CASTING
OF
LONG AND THIN PLATES
OF
URANIUM-MOLYBDENUM ALLOYS

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ABSTRACT

This report describes the development of procedures for the vacuum induction casting of U-Mo alloys into both thin (0.010 to 0.100-in. thick) plates and long (36 in.) plates. Melting and casting cycles were developed, and casting techniques established, which resulted in sound, integral plates. These plates were evaluated by radiographic and metallographic examination, and by chemical analysis.

The results of this work indicate the feasibility of the process for the fabrication of fuel plates for nuclear reactors. The process promises a potential reduction in fabrication costs, by eliminating waste.

I. INTRODUCTION

Prior to this investigation, the as-cast dimensions of U-Mo alloy fuel plates were limited to a thickness of not less than 1/8 in. and a length of 12-1/2 in.¹ These dimensions were specified for power reactor fuel elements. However, the need for higher efficiency and lower fabrication costs prompted the initiation of a development program to determine the minimum thickness and maximum length of U-Mo alloy fuel plates that could be cast directly to size.

II. EXPERIMENTAL PROCEDURES

Two series of experiments were performed. The first was concerned with the development of an optimum technique for casting sound, integral fuel plates, ranging in thickness from 0.010 to 0.100 in. Length and width were held constant at 12-1/2 and 3 in. respectively. The second was concerned with developing an optimum technique for casting sound, integral long plates, up to 36 in. in length, while the width and thickness were held constant at 3 and 0.100 in. respectively.

Both series of experiments involved vacuum induction melting in oxide coated, bottom-pour graphite crucibles, and casting into coated graphite molds. The molds were machined from ATJ-grade graphite and vacuum outgassed at 871°C for 20 hr, prior to coating with a aqueous slurry of either MgZrO_3 or ZrO_2 (stabilized with 15 wt % Y_2O_3). MgZrO_3 was used for pouring temperatures up to 1500°C, and ZrO_2 for temperatures in excess of 1500°C. After coating, the molds were baked at 260°C for 4 hr to remove residual moisture. Typical molds are shown in Figure 1.

A. THIN PLATES

To minimize cost and time, in the development of cast thin plates (0.010 to 0.060 in. thick), a multiple cavity graphite mold was fabricated to permit simultaneous casting of two plates each of thicknesses 0.010, 0.020, 0.030, 0.040, 0.050, and 0.060 in. by 12-1/2 in. long by 3 in. wide. An exploded view of this type mold can be seen in Figure 1a.

a. Thin Plates (Components)

b. Long Plates (Assembled)

Figure 1. Molds for Casting of Plates

During the developmental phase of casting the fuel plates, it was learned that casting thin plates with the long dimension of the mold positioned vertically resulted in a severe porosity problem, due to poor venting, and mold outgassing. Radiographs of vertically cast 0.100 by 12-1/2 in. plates are shown in Figure 2a. Casting the plates horizontally eliminated this porosity, and produced consistently sound plates, as shown by the radiographs in Figure 2b. Typical 0.100-in. thick plates, from two heats poured in a horizontal position, are shown in Figure 3. In both series of experiments in this development, the graphite molds were designed and arranged in the furnace to permit casting the plates with their longest dimensions in a horizontal position.

To obtain good results, the use of mold heating coils proved essential. For the thin plate mold, a rectangular induction coil (Figure 4) was fabricated to fit the mold. The molds were heated to 927°C during melting, and maintained at this temperature until casting was complete. The heaters served two important functions: (1) they allowed further outgassing of the molds, and (2) they prevented premature solidification of the alloy during pouring.

Briefly, the melting and casting procedure consisted of: (1) combining specified quantities of U and Mo, or U, Mo, and Al, in a graphite crucible, placing the Al on the bottom, followed by the Mo and U; (2) heating the mixture to the desired pouring temperature, in the range of 1500 to 1700°C, allowing sufficient time for homogenization; and (3) casting into preheated molds by lifting a stopper-rod away from the pour hole at the base of the crucible. Alloys which were cast were U - 3.8 wt % Mo - 0.15 wt % Al, U - 10 wt % Mo, and U - 12 wt % Mo. The average charge melted for thin plates was 10 kg. A typical melting and casting cycle for thin plates is given in Table I.

B. LONG PLATES

Due to furnace limitations, the maximum length of plate castings was 36 in. The mold length was 40 in.; and two plates, 36 in. by 3.00 in. by 0.100 in., could be cast per heat, using an average charge of 15 kg. Figure 5 shows the component parts of the mold, and Figure 2 shows the assembled mold. For the long plate mold, a molybdenum filament, Inconel-sheathed, rectangular resistance coil was used, as shown in Figure 6.

The procedure for melting and casting long plates is essentially the same as that described previously for thin plates. A typical melting and casting cycle is given in Table II.

a. Vertically Cast

b. Horizontally Cast

Figure 2. Radiographs of Thin Plates

Figure 3. Horizontally Cast Thin Plates

Figure 4. Heating Coil for Thin Plate Mold

Figure 5. Components of Mold for Casting Long Plates

Figure 6. Heating Coil for Long Plate Mold

TABLE I
TYPICAL MELTING AND CASTING CYCLE FOR THIN PLATES
(Average Charge 10 kg)

Time	Remarks	Meter Readings					Temperature	
		Voltage (v)	Current (amp)	Power (kw)	KVAR	Vacuum (μ)	Metal ($^{\circ}$ C)	Mold ($^{\circ}$ C)
9:00	Power on	365	65	20	+6	70	Room	Room
9:25	Melting Started Reduced power	315	55	15	+6	140	1115	288
9:55	No change	315	55	15	+6	100	1315	593
10:25	Reduced power	275	45	10	+6	85	1400	750
10:50	Increased power	315	45	15	+6	70	1350	807
11:15	Increased power	345	54	16	+6	60	1405	899
11:25	Increased power	390	62	20	+7	65	1450	927
11:30	Poured charge					90	1500	927

NOTE: Temperature of charge obtained with Optical Pyrometer
Temperature of mold obtained with Thermocouple (CA)

TABLE II
TYPICAL MELTING AND CASTING CYCLE FOR LONG PLATES
(Average Charge 15 kg)

Time	Remarks	Meter Readings					Temperature	
		Voltage (v)	Current (amp)	Power (kw)	KVAR	Vacuum (μ)	Metal ($^{\circ}$ C)	Mold ($^{\circ}$ C)
2:00	Power	235	80	20	+3	90	Room	Room
2:30	Melting started Reduced power	210	72	15	+1	160	1115	50
2:45	Reduced power	190	58	10	+1	170	1255	114
3:15	No change	190	58	10	+1	180	1270	405
3:35	Increased power	220	71	15	+1	170	1300	816
3:45	Increased power	260	81	20	+1	170	1450	863
3:55	No change	260	81	20	+1	165	1480	920
4:05	Increased power	296	90	25	+1	170	1550	927
4:10	No change	296	90	25	+1	170	1580	927
4:15	Poured charge						1600	927

III. EVALUATION PROCEDURES

A. RADIOGRAPHIC INSPECTION

All castings were radiographically examined for internal defects, using a cobalt-60 source.

B. CHEMICAL ANALYSIS

The methods used to quantitatively determine each constituent in the raw material and castings are given in Table III.

TABLE III
QUANTITATIVE METHODS USED TO OBTAIN
ANALYSIS OF U-Mo ALLOYS

Element	Method
Al	Volumetric
C	Conductometric
O	Vacuum Fusion
N	Kjeldahl
Mo	X-Ray Fluorescence
Impurities	Emission Spectrograph
U	Balance (By Difference)

C. METALLOGRAPHY

Sections of plates were prepared for metallographic evaluation by electropolishing, followed by electroetching. Procedures for polishing and etching had to be developed to correspond with the etching characteristics of the alloys cast. These procedures are given in Table IV.

TABLE IV
ELECTROPOLISHING AND ELECTROETCHING PROCEDURES
FOR U-Mo ALLOYS

Nominal Alloy	Solution	Current Density (amp/cm ²)	Time (sec)	Temp (°C)	Operation
U - 3.8 Mo - 0.15 Al	H ₃ PO ₄ -8 parts C ₂ H ₅ OH-5 parts Glycerine-5 parts	2.5	20	20	Electropolish
U - 10 to - 12 Mo		4.0	20	20	Electropolish
U - 3.8 Mo - 0.15 Al	10% Oxalic Acid Soln	0.5	8-12	20	Electroetching
U - 10 to - 12 Mo		0.8	15-25	20	Electroetching

Samples were rinsed in a glycerine-ethyl alcohol solution after each operation.

IV. RESULTS AND DISCUSSION

A. THIN PLATES

1. Casting

The degree of success in casting sound, integral plates, 0.010 to 0.060 in. thick, varied with the weight percent of Mo in the alloy, the degree of superheat (pouring temperature), and most significantly, the plate thickness. Figure 7a shows the results, and a complete comparison is given in Table V.

TABLE V
PERCENT OF MOLD CAVITY FILLED (AVERAGE)

Alloy	Plate Thickness (in.)						Pouring Temp (°C)
	0.010	0.020	0.030	0.040	0.050	0.060	
U-3.8 Mo-0.15 Al	30	70	95	100	100	100	1500
U-3.8 Mo-0.15 Al	40	80	100	100	100	100	1600
U-10 Mo	0	20	70	95	100	100	1500
U-10 Mo	5	60	80	100	100	100	1615
U-12 Mo	0	0	30	50	90	95	1500

The major casting defects encountered, when the mold cavity was not completely filled, were small gas pits and cold shuts. The surfaces of the resultant plates were good, as shown in Figure 7b.

2. Radiography

The radiographs shown in Figure 4 demonstrate the internal soundness of horizontally cast plates. Such soundness was found to be typical, for plate thicknesses of 0.040 in. and greater, after the correct pouring temperature had been established.

3. Chemical Analysis

The attainable composition homogeneity was determined from the results of the typical analyses shown in Table VI.

a. Showing Degree of Success in Casting

b. Showing Surfaces of Plates

Figure 7. Thin Plates

TABLE VI
COMPOSITION OF THIN PLATES (wt %)

Nominal Alloy	Element	End		Middle		End	
		Top	Bottom	Top	Bottom	Top	Bottom
U - 3.8 Mo - 0.15 Al	Mo	3.82	3.84	3.84	3.81	3.80	3.81
	C	0.048	0.047	0.041	0.049	0.050	0.042
	Al	0.17	0.15	0.16	0.16	0.16	0.13
U - 10 Mo	Mo	10.26	10.10	10.30	10.40	10.26	10.30
	C	0.078	0.077	0.076	0.078	0.077	0.064

4. Microstructure

The microstructures of U - 3.8 Mo - 0.15 Al thin plates, as cast in a multiple-cavity graphite mold at 1500°C, are shown in Figure 8. The presence of Al in the ternary appears to yield a precipitate which exists both inter- and intragranular, and is probably the intermetallic UAl_2 . A comparison was made of the grain size [mean grain diameter (M.G.D.)], top, and bottom with plate thicknesses. As expected, the top is larger than the bottom, for each plate thickness shown. However, the difference is not consistent, and appears to be a maximum at 0.040 in. but decreases with increasing plate thickness.

The microstructures of U - 10 wt % Mo thin plates, cast in the same mold at 1615°C, are shown in Figure 9. Randomly dispersed spots are a combination of inclusions and etching pits. The etching pits were a more common occurrence with the higher Mo-content uranium alloys. A grain size comparison with plate thickness gave the expected, top grains larger than bottom grains. However, the difference was found to be much less than for the U - 3.8 Mo - 0.15 Al alloy.

Typical microstructures of 0.100-in. thick plates, cast horizontally, 15 per heat, are shown in Figure 10. In contrast, the microstructures of 0.100-in. thick plates, cast vertically, are shown in Figure 11. There is little doubt that, on the basis of grain size, the metallurgical properties of horizontally cast plates would tend to be more uniform throughout than those of vertically cast plates.

(1.) Top (M.G.D. = 0.0725 mm)

75X

(2.) Bottom (M.G.D. = 0.0389 mm)

75X

a. 0.020-in. Thick Plate

Figure 8. Photomicrographs of U - 3.8 Mo - 0.15 Al Thin Plates

(1.) Top (M.G.D. = 0.1515 mm)

75X

(2.) Bottom (M.G.D. = 0.0533 mm)

75X

b. 0.030-in. Thick Plate

Figure 8. Photomicrographs of U - 3.8 Mo - 0.15 Al Thin Plates (Continued)

(1.) Top (M. G. D. = 0.2380 mm)

75X

(2.) Bottom (M. G. D. = 0.0705 mm)

75X

c. 0.040-in. Thick Plate

Figure 8. Photomicrographs of U - 3.8 Mo - 0.15 Al Thin Plates (Continued)

(1.) Top (M. G. D. = 0.1430 mm)

75X

(2.) Bottom (M. G. D. = 0.1473 mm)

75X

d. 0.050-in. Thick Plate

Figure 8. Photomicrographs of U - 3.8 Mo - 0.15 Al Thin Plates (Continued)

(1.) Top (M.G.D. = 0.1225 mm)

65X

(2.) Bottom (M.G.D. = 0.0942 mm)

65X

e. 0.060-in. Thick Plate

Figure 8. Photomicrographs of U - 3.8 Mo - 0.15 Al Thin Plates (Continued)

a. 0.010-in. Thick Plate - Top
(M.G.D. = 0.0933 mm)

88X

b. 0.030-in. Thick Plate - Top
(M.G.D. = 0.0478 mm)

55X

Figure 9. Photomicrographs of U - 10 Mo Thin Plates

(1.) Top (M.G.D. = 0.0620 mm)

75X

(2.) Bottom (M.G.D. = 0.0363 mm)

80X

c. 0.040-in. Thick Plate

Figure 9. Photomicrographs of U - 10 Mo Thin Plates (Continued)

(1.) Top (M.G.D. = 0.0586 mm)

75X

(2.) Bottom (M.G.D. = 0.0350 mm)

75X

d. 0.050-in. Thick Plate

Figure 9. Photomicrographs of U - 10 Mo Thin Plates (Continued)

(1.) Top (M. G. D. = 0.0555 mm)

80X

(2.) Bottom (M. G. D. = 0.0414 mm)

80X

e. 0.060-in. Thick Plate

Figure 9. Photomicrographs of U - 10 Mo Thin Plates (Continued)

a. Top

100X

b. Bottom

100X

Figure 10. Photomicrographs of Horizontally Cast U - 3.8 Mo - 0.15 Al
0.100-in. Thick Plates

a. Top

100X

b. Bottom

100X

Figure 11. Photomicrographs of Vertically Cast U - 3.8 Mo - 0.15 Al
0.100-in. Thick Plates

B. LONG PLATES

1. Casting

The development of an optimum casting technique for long plates was extrapolated from the effort expended on thin plates. The length of the castings produced was maximized at 36 in., due to furnace limitations, while the thickness was constant at 0.100 in. Although the pouring temperature was varied from 1500 to 1700°C, and the composition of Mo varied to 10 wt %, the entire 36-in. length of each mold cavity filled with relative ease during each pouring. The major problem encountered with long plates was porosity. The first series of long plates were cast in graphite molds (See Figures 1b and 5), not preheated. The result indicated very severe porosity throughout each plate (See Figure 12a). This was probably due to outgassing of the mold when hot molten metal contacted the cold graphite. Using a mold preheated to 927°C very nearly eliminated the porosity problem. The preheating was accomplished by the use of a rectangular resistance coil shown in Figure 6. The resultant plates are shown in Figure 12b.

2. Radiography

The radiographs shown in Figure 2 are representative of those obtained for the long plate castings, with the only difference being in the length.

3. Chemical Analysis

Typical analyses of long plates, demonstrating the degree of homogeneity achieved by the process, are given in Table VII.

TABLE VII
COMPOSITION OF LONG PLATES
(wt %)

Nominal Alloy	Element	End		Middle		End	
		Top	Bottom	Top	Bottom	Top	Bottom
U - 3.8 Mo - 0.15 Al	Mo	3.74	3.72	3.78	3.77	3.82	3.83
	C	0.041	0.043	0.051	0.051	0.075	0.042
	Al	0.19	0.16	0.20	0.16	0.19	0.14
U - 10 Mo	Mo	10.13	10.05	10.20	10.40	9.90	9.87
	C	0.085	0.082	0.091	0.081	0.086	0.090

a. Cast in Mold Not Preheated

b. Cast in Preheated Mold

Figure 12. Long Plates, Showing Surfaces Resulting From Different Casting Conditions

4. Microstructure

The microstructure of plates, 36 in. long and 0.100 in. thick, was found to be similar to that of the 0.100 in. plates of the ternary cast horizontally, shown in Figure 10. Some variation in grain size was observed, from center to end, the center being 1.5 times as large as the end. This is believed due to a mold temperature gradient from center to end.

V. CONCLUSIONS

Using the procedure described, sound, integral fuel plates, 12-1/2 in. long by 3.00 in. wide, of U - 3.8 Mo - 0.15 Al and U - 10 Mo, may be gravity cast, as thin as 0.040 in., in multiple cavity graphite molds. Plates 36 in. long by 3 in wide by 0.100 in. thick can be cast by the methods described.

Since U-Mo fuel plates, 36 in. long by 3.00 in. wide by 0.100 in. thick, were cast with relative ease, it appears likely that sound castings, 5 ft long, are feasible.

ZrO₂, stabilized with 15 wt % Y₂O₃, appears to offer good protection for graphite components in contact with molten U-Mo alloys, for all temperatures up to 1700°C. MgZrO₃ offers good protection, for temperatures up to 1500°C.

The feasibility of casting sound thin plates and long plates of U-Mo fuel materials implies a potential reduction of fabrication costs, by eliminating the waste inherent in wrought methods for producing similar-dimensioned fuel.

Further effort is recommended, to refine the casting processes developed here and create a capability for reproducing, when necessary, large quantities of sound, integral fuel plates.

REFERENCES

1. M.H. Binstock and J.A. Stanley, "Casting Development for Uranium-Molybdenum Alloy Shapes," NAA-SR-4030 (November 15, 1959)