ATJ)

The melting furnace consisted of a water-cooled, stainless steel bell-jar vacuum chamber. An induction-coil insulator assembly was suspended from the bell jar. The bell jar sealed to a water-cooled flange and bottomplate against which mold assemblies could be clamped. The chamber was evacuated by a 6-in oil diffusion pumping system.

Production of sound castings depends upon directional solidification and proper feeding of the molten metal. A temperature gradient of about 300°C was established by placing the molds on a copper pedestal block that in turn rested on the water-cooled furnace bottom. Electrical-resistance heaters were clamped against the sides of the mold assembly,

while the top of the assembly was heated by radiation from the furnace melting zone. An average mold temperature was obtained by means of a thermocouple inserted into the center of a partition between the mold cavities.

The crucible was placed upon a spacer immediately above the molds. When the molds were fed from an integral sprue or runner, difficulties were experienced with uniformity of filling and separation of castings from the molds. An improved technique was employed in making U^{233} castings by which a separate "runner box" or tundish fed each mold cavity independently.⁽⁵⁾ When a large number of castings were poured, the molds filled more uniformly from the separate tundish with multiple gate, and the castings were more easily removed than from the integral runner.

The melt temperature was determined by means of an optical pyrometer. A calibration correction of about $+25^{\circ}\text{C}$ was required to compensate for the filtering effect of the glovebox window, furnace sight glass, and a prism.

Casting Uranium-Plutonium-Iron Alloys

Most of the work was done on uranium-plutonium alloys with iron or molybdenum additions. One melt was made with a vanadium addition and one with a titanium addition. The conditions under which the castings were made are shown in Table I.

Iron was reported to have a beneficial effect on uranium-plutonium alloys.⁽³⁾ Because iron will be a major structural component of fast reactors, it does not add an extra parasitic neutron absorber that must be considered in the experiment. Iron was tried in 3.8 w/o and 1.5 w/o additions. Fluidity and mold replication of the 3.8 w/o iron alloy was found to be very good. The mold surfaces reproduced precisely, but there was little contraction of the castings in the molds when they cooled to room temperature. The material was extremely brittle and essentially all of the castings fractured upon removal from molds or in subsequent handling (see Figure 2). The castings were initially metallic in appearance. The

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Figure 2. Vacuum-cast U-20w/oPu-3.8w/oFe Alloy Fuel Plates Cracked on Removal from the Molds

fractured surfaces had a specular luster which became brass colored when exposed to the glovebox atmosphere or to air, but showed no further darkening. Fractures displayed coarse cubic planes or columns extending inward from the surface. Although the 1.5 w/o iron alloy was less brittle than the 3.8 w/o alloy, it was also easily fractured. Small cracks were seen on the surfaces of some of the castings and were observed to propagate as the castings aged.

Casting Uranium-Plutonium-Molybdenum Alloys

A total of 23 melts were made with U-20w/oPu-2.5w/oMo to establish the optimum casting parameters and mold-shrinkage values, and to develop satisfactory procedures of fuel plate manufacture. Specimens were also furnished to the Applied Physical Metallurgy Group for evaluation of the mechanical properties, metallography, and dilatometry.⁽³⁾

Molybdenum dissolves rather slowly and requires a high temperature for solution. A U-3.12w/oMo master alloy was prepared to permit use of lower temperatures. This was analyzed and remelted with a 20w/oPu addition to the casting melts.

Melt and mold temperatures were varied to determine their effect upon casting shrinkage and surface quality. The melts were cast into the graphite molds by means of a bottom-pour graphite crucible. Mold replication was good. The fine machining marks and scribed numbers in the molds were reproduced on the casting surfaces. It was noted that the end cavities of a seven-cavity mold did not fill as well as the center cavities, and it was subsequently determined that they were nearly 100°C cooler than the center cavities.

The melt temperatures were varied from 1075 to 1345°C; mold temperatures were varied from 170 to 640°C. When the melt temperature was above 1275°C, surface shrinking or dimpling was evident on the cast plates. Below 1210°C, cold shuts appeared at some casting edges. The castings poured at 1275°C into molds at 545°C were satisfactory for fuel plate production. Figure 3 shows a partially disassembled graphite mold and typical cast fuel plates.

A number of the castings were sectioned to determine internal soundness. Shrinkage voids were not found. A cold shut was seen on one casting from Melt R-164. The alloy machined well without coolant when standard high-speed steel milling cutters were used. The machined surfaces were good, although in milling there was a tendency for the unsupported edge of the casting to flake as the cutter point left the work. Short discontinuous chips were produced when the metal was turned.

Figure 3 4.5 x 14.7-cm Graphite Mold and Fuel Plate Castings

The casting dimensions are shown in Table II. They ranged from 1.769 x 2.664 x 0.086 in (4.493 x 6.767 x 0.218 cm) to 1.777 x 5.780 x 0.223 in (4.514 x 14.681 x 0.566 cm). An average thickness shrinkage factor of 2.25 percent was determined. A slightly different shrinkage factor of 1.75 percent was determined for length and width. Table I lists the

Table II
AS-CAST PLATE DIMENSIONS

Melt Number	Plate Number	Difference from Nominal Size		
		Length (in.)	Width (in)	Thickness (in.)
R-176C	1	0.001 (0.025 mm)	0.002 (0.051 mm)	0.000
	2	0.002 (0.051 mm)	0.002 (0.051 mm)	0.000
	3	0.001 (0.025 mm)	0.003 (0.076 mm)	0.001 (0.025 mm)
	4	0.001 (0.025 mm)	0.002 (0.051 mm)	0.001 (0.025 mm)
	5	0.002 (0.051 mm)	0.002 (0.051 mm)	0.001 (0.025 mm)
R-183A	1	0.000	0.004 (0.102 mm)	0.002 (0.051 mm)
	2	0.001 (0.025 mm)	0.006 (0.152 mm)	0.000
R-183	1	0.002 (0.051 mm)	0.009 (0.229 mm)	0.002 (0.051 mm)
	2	0.001 (0.025 mm)	0.011 (0.279 mm)	0.001 (0.025 mm)

actual shrinkage experienced with several typical melts. Most of the castings were found to have satisfactory flatness. A maximum flatness variation of 0.003 in. (0.08 mm) was experienced with 1.769 x 2.664 x 0.086-in. castings.

Titanium and Vanadium Alloy Additions

One melt each was made with 1.26 w/o titanium and with 1.35 w/o vanadium additions to the U-20w/oPu alloy. The casting properties appeared quite similar to those of the molybdenum alloy. When machined, both alloys produced long continuous turnings. Slightly better machined surface finishes were produced on the titanium than on the vanadium alloy. The turnings from both alloys oxidized to a powder in a short time in the glovebox atmosphere, and pieces of the alloys blackened rapidly on fractured or machined surfaces.

SUMMARY OF CASTING RESULTS

1. Fuel plates of uranium-plutonium-molybdenum alloy, cast in graphite molds, may be held within ± 0.1 percent of width and length, and ± 0.4 percent of thickness. Flatness may be held to less than 0.2 percent of the distance indicated.
2. Graphite molds may be recoated with yttria and reused several times without loss of precision.
3. Copper molds were unsatisfactory because of large number of defective castings and because of the danger of copper contamination.
4. Alloys with iron, vanadium, and titanium additions were less satisfactory than molybdenum alloy. The 1.5 w/o iron alloy showed a marked tendency for surface cracking and was brittle. The 3.8 w/o iron alloy could not be cast without cracks. Both the vanadium and titanium alloys corroded in the helium glovebox atmosphere.
5. The molybdenum alloy castings were satisfactory with regard to casting properties and oxidation resistance.
6. Close control of both melt and mold temperatures is required to control casting dimensions and to produce acceptable surfaces.

JACKET DESIGN AND FABRICATION

Two jacket designs were investigated. The first consisted of a sleeve and end-plug assembly. The sleeve was made from a single piece

of strip bent into an open-ended box and TIG (tungsten-electrode, inert-gas shield) welded along one edge. The open ends of the sleeve were closed with solid plugs and sealed by TIG welding. Figure 4 shows the sleeve and end-plug jacket assembly and components.

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Figure 4. ZPR-III Sleeve and End-plug Jacket Assembly. The disassembled components for a sleeve and end-plug jacketed fuel assembly (A) are shown with a finished seal-welded fuel element (B).

The sleeve and end-plug design has several disadvantages. Loading without external contamination of the jacket proved to be difficult. Welding the thin sleeve to the relatively heavy end plugs caused warping and distortion, so that flatness and thickness tolerances were not easily met. When sufficient power was applied in the arc to fuse the end plug, the sleeve was often burned through. Hand filing, or press flattening, was required to meet dimensional tolerances.

In order to slide a plutonium plate into a sleeve, sufficient clearance had to be provided for insertion of a protective loading sheath. This sheath cannot be too thin or it wrinkles and binds as the plate is inserted. Experience has shown that a minimum thickness of 0.002-in. (0.05-mm) brass shim stock and at least 0.005 in. (0.13 mm) of clearance is required. The shim stock sheaths are costly precision fabrications. Since the plate acts like a piston, loose particles of plutonium dust are swept out by the displaced gas. These add to the contamination problem. Carbonyl nickel coating of the fuel plates proved to be a time-consuming, costly solution for control of contamination.

Press flattening in closed dies has been used to upset the weld bead and to remove the distortion from jacketed, delta-stabilized plutonium ZPR-III plates. This is satisfactory only when the core displays some deformability. The U-20w/oPu-2.5w/oMo alloy did not possess sufficient ductility for this treatment. Press flattening also jeopardizes the integrity of the seal welds.

The main advantage of the sleeve and plug jacket design appears in the possibility of achieving a zero end clearance assembly which might be made by pressing the end plug tightly against the core as it is welded in place. Here, the problem is to control temperature to prevent the stainless steel-plutonium alloy interface from reaching the eutectic reaction temperature during TIG welding.

A second jacket design (see Figures 5a, b, and c) was developed to circumvent the difficulties of assembling and loading sleeve and plug jackets. This design consisted of two half-jacket panels formed from 0.012-in. (0.30-mm) stainless steel. Weld metal was provided by turned-out rims or flanges. Assembly was accomplished by placing the fuel plate on one jacket panel and covering it with the second panel, without touching the flanges.

The flanges were clamped between copper chills and fused together by TIG welding. Near-optimum welding conditions existed because the two rims were of the same thickness. The chills prevented heat from penetrating to the jacket cavity or fuel plate, thereby preventing distortion, expulsion of contaminating particles, or a eutectic reaction.

NOMINAL	AS MACHINED
51 X 25	1981 ^{+0.00} _{-0.05}
51 X 51	4521 ^{+0.00} _{-0.05}
51 X 76	7061 ^{+0.00} _{-0.05}
51 X 127	12141 ^{+0.00} _{-0.08}
51 X 152	14681 ^{+0.00} _{-0.08}
51 X 178	17221 ^{+0.00} _{-0.10}

NOMINAL	AS CAST
51 X 25	2007 ± 0.013
51 X 51	4547 ± 0.013
51 X 76	7087 ± 0.013
51 X 127	12167 ± 0.013
51 X 152	14707 ± 0.013
51 X 178	17247 ± 0.013

NOTE

THE FINISHED CORE PLATE
SHALL PASS BETWEEN
PARALLEL PLANES
SEPARATED BY 0.566
ALL DIMENSIONS ARE IN
CENTIMETERS

350-715

Figure 5-a Drawing of ZPR-III Fuel Plate

NOMINAL	A	B
51 X 25	1986 ± 005	3073 ± 005
51 X 51	4526 ± 005	5613 ± 005
51 X 76	7066 ± 005	8153 ± 005
51 X 127	12146 ± 005	13233 ± 005
51 X 152	14686 ± 005	15773 ± 005
51 X 178	17226 ± 005	18313 ± 005

NOTE

CENTER LINES OF CAVITY AND
EDGES TO BE COINCIDENT
WITHIN 0 005
ALL DIMENSIONS ARE IN
CENTIMETERS

350-716

Figure 5-b. Drawing of ZPR-III Half-jacket Panel

NOMINAL	MACHINED
51 X 25	2565 ± 000
51 X 51	5105 ± 000
51 X 76	7645 ± 000
51 X 127	12725 ± 000
51 X 152	15265 ± 000
51 X 178	17805 ± 000

NOTE

- 1 THE FINISHED FUEL ELEMENT SHALL PASS BETWEEN PARALLEL PLANES SEPARATED BY 0 635
- 2 ALL DIMENSIONS ARE IN CENTIMETERS
- 3 NO MACHINING SHALL BE PERFORMED ON EDGE WELDS

350-717

Figure 5-c. Drawing of ZPR-III Fuel Element

The fit of the jacket on the fuel plate is a function of the precision of the parts. The clearances required for assembly may be small because the depth of the jacket cavity is only 0.120 in. (3.05 mm), and the forming operation provides a small lead-in angle. The as-cast dimensions were generally acceptable, except for length. Precise length was achieved by machining. The dimensions of finished fuel element components are shown in Figures 5a and 5b. Both ends of the fuel plates were machined.

End Shoe Design

The fuel elements are loaded end-to-end in drawers, being contained at one end by a spring element against which the column of fuel elements may expand. Thermal expansion of the assembly is one mechanism providing a negative coefficient of reactivity and stable reactor control.

One advantage of the sleeve and end-plug jacket design is that the end plugs provide reinforced contact surfaces between adjacent fuel elements. The edge-welded half-jacket panel design did not provide such flat contact surfaces.

Several methods of applying stainless steel end shoes to the jacketed plates were tested. The resulting end shoes are shown in Figure 6. Items A and B show grooved bars attached by end welding and by plug welding to the jacket flange. Methods used to produce these were rejected because no nondestructive method of inspecting the weld was known. Item C is a surrounding picture frame that was welded at the corners. The method used constrained the expansion of the element and was unacceptable.

350-693

Figure 6. Four Types of Developmental End Shoes Applied to ZPR-III Half-jacket Fuel Elements

Item D is a half-jacket assembly having two U-shaped bars TIG welded to each end. The bars and jacket panels form a four-ply weld seam as shown by Figure 7. The jacket was sealed and the bars were

39323

20X

39324

100X

Figure 7. Photomicrographs of Typical Cross Sections from U-bar End Shoes Welded to ZPR-III Half-jacket Fuel Assemblies

attached in a single weld pass. This design was abandoned because the precision machined bars were too costly and bearing surfaces were too small. All attached shoes were difficult to decontaminate.

Figure 8 shows a fuel element with integrally weld-cast bearing shoes. This was an easily decontaminated design. The weld-cast shoes could be machined after casting to provide the desired flat, parallel bearing surfaces. The weld castings were low in cost and relatively easily made.

350-701

Figure 8. ZPR-III 5.1 x 15.2-cm Fuel Element Assemblies Showing Weld-cast End Shoes in Various Stages of Manufacture. View A shows an assembled fuel element ready for welding with run-out bars and filler strips. View B shows the as-weld-cast shoes with the run-out bars removed, and C shows the finished machined weld-cast end shoes.

HALF-JACKET PANEL FABRICATION

Type 304 stainless steel strip, 0.012 in. (0.30 mm) thick, was selected for forming half-jackets. This was obtained with a No. 2 mill finish: hot rolled, annealed, pick led, and cold finished. In production, a No. 2-B, bright-temper mill finish might be desirable for better surface and closer gage.

The jacket configuration was developed empirically by fabricating 50 to 100 jacket panels for each of the following size elements: 2 x 2 x 0.204 in. (5.1 x 5.1 x 0.52 cm); 2 x 3 x 0.204 in. (5.1 x 7.7 x 0.52 cm); 2 x 3 x 0.250 in. (5.1 x 7.7 x 0.635 cm); and 2 x 6 x 0.250 in. (5.1 x 15.3 x 0.635 cm).^{*} A lignin resin hardboard die stock^{**} was used in the experimental forming dies to develop the necessary edge and corner radii, and

^{*}Nominal dimensions of experimental elements are used here. For final tolerances specified for fuel elements see Figure 5-b.

^{**}Benelex-70, manufactured by Masonite Corporation, Chicago 6, Ill.

to determine clearances. This material is very easily machined, and a set of forming dies could be manufactured in one to two man days, compared with nearly a man-week to produce a set of steel dies. In order to compare results from steel dies with those of the nonmetallic dies, a hardened steel die set was made with a nominal size of 2.00 x 3.00 x 0.250 in. (5.080 x 7.620 x 0.635 cm). The dies were mounted on a die shoe as shown in Figure 9.

350-665

Figure 9. Die Assembly for Forming 5.1 x 7.6-cm Half-jacket Panels, and Panels in Various Stages of Fabrication. View A shows a stainless steel blank for a 5.1 x 7.6-cm jacket panel. View B shows the as-formed half-jacket panel and C the trimmed panel.

All jacket panels were fabricated on a 12-ton (11 tonne) hydraulic press from 0.012-in. (0.30-mm) Type 304 stainless steel. The minimum allowable local thickness of the fabricated jacket panels was 0.010 in. (0.25 mm). Excessive thinning occurred when edge radii on the punch and die were less than 0.020 in. (0.51 mm). Satisfactory jacket panels were produced when edge radii were between 0.025 and 0.030 in. (0.64 and 0.76 mm). Excessive hold-down plate pressure also caused thinning or tearing of the walls of the jacket panel cavity. But if hold-down pressure was insufficient, wrinkling occurred. A compromise was reached with 0.025-in. (0.64-mm) edge radii, and a plate pressure that produced a barely discernible wrinkling of the flange but none in the cavity.

Colloidal graphite and molybdenum disulfide dry die lubricants were tested, but these were difficult to remove from the fabricated pieces. They also tended to build up on the punch, reducing the effective die clearance. SAE-30 lubricating oil was a satisfactory die lubricant and was easily removed by washing the parts in solvent.

Jacket panels of all sizes were formed with equal ease. The jacket panels produced by a given die varied in cavity width, length, and depth by less than 0.002 in. (0.05 mm). When viewed from the outside, the jacket panels showed a concave bow of 0.010 to 0.030 in. (0.25 to 0.76 mm) in the longitudinal direction. The larger jackets had the greater bow. In the transverse direction, the bow was also concave from 0.003 to 0.010 in. (0.08 to 0.25 mm). This bow and the slight edge wrinkling did not interfere with assembling and edge welding. The bow was pulled out when assemblies were clamped for welding.

The experimental formed jackets were trimmed on a shear. Production dies should incorporate a trimming die. All formed jackets were cleaned with acetone and ethyl alcohol, and were oven dried just before assembly.

Application of Filler Strips

Filler strips to provide metal for weld casting were 0.031 x 0.130 in. (0.79 x 3.30 mm) Type 304 stainless steel strips. The filler strips were resistance spot welded to the 2-in. edges of the half-jackets. A 500-W-sec stored energy (Hughes Aircraft Corporation Model VTW-33) spot welder was used for application of the filler strips. No filler metal was used on the longitudinal edge welds.

FUEL ELEMENT ASSEMBLY

All fuel element assembly and welding operations were performed in a helium-atmosphere glovebox. A procedure (see Figure 10) to reduce the frequency of contamination was developed to assemble the core plates between jacket panels. The jacket panels and fuel plates are manipulated by means of vacuum lifters, consisting of bent 5/16-in. (8-mm) OD tubes, each fitted with a soft plastic tip. Each tube was connected through a 3-way vacuum-break valve and flexible tube to a vacuum line.

To use the lifter, the vinyl tip was pressed against the piece and the vacuum valve opened. To release the piece, the valve was moved to the "vacuum break" position. One lifter was used for fuel plates exclusively, being painted red for visual identification. The second lifter was white and was kept clean of contamination for manipulating jacket panels.

350-664

Figure 10. ZPR-III Fuel Element Assembly Fixture
Showing Vacuum Lifters Used to Manipulate Components

Assembly of the fuel elements was done on a small fixture table. A welding chill was manually positioned in a recess on this fixture. A jacket panel was placed in the chill by means of the white lifter. A carefully cleaned fuel plate was picked from its transfer tray by means of the red lifter, carefully positioned over the jacket panel cavity, and lowered into the cavity with a straight vertical motion. The second jacket panel was placed over the fuel plate by means of the white lifter. Care was taken to keep the fuel from touching the welding flanges during assembly. The second chill was next positioned manually, and the clamp screws were turned down to draw the edges of the jacket panels tightly together. Because assembly was done in a helium atmosphere, there was no need to flush the back of the weld joint with inert welding shield gas.

Careful brushing and cleaning of the fuel plates before transfer to the assembly station reduced spread of contamination, but it was nearly impossible to handle plutonium without some area contamination. Disposable plastic sheeting and metal foil were used on glovebox floors and equipment to aid in con-

tamination control. After assembly, the fuel element and chills were carefully surveyed for alpha contamination before welding. Particles of plutonium on the edge joints were volatilized by the arc and caused widely spread contamination of the equipment.

WELDING

Tungsten-electrode, inert-gas-shielded (TIG) arc welding was used to seal the jacket flanges and to cast the end shoes. The welding mechanism and chamber are shown in Figure 11. The vertical welding torch moved along precision rails by means of a motorized lead screw. Adjustments

were provided to position the welding torch vertically and horizontally perpendicular to the weld seam. The assembled chill and fuel element components were accurately fixtured below the welding torch for the torch must not deviate from the weld seam by more than 0.005 in. (0.13 mm) to produce a symmetrical weld.

350-696

Figure 11. Chamber and TIG Welding Torch Mechanism for Seal Welding ZPR-III Half-jacket Fuel Elements. A 5.1 x 15 2-cm fuel element with end shoe weld-casting chill bars is clamped in position beneath the welding torch. The chamber is located in a helium-atmosphere glovebox

The welder mechanism was installed in a chamber that allowed evacuation, gas purging, and welding at a reduced pressure. The purpose of reduced-pressure welding is to assure that the pressure within the jacket remains below the minimum barometric pressure at NRTS when the fuel is at operating temperature. Only the final weld was made at reduced pressure. The chamber was installed in a helium-atmosphere glovebox. The first three welds were made with the weld chamber open to the glovebox atmosphere.

Straight polarity (cathodic-electrode) DC welding power was supplied from a magnetic-amplifier-controlled single-phase transformer-rectifier. A high-frequency spark was used to start the arc. An automatic programmer controlled shield-gas flow, high-frequency spark, arc start, torch traverse, current taper, arc cut-off, and gas-flow cut-off.

The two edge welds were made at one-atmosphere pressure with a gas flow of 20 cfh (9.44 liters/min) helium-10 cfh (4.72 liters/min) argon.

The chill plate and jacket panel assembly are shown in Figure 12. In addition to clamping the jacket panel flanges together, the chills provided a low resistance path for the weld current, and they conducted the heat away, reducing the heat-affected zone in the jacket. The settings and conditions that produced satisfactory edge welds are shown in Table III.

350-695

Figure 12. Copper Chill Plates for Seal Welding the Edges of ZPR-III 5.1 x 15.2-cm Half-jacket Fuel Elements. To the left is an exploded view of the components of a fuel element showing the half-jacket panels and fuel plate. An assembled fuel element is positioned in the copper chill plate.

Table III

WELDING CONDITIONS RESULTING IN ACCEPTABLE WELDS

Condition	(a) Edge Weld	(b) Shoe Weld	(c) Shoe Weld
Pressure	14.7 psia (760 Torr)	14.7 psia (760 Torr)	6 psia (310 Torr)
Electrode, W-1w/oTh, dia	0.040 in (1.02 mm)	0.062 in (1.57 mm)	0.062 in. (1.57 mm)
Shielding gas (Helium)	20 cfh (9.44 l/min)	15 cfh (7.08 l/min)	10 cfh (4.72 l/min)
(Argon)	10 cfh (4.72 l/min)	10 cfh (4.72 l/min)	10 cfh (4.72 l/min)
Electrode gap	0.020 in (0.51 mm)	0.035 in (0.89 mm)	0.035 in. (0.89 mm)
Torch Traverse	8 in./min (203 mm/min)	3 in./min (76 mm/min)	3 in./min (76 mm/min)
Arc Current, Amp	12	130	120
Arc Voltage, V	16	14	14

Welding Machine - Vickers Model #200, Type 51E28-2, DC magnetic amplifier controlled with ANL programmer.

Slight rippling was evident in the edge welds, and a raised area occurred at the point where the arc transferred from the stainless steel to the copper chill block. The chill plates effectively constrained the fusion

zone and reduced the heat-affected region. Grain growth in the heat-affected zone extended from 0.003 to 0.005 in. (0.08 to 0.13 mm) beyond the fusion zone. Seal welds were maintained at a 0.010-in. (0.25-mm) minimum thickness. Figures 13 and 14 show transverse cross sections from typical edge welds. The unaffected base-metal grain size was ASTM 9. Grain size in the heat-affected zone immediately adjacent to the fusion zone was ASTM 7.

39075

Figure 13. Photomicrograph of a Cross Section from a ZPR-III Fuel Element Jacket Edge Weld at 15X Magnification

39071

Figure 14. Photomicrograph of a Cross Section from a ZPR-III Fuel Element Jacket Edge Weld at 75X Magnification

After edge welding, the element was surveyed for alpha-particle emission and then removed from the edge chill assembly. One end was clamped in the shoe chills, as shown in Figure 15. These chills are formed to provide a mold for casting a cylindrical weld bead as shown in the insert.

Metal to form the shoes was provided by extending the weld flange well above the chills and by application of the filler strips described before. However, when the first shoe castings were made, the metal tended to ball up at each end of the shoe casting, because of the surface tension of the molten metal and the tendency of the arc to be drawn out as the torch traveled across the corner. The condition was corrected by inserting two Type 304 stainless steel run-out pins through the ends of the chill to the corners of the jacket panels. The pins were of the same diameter as the shoe casting. The arc was started on a run-out pin about 0.25 in. (6 mm)

from one jacket and continued 0.25 in. (6 mm) beyond the other jacket corner. The conditions required to produce satisfactory shoe welds at one atmosphere are shown in column (b) of Table III.

350-694

Figure 15. Water-cooled Copper Chill Bars for Weld-casting End Shoes on ZPR-III Fuel Assemblies. In the foreground are fuel elements showing A a final machined end shoe and B an as-weld-cast end shoe. A fuel element with filter strips and run-out bars is in position in the chill bar. The cross-section diagram shows the arrangement of welding chill bars and fuel element assembly.

Reduced-pressure Welding

The final shoe casting was made at about 6 psia (310 Torr). The chill mold was assembled on the opposite end of the element, and the weld run-out pins were installed. The assembly was left loose to provide a slight gap between the jacket flanges when installed in the welding machine. (The chamber should be provided with a means for tightening the chill after evacuation.) The chamber was closed and evacuated to 0.1 Torr for not less than 15 min. The chill assembly was clamped, and the chamber was filled with 40% HE-60% A. The vacuum pump was left on, and the vacuum-line valve throttled to produce a dynamic chamber pressure of 0.4 to 0.5 standard atm with a flow of 20 cfh (9.44 liter/min) of weld gas through the torch. The second shoe was cast with about 120 Amp at 14 V. Arc instability and arc-voltage variations tended to be a greater problem at reduced pressure than at atmospheric pressure. Precise setting and control of the power source and careful pressure control promoted arc stability. Automatic pressure regulation is recommended for production equipment for close reproduction of welding conditions. The settings and conditions that produced acceptable shoe welds are shown in column (c) of Table III. Figures 16 and 17 show transverse cross sections from typical weld-cast shoes.

39073

Figure 16. Photomicrograph of a Cross Section from a ZPR-III Weld-cast End Shoe at 15X Magnification

39069

Figure 17. Photomicrograph of a Cross Section from a ZPR-III Weld-cast End Shoe at 75X Magnification

MACHINING

The run-out pins are cut off. The root of the run-out pin is machined to about 0.001 in. (0.03 mm) from the edge weld. The two end shoes are milled to the specified flatness and parallelism with a shell end mill.

CONTAMINATION SURVEY AND LEAK DETECTION

All surfaces of the fuel elements were surveyed for alpha contamination. Before the elements were removed from the glovebox, the surfaces were wiped with an alcohol-moistened tissue. If the tissues showed background count only, the elements were passed to a clean glovebox chamber where they were surveyed with a scintillation counter. The scintillation counter can be used in a helium atmosphere, but it shows a low count rate resulting from gamma excitation even in the absence of alpha particles. Air-proportional counters cannot be used in a helium atmosphere and gas-proportional counters contaminate the helium atmosphere with methane. If the count rate appeared to be no higher than that expected from gamma-ray excitation of the scintillation counter, the specimens were removed

from the glovebox by means of vinyl-pouch seal-off methods. Each element was again surveyed outside the glovebox by means of a gas-proportional counter.

Some evidence of the tightness of the element was gleaned from its appearance and its feel. Jackets that do not have gross leaks were pressed tightly against the core by atmospheric pressure. Two additional tests for tightness were made. The elements were helium leak detected by placing them in a vacuum chamber and sampling the evacuated gas by means of a helium-sensitive mass spectrometer.

The elements were also bubble tested in alcohol at a reduced pressure. This last test was required to indicate leaks too large for the vacuum sampling technique.

CRACKS IN STAINLESS STEEL JACKETS

Leak detection revealed cracks in the jackets of several specimens adjacent to shoe welds. Microscopic examination of sections made through these cracks showed that in each case they occurred in the sheet metal at the bottom of the heat-affected zone. The cracks were intergranular, as shown by Figure 18, but no evidence of a grain-boundary constituent was seen in the microscopic examination. However, the presence of copper was detected by scanning across the crack with a microprobe analyzer.

It was demonstrated that copper was deposited on the jackets from the copper chills by rubbing or as particles formed during the installation of the run-out bars. Examination of fuel elements fixtured for welding showed copper particles imbedded in the stainless steel of several elements. The procedure used on these elements was to slide the assembled components between the copper chills and then to install the run-out bars through holes in the ends of the chills. The sharp corners of the run-out bars cut copper shavings that were, in turn, deposited on the stainless steel jackets. By installing the run-out bars before placing the assembly between the chills, the scuffing and shaving of copper was eliminated. Fourteen test fuel elements were welded with this change of procedure and the cracks appeared to have been eliminated.

In production welding such careful handling of the soft copper chills may not be possible. Two sets of plated chills have been made and tested. One set was plated with chromium, the second with rhodium. Preliminary tests have indicated that either of these two plate materials can be used to improve the durability of the copper chills. No cracks have appeared in the jackets of a limited number of elements welded with the chromium- and rhodium-plated chill assemblies.

350-745

Figure 18. Section beneath Shoe Weld Showing Cracks in Jacket Rim at 250X Magnification

CONCLUSIONS

A new design for ZPR-III test fuel elements has been developed. This design consists of U-20w/oPu-2.5w/oMo alloy fuel plates encapsulated in tight-fitting stainless steel jackets. These test elements can be fabricated by commercial suppliers using available conventional equipment. No special tooling or equipment is required. The necessary manufacturing processing steps have been delineated, and properties and requirements for the finished fuel elements have been established.

Equipment and optimum conditions for precision casting plates from the U-Pu-Mo alloy were determined. A cold-formed stainless steel jacket panel was successfully developed for encapsulating the fuel plates. A method was worked out for attaching bearing shoes integrally at each end of the fuel element by using a TIG welding arc to weld-cast the bearing shoes and seal the jacket in a single operation. A technique for controlling alpha contamination during assembling of the fuel elements was also developed.

This new fuel element design successfully meets the requirements⁽⁶⁾ set for the next ZPR-III fuel element loading.

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APPENDIX I

ZPR-III Fuel Element Fabrication Procedure

Fuel Plate Casting and Machining

All plutonium alloy fuel processing and storage are performed in inert atmosphere gloveboxes. Although helium was used in casting development, the protective atmosphere may be helium, argon, or nitrogen in which the impurities are closely controlled. Water vapor must be maintained below 35 ppm, oxygen below 500 ppm, and the total of all other impurities should not exceed 500 ppm.

An electric induction or resistance vacuum furnace is used to melt and cast the fuel alloy into precisely machined graphite molds. Although laboratory castings were made in top-fill book molds, production casting will require specially designed molds to assure the production of acceptable fuel plates. Attention must be devoted to mold filling, solidification rates, distribution of metal among mold cavities, and the location of sprues and runners. Centrifugal casting has the potential for producing large numbers of sound castings from a single melt.

Graphite casting mold sections, crucible and stopper rod are coated with a yttrium oxide wash to prevent excessive carbon pickup by the molten metal during melting and casting. A suspension of yttrium oxide in alcohol is brushed over the surfaces to produce a continuous adherent barrier film. The coated parts are visually inspected by the operator to assure the integrity of the coating. All coated components are dried and outgassed in a vacuum furnace for 60 min at 200°C. A dynamic vacuum of 5- μ maximum pressure is maintained by continuously pumping. The coated and outgassed crucible and molds are assembled on the hearth of the vacuum melting furnace.

Approximately 12.5 kg of charge consisting of 10 kg of U-Mo master alloy and 2.5 kg of unalloyed Pu are weighed and placed in the crucible. Part of the charge may also be made up of machining chips, cast scrap, and rejected fuel plates. At least 50 w/o of the total charge weight should be composed of virgin material. From a 12.5-kg casting batch, the following approximate quantities of each size fuel plate can be produced:

<u>Nominal Size</u>	<u>Number of Plates</u>
1.777 x 0.780 x 0.533 cm	125
1.777 x 1.780 x 0.533 cm	55
1.777 x 2.780 x 0.533 cm	35
1.777 x 4.780 x 0.533 cm	20
1.777 x 5.780 x 0.533 cm	17
1.777 x 6.780 x 0.533 cm	14

The furnace shell is closed and evacuated to less than 10^{-3} Torr. Heating is initiated below 0.01 Torr and requires approximately one hour for completion. The stopper rod is removed and the molds are gravity or centrifugally filled. Molten metal pours from the bottom spout of the crucible on to a graphite distributor which feeds several upright "book" molds or a group of molds fastened to the centrifugal casting table. Mold temperature is brought to 500 to 550°C just prior to filling and the melt is poured at approximately 1300°C. Resistance heaters attached to the sides of the molds are used to heat molds to the desired temperature. Mold temperature after casting should not exceed 700°C. The bottom of the molds rest on a water-cooled plate inside the furnace. The heat of casting is conducted through the mold bottom into the water-cooled plate. Cast fuel plates cool rapidly. They reach 700°C in less than five minutes.

The furnace is opened approximately 60 min after mold filling. The mold and fuel plates have reached about 80°C at this time. The molds are removed from the furnace and disassembled. The cast fuel plates are carefully removed from the graphite molds. Mold sections are reused unless damaged by removal of the cast plates. Excess sprue material is removed by sawing and returned for remelting. All plates are identified with a casting batch number and a serial number by scribing or vibratooling at the sprue end. Samples are selected for determination of chemical content.

Cast fuel plates are visually inspected for surface finish, porosity, mold filling, cold-shuts, and cracks. The sprue end of plates is machined tangent to the corner radii and then the plate is machined at the opposite end to final length. A 0.064 cm radius or chamfer is machined at the machined ends. The cast edges already contain radii. All machining is performed dry without benefit of lubricants or coolants.

Although the U-Pu-Mo alloy is very strong, it has little ductility. The plates should not be dropped, straightened, or hammered. Bending the plates while chucking for machining must be prevented. Finish machined fuel plates are brushed by hand, not power brushed, with a stainless steel brush to remove all loose particulate material. The identification number of each plate is visually inspected before and after brushing to insure against loss of identity.

Dimensional and geometrical properties of the plates are determined by gaging each finished plate. Length, width, and thickness are measured directly and flatness and squareness by pushing the plates through go, no-go gages.

The weight of each fuel plate is adjusted by removing metal with a calibrated drill. Plates are purposely cast heavier than required. Each plate is weighed and drilled to remove the appropriate amount of metal.

Drilled holes are randomly located to avoid the possibility of aligning holes in adjacent stacked fuel elements. Plates are weighed again after drilling to establish their final weight. The material removed from certain preselected plates is submitted for chemical and isotopic analyses to establish compliance with specification requirements.

Finished fuel plates are cleaned with acetone, dried and wrapped in aluminum foil until required for assembly into stainless steel jackets. Storage must be in a high purity inert atmosphere.

Fuel Element Fabrication

Stainless steel half-jacket panels are prepared outside the inert-atmosphere glovebox line. One half of each jacket assembly is identified with electroetched characters designating the chronology of fuel element assembly. All jacket panels are cleaned by wiping with acetone. Stainless steel welding filler metal strips are spot welded to the bearing-shoe ends of the panels. The panels are then ready to be assembled around the fuel plate.

Fuel element assembling and seal welding are performed inside inert-atmosphere gloveboxes. The working area within the glovebox is covered with 3-mil thick aluminum foil to prevent and to control the spread of radioactivity and to promote ease of clean-up. Fuel plates, preassembled half-jackets, and welding chills are gathered at a gloveport station. A loading fixture and two suction lifters are used in assembling the element. To prevent contamination of the jacket panels, fuel plates are handled with one of the probes and jacket panels with the other. Lifters are color coded for easy visual identification by the operator. In addition, the lifters and components are arranged for left and right-hand operation to prevent inadvertent confusion and consequent contamination of the jacketing components.

Fuel element assembly consists of: (1) placing a welding chill in the loading jig; (2) putting an identified jacket panel cavity side up, into the welding chill recess; (3) inserting the correctly identified fuel plate into the jacket panel; (4) placing the second jacket panel over the fuel plate; and (5) adding the second welding chill. Since the design clearance between the fuel plate and the jacket panel is 0.05 mm to 0.15 mm, insertion of the fuel plate into the jacket requires skillful manipulation to avoid contaminating the welding flanges.

The entire assembly is monitored for alpha contamination before welding. Assemblies showing an alpha count in excess of the acceptable level for finished fuel elements are removed from the working area and disassembled. Contaminated jacket components are discarded, but the welding chills are decontaminated.

Two edges of the fuel element are sealed by machine welding in the glovebox inert atmosphere using a straight-polarity direct-current welding arc from a nonconsumable thoriated tungsten electrode. The arc and weld are shielded during welding by a stream of helium-argon gas. After making the two edge welds, the chills are removed and replaced by the water-cooled shoe-molding chills and welding runout bars are inserted. The assembly is again checked for alpha contamination. The first shoe is weld cast by tungsten-arc machine welding with a flow of helium-argon through the torch. The fuel element assembly with welding chills attached is then placed in a chamber, which is evacuated to 10^{-6} maximum pressure, held for 20 min, and backfilled with helium to 0.3 to 0.6 atmospheres. The second shoe is then weld cast. The fuel element is then removed from the chamber, the welding chills are disassembled, and the fuel element and chills are checked for possible alpha contamination. If the average count level is less than one count per minute per square centimeter, the fuel elements are removed from the glovebox and processing is continued in room air.

All welds are visually inspected at 15X magnification for cracks, cold-shuts, surface porosity, surface roughness, and complete filling of the weld-casting mold cavity. All welds are left in the "as-welded" condition. The shoes are machined to length, producing flat end bearing surfaces. All machined fuel elements are measured directly and are passed through go, no-go gages to determine compliance with the dimensional and geometric requirements of the reference drawing. A 2-kg-maximum force is used to push the fuel element through the gages.

Fuel elements are tested for jacket integrity by two methods: one sensitive to large leaks, the other to small ones. To determine the presence of large leaks, the individual elements are submerged in a fluid such as alcohol and the pressure above the surface of the liquid is reduced to less than 0.14 atmosphere. The appearance of bubbles on any portion of the fuel element jacket indicates a rupture. Small leaks are determined with a helium mass spectrometer. Batches of 10 to 20 elements are checked at one time by placing them in a chamber which is rapidly evacuated to less than one micron. A mass spectrometer calibrated to detect 1×10^{-8} cm³/sec of helium is used to detect leaks.

Finished fuel elements are weighed and the data recorded for future reference. All fuel elements are visually inspected. All elements are given a final check for possible alpha contamination and then packaged for shipment.

A flow diagram for the above fabrication process is presented on the following page.

Fuel Element Fabrication Flow Diagram

APPENDIX II

ZPR-III Fuel Element Inspection Requirements

The quality-assurance inspection program for ZPR-III fuel elements is divided into two phases: pre-production qualification and production evaluation. The qualification program purpose is to insure that the fabricator selects adequate manufacturing equipment, institutes suitable fabrication processes, and is actually capable of producing ZPR-III fuel elements in compliance with specification and design drawing requirements. A limited number of sample fuel elements and components produced by approved reference processes will be subjected to evaluation by an independent laboratory. Production evaluation will consist of the fabricator's in-process inspection and also evaluation by an independent laboratory of approximately one out of every 100 fuel elements and components produced. In-process inspection requires no special or developmental inspection techniques or equipment.

The following outline gives the essential properties and attributes for ZPR-III fuel plates, half-jacket panels, and fuel elements. The inspection operations and an estimate of the level of inspection (Inspection Frequency) required to provide adequate quality assurance are also given.

ZPR-III Fuel Element Quality Assurance Inspection Outline

Component	Requirements	Inspection	Inspection Frequency
Fuel Plate	Scribed identification serial number.	Visual examination at 1X magnification.	100%
	Cleanliness - free from grease, oil, marking ink and all foreign materials.	Visual examination at 1X and 10X magnification.	100%
	Oxide - free from loose particulate oxide.	Visual examination at 1X magnification.	100%
	Soundness - free from surface cracks, voids, cold shuts, and porosity.	Visual examination at 1X and 10X magnification. Fuel plates shall be fractured to reveal internal defects and examined at 10X magnification.	100% 1%
	Weight - all core plates of the same nominal size shall be within 0.2 g of a fixed quantity.	Fuel plates will be weighed on an analytical balance.	100%
	Dimensional and geometric tolerances.	Fuel plates shall be measured to establish compliance with reference drawings. Length, width, and thickness shall be measured with a micrometer. Overall distortion shall be determined with knife edge and parallel plate gages. Parallelism and squareness shall be determined with dial gage and surface plate.	100%

Component	Requirements	Inspection	Inspection Frequency
Fuel Plate	Chemical content - Total Pu, U and Mo	Determined by emission spectrograph	Each casting melt
	Isotopic Pu ²³⁹ , Pu ²⁴¹ , U ²³⁵	Determined by mass spectrometer	
	Homogeneity Pu and Mo	Determined by emission spectrograph	
	Impurities Metallic and B, H, C, N, D, C F	Determined by emission spectrograph or hot vacuum extraction	
	Oxidation resistance and pyrophoricity	Exposure to circulating air for extended period	1%
	Positive coefficient of thermal expansion	Dilatometric test	1%
Jacket Panel	Surface finish - free from cracks, scratches, gouges, folds, wrinkles, stretcher strains, and bends as well as surface discoloration and oxide film	Visual examination at 1X and 10X magnification	100%
	- 2B mill finish	Comparison to visual standard	100%
	Dimensional and geometric tolerances	Panels shall be measured to establish compliance with reference drawings. Cavity length, width, and depth shall be measured with a micrometer. Edge and corner radii shall be determined with an optical projector (shadowgraph) on sections removed from sample panels. Overall length and width, and material thickness shall be determined with a micrometer.	25%
	Localized reduction in thickness of formed sections - 0.010 in (0.25 mm) minimum thickness	Filar micrometer measurement on metallographically prepared specimens removed from typical panels	4%
	Microstructure - Type 304-L - annealed and cold finished, free from laminations, cracks, and inclusions	Metallographic examination at 100X magnification of sections removed from typical panels	1%
	- ASTM grain size - number 7 to 9	Metallographic examination at 100X magnification of sections removed from typical panels	1%
	Bend test - 180° flat in longitudinal and transverse directions	Specimens removed from panels shall be bent 180° flat	1%
	Chemical content - Type 304-L	Wet analysis and spectrographic analysis to determine compliance with specification	Each coil of material
	Etched identification serial number	Visual examination at 1X magnification	100%
Fuel Element	Welds shall be "as welded" or "as-weld cast and machined" per reference drawings	Visual examination at 1X magnification	100%
	Welds shall be smooth and free from irregularities, craters, lack of fusion, cold shuts, undercutting, tungsten inclusions, excessive porosity, and oxide scale	Visual examination at 1X and 10X magnification	100%

Component	Requirements	Inspection	Inspection Frequency
Fuel Element	Surface oxidation of welds and adjacent material shall not exceed approved standards.	Visual examination at 1X magnification.	100%
	Dimensional and geometric tolerances.	Fuel elements shall be measured to establish compliance with reference drawings. Length, width, and thickness shall be measured with a micrometer. Overall distortion shall be determined with parallel plate gages. Parallelism and squareness shall be determined with dial gage and surface plate.	
	Alpha contamination - 200 cpm/61 cm ² maximum fixed count, and removable contamination less than 10 dpm/ft ² above background (or one disintegration per minute per square decimeter above background).	Measured with a gas proportional counter and scintillation chamber counter.	100%
	Jacket integrity - Helium leak test: The maximum permissible leak in the jacket cladding shall not exceed 1×10^{-8} std cc/sec of helium when tested at room temperature at a chamber pressure of 10 μ .	Fuel elements shall be tested in a vacuum chamber using a helium mass spectrometer leak detector calibrated to a sensitivity of 1×10^{-9} std cc/sec or less.	100%
	Alcohol leak test: No bubbles shall be evident when the fuel element is immersed in ethyl alcohol and the pressure over the alcohol is reduced to 2 in. (5.1 cm) mercury or less.	Fuel elements shall be tested in a chamber capable of being evacuated to 2 in. (5.1 cm) mercury pressure. The chamber shall be provided with a clear sight port for viewing the fuel plate immersed in alcohol.	100%
	Metallography - Edge welds: shall not be less than 0.010 in. (0.25 mm) thick and shall have a heat effected zone adjacent to the weld of less than 0.020 in. (0.5 mm).	Metallographically prepared sections removed from selected fuel elements shall be examined at 100X magnification and the thickness of weld measured with a filar micrometer.	5%
	Weld-cast shoes: shall not be less than 0.030 in. (0.75 mm) thick after final machining and the heat affected zone adjacent to the weld shall not exceed 0.020 in. (0.5 mm).		5%
	Radiography - Fuel plates shall be strong enough to cause a net expansion of the fuel element against the constraining force of the jacket during a power excursion.	Fuel plates shall be radiographed to confirm absence of fragmentation and minimal clearance between the jacket and the fuel plate.	2%
Weld Run-out Rod and Filler Strip	Chemical content - Type 304-L.	Wet analysis and spectrographic analysis to determine compliance with specification material.	Each lot of material