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URANIUM ALLOYS: THEIR PREPARATION AND FABRICATION
AS ZIRCALOY-2 CLAD FUEL RODS

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ABSTRACT

Alloys of uranium-niobium, uranium-niobium-platinum, uranium-molybdenum, and uranium-molybdenum-platinum were successfully duplex melted. These alloys were co-extruded in Zircaloy-2, cold drawn, and swaged to 0.304-in. diam rods. Several of the rods had an intermediate layer of a metal (Nb, Mo, Pd, or Pt) or of an alloy (U-Nb or U-Mo-Pt) between the fuel and the Zircaloy-2 cladding. Photomicrographs of the alloys and of the fuel rods before and after cold working are presented.

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URANIUM ALLOYS: THEIR PREPARATION AND FABRICATION
AS ZIRCALOY-2 CLAD FUEL RODS

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INTRODUCTION

As part of a general program to determine the nature of the cladding-to-fuel bond and the mechanism of fuel rod corrosion, fuel rods of various compositions were prepared. In an attempt to fabricate rods with improved corrosion resistance, some of the fuel rods were assembled with an intermediate metallic layer between the fuel and the cladding. This report describes the melting characteristics and metallographic structure of certain fuel alloys and the fabrication of clad rods of these alloys. The work was initiated in October, 1954 and completed in December, 1954.

PREPARATION OF FUEL ALLOYS

Melting and Casting

All of the fuel alloys were induction melted and cast into 1 1/4-in. diam molds. The uranium used was Fernald strip. This material was prepared by vacuum induction melting of uranium derbies in zirconia-washed graphite crucibles, casting, then hot rolling to 0.3-in. thick strip. The carbon content of the uranium was 40 ppm. Molybdenum and niobium were added in the form of 1/4-in. diam rods chopped into approximately 1-in. lengths. Platinum was added as 1/4-in. squares of platinum sheet. Induction melting data for the alloys are given in Table I.

Uranium-Niobium Alloys

Uranium alloys with 8, 10, and 12 w/o niobium were prepared.

U-8 w/o Nb - The first melt of U-8 w/o Nb was superheated to 1560°C and cast at 1500°C into a water-cooled copper mold. The metal seemed sluggish when poured and the resulting ingot was full of severe cold shuts and had to be scrapped.

A second melt of this alloy was superheated to 1610°C and cast at 1575°C. The metal was fluid at this temperature with no apparent sluggishness, and produced a satisfactory ingot.

U-10 w/o Nb - Five melts of this composition were cast. These alloys were superheated between 1675° and 1700°C and cast into water-cooled copper molds. At these temperatures the metal was fluid and it produced sound ingots. Four of the castings had rough sides but were acceptable as electrodes for remelting.

Although usable castings were obtained, the water-cooled copper mold is not suitable for casting U-10 w/o Nb alloy. Two of the five melts burned through the molds near the top. All of the melts attacked the copper so that the molds had to be sawed apart to extract the ingots. Later investigations have shown split graphite molds to be quite satisfactory for casting this alloy.

U-12 w/o Nb - One 12 w/o Nb ingot was made by superheating the melt to 1750°C and casting at 1740°C into a water-cooled copper mold having a 5/8-in. thick graphite liner of 1 1/4-in. ID. This liner was necessary to prevent burn-through at the high casting temperature. The alloy was fluid and poured to yield a smooth, sound casting.

Uranium-Niobium-Platinum

One melt of U-10 w/o Nb-1 w/o Pt was made and cast into the same type of mold arrangement used for the U-12 w/o Nb casting. The melt was superheated to 1730°C and cast at 1700°C. Although it appeared sluggish at this temperature,

it produced a good casting. The addition of 1 w/o Pt had no apparent effect on the melting characteristics of U-10 w/o Nb alloy.

Uranium-Molybdenum

No unusual results were noted in melting uranium-molybdenum alloys of 10.5, 12, and 13.5 w/o Mo. The alloys were superheated to 1475°C, 1480°C, and 1555°C respectively and cast into 1 1/4-in. diam water-cooled copper molds. This work is described in WAPD-121.

Uranium-Molybdenum-Platinum

One alloy of U-8 w/o Mo-1 w/o Pt and one of U-12 w/o Mo-0.50 w/o Pt were made. Each melt was superheated about 50°C more than the comparable binary U-Mo alloy because it appeared too viscous to pour at the temperatures used for casting the binary alloy. The melts were poured at 1410°C and 1450°C respectively; both of the castings were free of cold shuts and had excellent surface finish.

One alloy of U-15 w/o Mo-5 w/o Pt was made in order to fabricate an intermediate layer between the fuel and the Zircaloy-2 cladding. The melt was superheated to 1750°C and cast, with no temperature cut-back, into the same mold arrangement used for the U-12 w/o Nb alloy. The melt appeared sluggish at this temperature but yielded a good casting.

Observations made during melting of these alloys indicated that addition of small amounts of platinum to U-Mo alloys of 8 to 15 w/o Mo tends to raise the liquidus and/or increase the viscosity of the molten metal.

Remelting

Each induction casting was consumably remelted, in an atmosphere of approximately 50-50 argon and helium at 20-in. Hg, into a water-cooled copper

mold 2 5/16-in. diam. Most of the consumably remelted billets were arc-melted on the top and bottom with a tungsten-tipped electrode to eliminate any small holes. The top and bottom of each billet were sampled for chemical and metallographic analysis. Consumable remelt data are listed in Table II and chemical analyses are shown in Table III.

Figs. 1 and 4 are typical photomicrographs of uranium-10.5 w/o and 12 w/o Mo alloys. The small specks throughout the alloy matrix are inclusions of carbides, nitrides, oxides, etc.

Fig. 2 is a photomicrograph of the U-8 w/o Mo-1 w/o Pt alloy and Fig. 3 one of the U-12 w/o Mo-0.5 w/o Pt alloy. These photomicrographs indicate that there are few, if any, metallographic differences between binary alloys of U-8 to 12 w/o Mo and uranium alloys of similar molybdenum content with small platinum additions.

Fig. 5 is a photomicrograph of the U-15 w/o Mo-5 w/o Pt alloy. The difference in structure between top and bottom can be attributed to the fact that the bottom of the billet was remelted with a tungsten-tipped electrode whereas the top was not. The faster cooling rate of the arc-melted bottom probably accounts for the fact that the bottom does not exhibit as severe coring as the top. Furthermore, there was more platinum in the top of the billet--the top analyzed 5.16 w/o Pt and the bottom 4.86 w/o. A 1/4-in. thick slice cut off the top with an abrasive cut-off wheel cracked into three pieces while lying on a table, an indication of severe residual stresses. The hardness of the alloy was 40 Rockwell C, which is not exceptionally hard for a uranium alloy of this molybdenum content. To prevent cracking of the tube that was to be machined from this billet, the remelted billet was annealed in air for 2 hr at 1400°C. The hardness decreased to about 34 Rockwell C, and an oxide layer

approximately 0.01 in. thick formed on the billet. No machining difficulties were encountered in the fabrication of the tube.

Figs. 6a and 6b are photomicrographs of the U-10 w/o Nb-1 w/o Pt alloy. The dark areas are transformed alpha phase (determined by X-ray diffraction techniques). At this time no reason can be given to explain the presence of more alpha phase in the top of the ingot than in the bottom. The top of this ingot analyzed 1.12 w/o Pt and the bottom 1.59 w/o. Apparently a third phase exists which appears as the light gray constituent; there are, however, no indications as to what this might be.

Figs. 7a and 7b are photomicrographs of the U-8 w/o Nb alloy. The dark areas are transformed alpha phase. X-ray diffraction analysis indicates that the bottom contained about 5 per cent alpha and the top about 10 per cent. Again this difference can be attributed to the fact that the bottom was arc-melted whereas the top was not.

Figs. 8 and 9 show typical structures of U-10 w/o Nb alloys. According to X-ray diffraction analysis, the amount of transformed alpha varies from 30 to 50 per cent. Careful examination of Figs. 7a, 8a, and 8b indicates that a substructure underlies the primary grains. The top of Ingot J852, which appeared almost identical to that of Ingot J851 (see Fig. 8b), was over-etched by the cathodic vacuum technique to bring out this substructure. Fig. 9b is an excellent photomicrograph of this structure, showing the severe coring in these U-10 w/o Nb alloys.

Figs. 10a and 10b are photomicrographs of the U-12 w/o Nb alloy. Basically it is the same as the U-10 w/o Nb alloys except that the amount of transformed alpha phase varies from 50 to 60 per cent.

CLADDING OF FUEL INGOTS

After remelting, the billets were clad with Zircaloy-2. Six ingots of U-10.5 w/o Mo alloy were assembled with intermediate metallic barrier layers between the alloy and the Zircaloy-2. One ingot of U-10 w/o Nb was also assembled with an intermediate metallic layer. Assembly data are tabulated in Table IV.

Intermediate layers of the metals, platinum, niobium, and molybdenum were simply single pieces of metal foil wrapped around the ingot. The foil-wrapped ingot was then inserted in a Zircaloy-2 cup of 1.893-in. ID and 2.409-in. OD. However, the only palladium foil available was in very small pieces. Although these pieces were overlapped about 1/4 in., the foil shifted as the fuel billet was forced into the Zircaloy-2 cup, and the clad ingot so formed was not satisfactory.

Barrier layers of U-10 w/o Nb and U-15 w/o Mo-5 w/o Pt were made by machining sleeves from the consumably remelted ingots of these alloys and forcing them over the fuel billets. The sleeves were hollow cylinders of 1.892-in. OD and 1.833-in. ID. They made excellent barrier layers because of their uniform thickness. However, since only 4 per cent of the ingot is utilized in the sleeve, this procedure is not economical. If these sleeves were to be used in quantity, development of a process for forming them from sheet stock would be necessary.

After cladding, the Zircaloy-2 sheaths were closed, welded shut, coated with water glass, baked to remove water of hydration from the coating, and enclosed in copper jackets for extrusion. The water glass was applied in an attempt to prevent alloying of copper and Zircaloy-2 during extrusion. The coating proved effective since less than 5 per cent of the rod surface showed alloying after extrusion.

FABRICATION OF RODSExtrusion

The copper-jacketed billets were then extruded into rods. Extrusion data are listed in Table V with the rods listed in the order of extrusion.

Because no previous extrusion data were available for the niobium alloys, high extrusion temperatures were used for the first extrusions to afford a better chance of obtaining rod. Since extrusion tonnages at the high temperatures were not excessive, the temperature was lowered on successive runs.

After extrusion the copper jackets were removed by pickling in an aqueous solution of nitric acid (50 v/o HNO_3). Much of the copper, however, could simply be stripped off in areas where it had not broken through the water glass.

Each rod was sectioned from the front end into 16 in., 36 in., 48 in., and tail sections. The 16-in. and 48-in. sections were bright etched in an aqueous solution of hydrofluoric and nitric acids (5 v/o HF, 35 v/o HNO_3). The etching behavior of the rod surface indicated that no alloying had occurred between the copper and Zircaloy-2. These sections were radiographed to determine the fuel-cladding configuration, which was about the same as Zircaloy-2 clad U-12 w/o Mo rods. Fig. 27c is a photomicrograph at 7 diameters of a rod with a U-10 w/o Nb intermediate layer.

Drawing

Each 36-in. section was heated in air for approximately 20 min at 1250° F to oxidize the Zircaloy-2 and thereby prevent stripping the molybdenum disulfide lubricant from the rods during drawing.

About 12 in. at the end of each 36-in. section was heated in a salt

bath at 1650°F and swaged to point the end so that it could be led through the drawing die; this operation was necessary before each drawing pass. These rod sections were drawn through 0.437 in., 0.375 in., and 0.328 in. diam dies, effecting reductions of 18.6, 26.5, and 24.1 per cent respectively.

Rod Mo3a2-9 (U-10.5 w/o Mo fuel with U-15 w/o Mo-5 w/o Pt intermediate layer) was drawn through 0.437-in. and 0.375-in. dies only. It broke into three pieces while being drawn through a 0.375-in. die.

Drawing tonnages averaged about 6 tons for the first pass, 5 1/2 tons for the second pass, and 4 1/2 tons for the final pass. After cold drawing, the rods were sandblasted to remove the drawing lubricant and oxide scale. They were then swaged to 0.304-in. diam, a reduction of 14 per cent. Swaging straightened the rod and improved the surface finish.

Photomicrographs of the clad fuel rods are given as Figs. 11a through 27b. In each case the "a" figure represents the rod in the as-extruded condition, and the "b" figure the rod after drawing and swaging. Particular attention should be given to the uniformity of the diffusion zones and intermediate layers after both extrusion and cold working.

Fig. 13b shows that rod Mo3a1-4 was unbonded after cold work; therefore, the metallurgical bond between the Zircaloy-2 cladding and fuel must have been ruptured by the cold working. Figs. 20a and 20b show that rod Mo3a2-6 was unbonded after extrusion and cold drawing, probably because the intermediate layer of palladium foil shifted. Fig. 22a shows that rod Mo3a2-8, which had a platinum layer, was not bonded after extrusion. As can be seen in Fig. 22b, cold working of this rod established at least a mechanical bond between the cladding, intermediate layer, and fuel. Heating specimens from the as-extruded

rod for 24 hr at 900°C in vacuo produced no interdiffusion between cladding, intermediate layer, and fuel, but similar heating of specimens from the cold-worked rod produced an increase in thickness of the diffusion zone.

Fig. 27c is a photomicrograph of rod Mo3a2-13 after extrusion. The fuel-cladding configuration is typical of the rods in which intermediate layers were used. Fig. 27d is a photomicrograph of the same rod after drawing and swaging, showing that the fuel tends to round after drawing. This rounding is a common phenomenon and has been observed in many rods.

After swaging the rods were etched in an aqueous solution of hydrofluoric and nitric acids (5 v/o HF, 35 v/o HNO₃) to obtain bright, smooth surfaces.

CONCLUSIONS

Uranium-niobium alloys up to 12 w/o Nb can be successfully vacuum induction melted. (Previously reported in references 1 and 2).

On the basis of the very limited data obtained in this work, it appears that platinum additions tend to segregate slightly in the melt. Chemical analysis and metallographic examination confirm this. Changes in melting techniques such as longer alloying time or double induction melting would probably overcome this difficulty.

Uranium alloys of 10 w/o niobium or greater should be cast into graphite molds instead of water-cooled copper molds to prevent burning through the mold wall.

As indicated by the lower pressures required during extrusion and drawing, uranium alloys of 8 to 12 w/o Nb are easier to extrude and draw than alloys of 10.5 to 12 w/o Mo.

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TABLE I
INDUCTION MELTING DATA

<u>Ingot No.</u>	<u>Nominal Composition</u>	<u>Alloy Temp. (°C)</u>	<u>Crucible</u>	<u>Condition</u>
Z114	12 w/o Mo	1480	ZrO ₂ washed graphite	Good
Z113	10.5 w/o Mo	1450	ZrO ₂ washed graphite	Good
Z119	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z121	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z124	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z123	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z120	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z122	10.5 w/o Mo	1475	ZrO ₂ washed graphite	Good
Z115	13.5 w/o Mo	1635	ZrO ₂ washed graphite	Scrap ¹
Z117	13.5 w/o Mo	1655	BeO	Good
Z108	8 w/o Mo-1 w/o Pt	1415	BeO	Good
Z107	12 w/o Mo-0.5 w/o Pt	1525	BeO	Good
Z109	10 w/o Nb	1700	BeO	Good
Z125	10 w/o Nb-1 w/o Pt	1730	BeO	Scrap ²
Z126	10 w/o Nb-1 w/o Pt	1730	BeO	Good
Z105	8 w/o Nb	1560	BeO	Scrap ³
Z106	8 w/o Nb	1610	BeO	Good
Z111	10 w/o Nb	1685	BeO	Good
Z112	10 w/o Nb	1700	BeO	Good
Z132	12 w/o Nb	1750	BeO	Good
Z127	15 w/o Mo-5 w/o Pt	1745	BeO	Scrap ²
Z128	15 w/o Mo-5 w/o Pt	1750	BeO	Good
Z110	10 w/o Nb	1700	BeO	Good
Z166	10 w/o Nb	1675	BeO	Good

All molds were water-cooled copper except for casting of Ingots Z125, Z126, Z127, Z128, and Z132. See text for complete description.

Zirconia-washed stopper rods were used with zirconia-washed crucibles. Thoria stopper rods were used with beryllia crucibles. The weight of each charge was approximately 15.5 lb.

TABLE II
CONSUMABLE REMELT DATA

<u>Induction Melt No.</u>	<u>Consumable Remelt No.</u>	<u>Amps</u>	<u>Volts</u>	<u>Top Remelted</u>	<u>Bottom Remelted</u>	<u>Hardness</u>	
						<u>Top</u>	<u>Bottom</u>
Z114	J848	1100	36	Yes	Yes	341	341
Z113	J843	1100	36	Yes	Yes	302	302
Z108	J825	1000	36	Yes	Yes	269	269
Z107	J824	1000	36	Yes	Yes	321	321
Z117	J828	1000	36	Yes	Yes	381	341
Z109	J813	1000	36	Yes	Yes	321	321
Z126	J870	1250	32	Yes	Yes	321	321
Z106	J840	1000	18	No	Yes	321	---
Z111	J851	1250	34	Yes	Yes	285	285
Z112	J852	1250	34	Yes	Yes	302	302
Z119	J858	950	18	No	No	302	302
Z132	J915	1700	35	Yes	Yes	---	302
Z121	J884	1000	34	Yes	Yes	302	302
Z124	J862	1150	35	Yes	Yes	311	302
Z128	J869	1000	36	No	Yes	375	---
Z123	J886	1000	34	Yes	Yes	302	321
Z110	J842	1100	36	No	No	302	302
Z120	J888	1000	34	Yes	Yes	302	302
Z122	J892	1000	34	Yes	Yes	321	321
Z166	J958	1400	33	Yes	Yes	302	302

Melting atmospheres were 20 in. of 50-50 helium and argon. Hardness readings are Bhn with a 3000 kg load.

TABLE III
CHEMICAL ANALYSIS

<u>Ingot No.</u>	<u>Mo Top</u>	<u>Mo Bottom</u>	<u>C Top</u>	<u>C Bottom</u>	<u>Nb Top</u>	<u>Nb Bottom</u>	<u>Pt Top</u>	<u>Pt Bottom</u>
J828	13.3	12.6	0.018	0.095				
J848	12.0	12.0	0.020	0.072				
J843	10.5	10.6	0.014	0.018				
J824	12.2	12.1	0.010	0.019			0.51	0.56
J858	10.5	10.5	0.026	0.018				
J884	10.5	10.4	0.036	0.044				
J862	10.4	10.3	0.032	0.024				
J886	10.5	10.5	0.046	0.023				
J888	10.3	10.3	0.019	0.055				
J892	10.5	10.5	0.033	0.062				
J825	8.0	----	0.012	-----			1.02	
J869	14.8	14.5	0.012	0.014			5.0	3.2
J870			0.075	0.048	10.6	9.9	1.12	1.59
J813					10.3			
J840			0.018	0.014	8.3	8.2		
J851			0.018	0.020	10.7	10.4		
J852			0.023	0.019	10.2	10.1		
J915			0.022	0.028	12.3	12.0		
J958			0.017	0.021	10.2	10.4		
J842			0.009	0.026	10.5	9.9		

Molybdenum values are within $\pm 3\%$ of the amount reported. Carbon values are within ± 40 parts per million. The accuracy of the niobium and platinum determinations is unknown.

TABLE IV
ASSEMBLY DATA

<u>Ingot No.</u>	<u>Nominal Composition</u>	<u>Fuel:Clad Intermediate Layer</u>	<u>Rod No.</u>
J915	12 w/o Nb	None	Mo3a2-7
J852	10.5 w/o Mo	0.030-in. cylinder of J958	Mo3a2-13
J840	8 w/o Nb	None	Mo3a2-3
J851	10 w/o Nb	None	Mo3a2-4
J852	10 w/o Nb	None	Mo3a2-5
J842	10 w/o Nb	None	Mo3a2-11
J813	10 w/o Nb	0.010-in. Nb foil	Mo3a2-1
J870	10 w/o Nb-1 w/o Pt	None	Mo3a2-2
J858	10.5 w/o Mo	0.0025-in. Pd foil	Mo3a2-6
J884	10.5 w/o Mo	0.005-in. Pt foil	Mo3a2-8
J886	10.5 w/o Mo	0.010-in. Nb foil	Mo3a2-10
J888	10.5 w/o Mo	0.010-in. Mo foil	Mo3a2-12
J862	10.5 w/o Mo	0.030-in. cylinder of J869	Mo3a2-9
J848-1	12 w/o Mo	None	Mo3a1-1
J843	10.5 w/o Mo	None	Mo3a1-2
J848-2	12 w/o Mo	None	Mo3a1-3
J825	8 w/o Mo-1 w/o Pt	None	Mo3a1-4
J824	12 w/o Mo-0.5 w/o Pt	None	Mo3a1-5
J828-1 ¹	13.5 w/o Mo	None	Mo3a1-6
J828-2 ¹	13.5 w/o Mo	None	Mo3a1-7

Zircaloy-2 Cup Dimensions

OD 2.409 in. Length - 3.500 in.
ID 1.893 in. Depth of Wall - 3.250 in.

Billet Dimensions

OD (Includes Barrier Layers) 1.892 in.
Length - 3.250 in.

Copper jackets of 0.062-in. wall thickness covered Zircaloy-2.
Total length of assembly - 7 in.

1. Fuel was 1.203-in. diam by 3.000 in. long. Zircaloy-2 cups were 1.469-in. in diameter.

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TABLE V
EXTRUSION DATA

Rod No.	Filler	Ingot No.	Load Start	Load Running	Ram Speed	Loading Time	Temp. (°F)
1 Mo3a1-5	13.5 w/o Mo	J828-1	175	165	50	13	1950
1 Mo3a1-6	13.5 w/o Mo	J828-1	180	160	60	15	1945
Mo3a2-3	8 w/o Nb	J840	290	270	30-35	10	1750
Mo3a2-4	10 w/o Nb	J851	260	220	63	--	1750
Mo3a2-5	10 w/o Nb	J852	290	270	34	6	1675
Mo3a2-11	10 w/o Nb	J842	300	280	24-34	10	1595
Mo3a2-1	10 w/o Nb + Nb IL	J813	310	290	30-35	9	1590
Mo3a2-2	10 w/o Nb-1 w/o Pt	J870	290	280	20-33	10	1620
Mo3a2-6	10.5 w/o Mo + Pd IL	J858	380	350	20-33	8	1580
Mo3a2-8	10.5 w/o Mo + Pt IL	J884	350	330	20-33	--	1615
Mo3a2-10	10.5 w/o Mo + Nb IL	J886	380	350	30-40	--	1580
Mo3a2-12	10.5 w/o Mo + Mo IL	J888	360	340	21-31	9	1610
Mo3a2-9	10.5 w/o Mo + J869 IL	J862	390	360	20-45	8	1580
Mo3a1-1	12 w/o Mo	J848-1	400	370	20-38	9	1595
Mo3a1-2	10.5 w/o Mo	J843	380	350	20-35	9	1590
Mo3a1-3	12 w/o Mo	J848-2	440	410	20-30	--	1615
Mo3a1-4	8 w/o Mo-1 w/o Pt	J825	360	330	20-38	9	1580
Mo3a1-5	12 w/o Mo-0.5 w/o Pt	J824	420	380	28-38	--	1610
Mo3a2-7	12 w/o Nb	J915	350	320	30-40	10	1600
Mo3a2-13	10.5 w/o Mo + J958 IL	J892	400	370	30-40	9	1610

Rods are tabulated in the order in which they were extruded.

Die - 0.498-in. diam chromium plated
Heating Time - 15 min
Salt Bath - Chloride
Nose Plug - Copper
Ram Speed - inches per minute
Load - Tons

Lubricant - "Led-Plate"
Container Temp. - 750 F
Temp. - Degrees Fahrenheit
Loading Time - Seconds
Cut-Off - Copper
IL - Intermediate Layer

1. Die Size - 0.314-in. diam, heating time 9 min, other data were the same.

SECRET

Fig. 1a

Bottom

Fig. 1b

Top

Ingot J843, U-10.5 w/o Mo, used for rod Mo3al-2. Magnification 370X, cathodic vacuum etched, bright field illumination. Small dark specks are inclusions of oxides, nitrides, etc.

Fig. 2a

Bottom

Fig. 2b

Top

Ingot J825, U-8.0 w/o Mo-1.0 w/o Pt, used for rod Mo3al-4. Magnification 370X, cathodic vacuum etched, bright field illumination. Notice similarity to sample 1.

Fig. 3

Top

Ingot J824, U-12 w/o Mo-0.5 w/o Pt, used for rod Mo3a1-5. Magnification 370X, cathodic vacuum etched bright field illumination. Notice substructure.

Fig. 4

Top

Ingot J862, U-10.5 w/o Mo, used for rod Mo3a2-9. Magnification 370X, cathodic vacuum etched, bright field illumination.

Fig. 5a

Bottom

Fig. 5b

Top

Ingot J869, U-15 w/o Mo, 5 w/o Pt, used as the intermediate layer in rod Mo3a2-9. Magnification 370X, top is cathodic vacuum etched more than bottom to accentuate coring which was produced by arc melting top, bright field illumination.

Fig. 6a

Bottom

Fig. 6b

Top

Ingot J870, U-10 w/o Nb-1 w/o Pt, used for rod Mo3a2-2. Magnification 370X, cathodic vacuum etched, bright field illumination. Dark areas are alpha phase, gray areas are unknown constituent. Predominance of alpha phase in top cannot be attributed to any known factors.

Fig. 7a

Bottom

Fig. 7b

Top

Ingot J840, U-8 w/o Nb, used for rod Mo3a2-3. Magnification 370X, cathodic vacuum etched, bright field illumination. Dark areas are alpha phase. Notice substructure in top.

~~CONFIDENTIAL~~

WAPD-133

Fig. 8a

Bottom

Fig. 8b

Top

Ingot J851, U-10 w/o Nb, used for rod Mo3a2-4. Magnification 370X, cathodic vacuum etched, bright field illumination. Dark areas are alpha phase. Notice substructure showing coring.

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~~CONFIDENTIAL~~

WAPD-133

Fig. 9a

Bottom

Fig. 9b

Top

Ingot J852, U-10 w/o Nb, used for rod Mo3a2-5. Magnification 370X, cathodic vacuum etched, bright field illumination. Top was over etched to show coring which appears as substructure in 7b, 8a, and 8b. This specimen appeared the same as 8b prior to over etching.

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RECORDED

Fig. 10a

Bottom

Fig. 10b

Top

Ingot J951, U-12 w/o Nb, used for rod Mo3a2-7. Magnification 370X, cathodic vacuum etched, bright field illumination. The dark areas are alpha. Notice cored structure in top.

Fig. 11a

Rod Mo3al-1 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-12 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 11b

Rod Mo3al-1 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-12 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 12a

Rod Mo3al-2 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 12b

Rod Mo3al-2 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 13a

Rod Mo3al-4 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-8 w/o Mo-1 w/o Pt on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 13b

Rod Mo3al-4 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Notice how bond between Zircaloy-2 on left and U-8 w/o Mo-1 w/o Pt on right has been ruptured. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 14a

Rod Mo3al-5 after extrusion from a 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-12 w/o Mo-0.5 w/o Pt fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 14b

Rod Mo3al-5 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 on left, U-12 w/o Mo, 0.5 w/o Pt on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 15a

Rod Mo3a2-1 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left. Nb intermediate layer, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 15b

Rod Mo3a2-1 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, Nb intermediate layer, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 16a

Rod Mo3a2-2 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb-1 w/o Pt fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 16b

Rod Mo3a2-2 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb-1 w/o Pt on right. Cathodic vacuum etched, bright field illumination. Magnification 500X.

Fig. 17a

Rod Mo3a2-3 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-8 w/o Nb on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 17b

Rod Mo3a2-3 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-8 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 18a

Rod Mo3a2-4 after extrusion from a 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 18b

Rod Mo3a2-4 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 19a

Rod Mo3a2-5 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 19b

Rod Mo3a2-5 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 20a

Rod Mo3a2-6 after extrusion from 2.6-in. diam to 0.5-in. diam. Notice Zircaloy-2 cladding on left, Pd intermediate layer, and U-10.5 w/o Mo fuel on right are unbonded. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 20b

Rod Mo3a2-6 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Notice Zircaloy-2 cladding on left, Pd intermediate layer, and U-10.5 w/o Mo fuel on right are unbonded. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 21a

Rod Mo3a2-7 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-12 w/o Nb on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 21b

Rod Mo3a2-7 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-12 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 22a

Rod Mo3a2-8 after extrusion from 2.6-in. diam to 0.5-in. diam. Notice Zircaloy-2 cladding on left, Pt intermediate layer and U-10.5 w/o Mo fuel on right are un-bonded. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 22b

Rod Mo3a2-8 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Notice Zircaloy-2 cladding on left, Pt intermediate layer, and U-10.5 w/o Mo fuel on right are bonded. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 23a

Rod Mo3a2-9 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-15 w/o Mo-5 w/o Pt intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 23b

Rod Mo3a9-9 after drawing and swaging from 0.5-in. diam to 0.375-in. diam. Zircaloy-2 cladding on left, U-15 w/o Mo-5 w/o Pt intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 24a

Rod Mo3a2-10 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, Nb intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 24b

Rod Mo3a2-10 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Nb intermediate layer and U-10.5 w/o Mo fuel on right appear darker because of longer cathodic vacuum etch. Bright field illumination, magnification 250X.

Fig. 25a

Rod Mo3a2-11 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination. Magnification 250X.

Fig. 25b

Rod Mo3a2-11 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 26a

Rod Mo3a2-12 after extrusion from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, Mo intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 250X.

Fig. 26b

Rod Mo3a2-12 after drawing and swaging from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, Mo intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 27a

Rod Mo3a2-13 extruded from 2.6-in. diam to 0.5-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched bright field illumination, magnification 250X.

Fig. 27b

Rod Mo3a2-13 drawn and swaged from 0.5-in. diam to 0.304-in. diam. Zircaloy-2 cladding on left, U-10 w/o Nb intermediate layer, U-10.5 w/o Mo fuel on right. Cathodic vacuum etched, bright field illumination, magnification 500X.

Fig. 27c

Rod Mo3a2-13 extruded from 2.6 in. diam to 0.5-in. diam. HNO_3 HF H_2O etch. Magnification 7X. Etch causes pitted appearance of fuel.

Fig. 27d

Rod Mo3a2-13 drawn and swaged to 0.304-in. diam. HNO_3 HF H_2O etch. Magnification 7X. Notice how fuel has tended to round.