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METALLURGY AND CERAMICS

THE FABRICATION OF ZIRCALOY-2 CLAD U-Mo AND U-Nb RODS FOR
IRRADIATION IN THE MATERIALS TESTING REACTOR

by

W. B. Haynes

October 31, 1955

CONTRACT AT-11-1-GEN-14

CLASSIFICATION CANCELLED

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THE FABRICATION OF ZIRCALOY-2 CLAD U-Mo AND U-Nb RODS FOR
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INTRODUCTION

Zircaloy-2 clad fuel rods whose fuel alloys were U-9 w/o Mo, U-10.5 w/o Mo, U-12 w/o Mo, 13.5 w/o Mo, and U-10 w/o Nb and rods each of whose fuel contained 5 w/o U²³⁵ and whose alloy content was U-9 w/o Mo, U-10.5 w/o Mo, U-12 w/o Mo, and U-13.5 w/o Mo were manufactured for testing in the Materials Testing Reactor. This report is issued to familiarize the interested parties with the procedures used in fabricating the material and the evaluation techniques utilized in determining its quality.

The purposes of the in-pile testing were to:

- a) Determine the corrosion resistance and effects of irradiation on the U-10 w/o Nb alloy.
- b) Determine the characteristics of the transformation caused by heat and irradiation of unclad U-10 w/o Nb samples in NaK filled capsules.
- c) Determine the effects of long time burn-up of U-Mo fuel both clad and unclad, which had been extruded directly to size.
- d) Determine the effects of radiation on the U-Mo fuel alloys which had been heat treated to various metallographic structures prior to exposure.

VACUUM INDUCTION MELTING

All of the alloys except the U-13.5 w/o Mo and the U-10 w/o Nb were melted in zirconia washed graphite crucibles. The U-13.5 w/o Mo and the U-10 w/o Nb alloys

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were melted in beryllia washed graphite crucibles. All of the natural uranium melts were cast into 1 1/4-in. diam water cooled copper molds with the exception of Ingot Y545 which was cast into a 3/4-in. diam graphite mold. All of the alloys containing 5 w/o U²³⁵ were cast into 3/4-in. diam molds to conserve material.

The natural uranium melting constituent for all of these melts was Fernald strip approximately 3/4-in. square by 0.3 in. thick. This was prepared by vacuum induction uranium derbies and machine chips in zirconia washed graphite crucibles and hot rolling to size. The molybdenum and niobium additions were 1/4-in. diam rod chopped into about 1-in. lengths. For making the enriched alloys, pellets approximately 1/8-in. diam by 1/8 in. thick of high U²³⁵ content were used.

Induction melting data are listed in Table I.

CONSUMABLE REMELTING

All of the material which was cast to 1 1/4-in. diam was consumably arc remelted to 2 5/16-in. diam and the ingots cast to 3/4-in. diam were consumably remelted to 1 1/2-in. diam. Clean machine chips machined from the consumable electrode were used to strike the starting arc.

It was found that increasing the melting rate on the 3/4-in. diam electrodes greatly improved the surface finish of the consumable remelt. Previously these 3/4-in. diam ingots had been consumably remelted to 1 1/2-in. diam billets in about 4 to 5 minutes which produced a billet with very rough sides. By increasing the melting rate to two minutes, this difficulty was overcome.

The top and bottom of each consumably remelted billet was arc melted with a tungsten tipped electrode to eliminate any small holes.

Consumable remelt data are listed in Table II.

FORGING

All of the billets consumably remelted to 2 5/16-in. diam were forged to

1.5-in. octagons. The billets were heated in air; 1900°F was used for forging the uranium-molybdenum alloys and 2000°F for the U-10 w/o Nb alloy. About 1/4-in. reduction was made per forging pass before reheating. All of the alloys forged quite readily with the exception of the U-13.5 w/o Mo billet J956 which split and was scrapped.

No forging was done on the billets consumably remelted to 1 1/2-in. diam.

ASSEMBLY

Each 1.5-in. diam consumable remelt and each forged piece was machined into extrusion billets 1.203-in. diam by 3.000 in. long. One of the U-10 w/o Nb billets was only 2.360 in. long, however, since the forging from which it was machined was not long enough to obtain three 3.000-in. long billets. No billet exhibited any porosity after machining.

All of the billets were washed and assembled into Zircaloy-2 cups of 1.204-in. inside diameter and 1.550-in. outside diameter. Each assembly was covered with a Zircaloy-2 end cap and welded closed in a welding box which had been evacuated and filled with helium. No metal jacketing of any kind was used to cover the extrusion assembly. (See Fig. 1).

EXTRUSION

Extrusion data are listed in Table III. The cause of stuck billets was a rough container. However, a method of honing the container periodically was inaugurated at this time, after which there was no more trouble with billets failing to extrude.

Heating was done in a chloride salt bath for about 10 minutes prior to extrusion. All extrusion was done through 0.314-in. diam, chromium plated dies.

The resulting rod size was about 0.308 ± 0.002 -in. diam.

The surface finish of the initial rods was only fair due to the rough container. However, all the rods extruded after the container was honed had an excellent surface finish.

ROD PROCESSING

After extrusion the rods were sandblasted to remove oxide scale and salt picked up during extrusion, the resulting rod size was 0.306 ± 0.002 in. With the exception of Rod Mo3a9-11 (U-10 w/o Nb fuel alloy) each rod was cold swaged through a 0.300-in. diam swaging die to improve the surface finish of the Zircaloy-2 and to straighten the rod. The diameters of the rods after swaging were 0.304 ± 0.0011 in. This was the variation from rod to rod and also the variation within any particular rod.

The rods were cleaned of oil and grease picked up during swaging by wiping with rags saturated in perchlorethylene. They were bright etched in a solution of 35 v/o HNO_3 -5 v/o HF -60 v/o H_2O to obtain a bright smooth surface.

After etching the rods were cut at their approximate centers and radiographed at two positions to each other. One radiograph of each exposure angle was transferred to the Metallurgy Subdivision with the material.

Figs. 2 through 16 are plots of the fuel diameter variations along the rod length. The radiographs of Rods Mo3a9-3 through Mo3a9-7 were lost and consequently it was impossible to make a plot of the fuel diameter variations along the rod length for these rods. However, they were essentially the same as the other rods with respect to fuel diameter.

The enriched rods were machined into specimens as indicated by Fig. 17. Table IV lists the number of specimens cut from each rod.

EVALUATION

Each rod was evaluated to insure that it met the quality required of material to be tested in the Materials Testing Reactor. As stated previously each rod was radiographed from two angles at 90° to each other. This was done to insure that no clad fuel elements would be fabricated from rods having less than 0.025-in. thick Zircaloy-2 cladding.

The thickness of the diffusion zone between the fuel and the Zircaloy-2 was measured by means of a Tukon testing machine using a 4 mm objective. These measurements are listed in Table V. Figs. 18b through 36b are photomicrographs at 1000 diameters showing the diffusion zone, in each case the fuel is on the right and the Zircaloy-2 cladding on the left. The diffusion zones of the U-Mo alloy rods appear as black lines instead of continuous crystallographic structures because it is impossible to focus on both the Zircaloy-2 cladding and the fuel at such high magnification because of the different etching characteristics of the materials. However, the diffusion zones of the Zircaloy-2 clad U-10 w/o Nb rods (Figs. 26b through 28b) do appear as continuous crystallographic structures. Apparently the U-10 w/o Nb alloy has different etching characteristics than the U-Mo alloys.

These measurements and examinations were made to establish the fact that there was a metallurgical bond between the cladding and the fuel and to determine the thickness of the diffusion zone. Certain areas of the diffusion zone are not corrosion resistant and allow corrosion of the fuel element to propagate at an accelerated rate if a failure is encountered in the cladding. Therefore, it is desirable to keep the diffusion zone to a minimum and yet maintain a metallurgical bond.

Figs. 18a through 36a are photomacrographs at 7 diameters showing the fuel-cladding configuration. The porous appearing structure of the fuel is due to the

stain applied to contrast the fuel with the Zircaloy-2. Actually the fuel is quite dense and appears mirror-like when polished.

Specimens from each rod were inspected by x-ray diffraction techniques which showed the fuel to be all gamma phase structure. It is imperative that the fuel be all gamma phase because alpha phase uranium alloys are not corrosion resistant and deteriorate rapidly in hot water.

Chemical analyses and isotopic assays were made on machine chips taken from the top and bottom of each consumable remelted ingot. These results are listed in Table VI. The alloy and U^{235} content of the alloys is very close to the nominal composition and is well within the $\pm 3\%$ accuracy limits of the analytical methods. The carbon content of these alloys tends to be slightly higher than normally expected in materials prepared in this manner.

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TABLE I
INDUCTION MELTING DATA

<u>Ingot No.</u>	<u>Holding Temp. °C</u>	<u>Pouring Temp. °C</u>	<u>Mold</u>	<u>Crucible</u>	<u>U Ingot No.</u>	<u>Nominal Composition</u>
Y509	1420	1380	1 1/4-in. Cu	ZrO ₂ washed graphite	Pl319	9 Mo
Z151	1450	1410	1 1/4-in. Cu	ZrO ₂ washed graphite	Pl319	10.5 Mo
Z153	1480	1420	1 1/4-in. Cu	ZrO ₂ washed graphite	Pl319	12 Mo
Z152	1650	1590	1 1/4-in. Cu	Beryllia	Pl319	13.5 Mo
Z117	1655	1600	1 1/4-in. Cu	Beryllia	Pl357	13.5 Mo
Y545	1660	1650	3/4-in. Graphite	Beryllia	Pl351	13.5 Mo
Z165	1710	1575	1 1/4-in. Cu	Beryllia	Pl354 & Pl318	10 Nb
Y559	1490	1410	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	9 Mo + 5 U ²³⁵
Y560	1490	1410	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	9 Mo + 5 U ²³⁵
Y561	1450	1450	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	10.5 Mo + 5 U ²³⁵
Y562	1450	1450	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	10.5 Mo + 5 U ²³⁵
Y563	1480	1480	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	12 Mo + 5 U ²³⁵
Y564	1480	1480	3/4-in. Graphite	ZrO ₂ washed graphite	Pl354 & U pellets	12 Mo + 5 U ²³⁵
Y565	1650	1650	3/4-in. Graphite	Beryllia	Pl354 & U pellets	13.5 Mo + 5 U ²³⁵
Y566	1650	1650	3/4-in. Graphite	Beryllia	Pl354 & U pellets	13.5 Mo + 5 U ²³⁵

No pouring block was used when casting into a 3/4-in. diam graphite molds.

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TABLE II
CONSUMABLE REMELT DATA

<u>Ingot No.</u>	<u>Remelt No.</u>	<u>Volts</u>	<u>Amperes</u>	<u>Melting Time</u>	<u>Nominal Composition</u>
Y509	J940	33	1200	5 min	9 Mo
Z151	J930	35	1200	4 min	10.5 Mo
Z153	J938	35	1200	5 min	12 Mo
*Z152	J956	34	1250	6 min	13.5 Mo
Z117	J828	36	1000	5 min	13.5 Mo
Y545	J974	31	1250	2 min	13.5 Mo
Z165	J962	32	1700	5 min	10 Nb
Y559	J970	—	550	2 min	9 Mo + 5 U ²³⁵
Y560	J971	31	950	2 min	9 Mo + 5 U ²³⁵
Y561	J972	32	1000	2 min	10.5 Mo + 5 U ²³⁵
Y562	J975	31	1200	2 min	10.5 Mo + 5 U ²³⁵
Y563	J977	31	900	2 min	12 Mo + 5 U ²³⁵
Y564	J978	30	1000	2 min	12 Mo + 5 U ²³⁵
Y565	J981	30	900	2 min	13.5 Mo + 5 U ²³⁵
Y566	J892	30	1000	2 min	13.5 Mo + 5 U ²³⁵

* Consumably remelted ingot split during forging and was scrapped.

TABLE IVSAMPLES OBTAINED FROM ENRICHED RODS AND 1 U-10 w/o Nb ROD

<u>Rod No.</u>	<u>A Spec</u>	<u>B Spec</u>	<u>C Spec</u>	<u>D Spec</u>
Mo3a9-1e	17	3	1	
Mo3a9-2e	15	3	1	
Mo3a9-3e	16	3	1	
Mo3a9-4e	16	3	1	
Mo3a9-5e	16	3	1	
Mo3a9-6e	16	3	1	
Mo3a9-7e	15	3	1	
Mo3a9-8e	16	3	1	
Mo3a9-11				25

TABLE III

EXTRUSION DATA

Date	Fuel	Rod No.	Nominal Composition	(F) Heating Temp.	(Tons) Load Start	(Tons) Loading Running	(ipm) Ram Speed	(sec) Loading Time
1/6/55	J938-2	Mo3a9-7	12 Mo	1945	160	150	60	15
1/7/55	J940-2	Mo3a9-6	9 Mo	1930	160	140	48	14
1/7/55	J940-1	Mo3a9-5	9 Mo	1955	150	135	32	17
1/7/55	J930-2	Mo3a9-1	10.5 Mo	1940	150	140	32	16
1/7/55	J930-1	Mo3a9-2	10.5 Mo	1950	160	150	30	—
1/7/55	J930-3	Mo3a9-3	10.5 Mo	1940	Stuck	Stuck	Stuck	15
1/7/55	J938-3	Mo3a9-8	12 Mo	1960	180	150	32	13
1/7/55	J938-1	Mo3a9-9	12 Mo	1935	180	Stuck	Stuck	14
1/7/55	J828	Mo3a9-4	13.5 Mo	1960	170	140	50	16
1/26/55	J970	Mo3a9-1e	9 Mo + U ²³⁵	1945	140	130	25	22
1/26/55	J971	Mo3a9-2e	9 Mo + U ²³⁵	1940	160	140	25	18
1/26/55	J972	Mo3a9-3e	10.5 Mo + 5 U ²³⁵	1950	150	140	35	22
1/26/55	J975	Mo3a9-4e	10.5 Mo + 5 U ²³⁵	1955	140	125	34	17
1/26/55	J977	Mo3a9-5e	12 Mo + 5 U ²³⁵	1955	150	135	29	16
1/26/55	J978	Mo3a9-6e	12 Mo + 5 U ²³⁵	1950	150	135	36	14
1/26/55	J982	Mo3a9-7e	13.5 Mo + 5 U ²³⁵	1965	170	140	46	13
1/27/55	J974	Mo3a9-10	13.5 Mo	1970	160	140	47	14
1/27/55	J962-1	Mo3a9-11	10 Nb	1975	150	115	47	14
1/27/55	J962-2	Mo3a9-12	10 Nb	1975	135	115	48	14
1/27/55	J962-3	Mo3a9-13	10 Nb	1985	140	115	41	14
1/27/55	J981	Mo3a9-8e	13.5 Mo + 5 U ²³⁵	1980	160	140	47	14

Die - Chromium Plated
 Die Size - 0.314 in.
 Bath - Chloride
 Container Temp. - 750° F
 Lubricant - Led-Plate
 Heating Time - 9-10 min
 Cut-off - Copper

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TABLE V

DIFFUSION ZONE MEASUREMENTS

These measurements represent an average of four readings taken at 90° to one another. Readings are in inches.

<u>Rod No.</u>	<u>Diffusion Zone Thickness (inches)</u>	<u>Fuel Composition</u>
Mo3a9-1	0.000053	10.5 Mo
Mo3a9-2	0.000058	10.5 Mo
Mo3a9-4	0.000055	13.5 Mo
Mo3a9-5	0.000048	9 Mo
Mo3a9-6	0.000045	9 Mo
Mo3a9-7	0.000059	12 Mo
Mo3a9-8	0.000055	12 Mo
Mo3a9-10	0.000069	13.5 Mo
Mo3a9-11	0.000075	10 Nb
Mo3a9-12	0.000053	10 Nb
Mo3a9-13	0.000051	10 Nb
Mo3a9-1e	0.000047	9 Mo, 5 U ²³⁵
Mo3a9-2e	0.000062	9 Mo, 5 U ²³⁵
Mo3a9-3e	0.000059	10.5 Mo, 5 U ²³⁵
Mo3a9-4e	0.000058	10.5 Mo, 5 U ²³⁵
Mo3a9-5e	0.000055	12 Mo, 5 U ²³⁵
Mo3a9-6e	0.000061	12 Mo, 5 U ²³⁵
Mo3a9-7e	0.000067	13.5 Mo, 5 U ²³⁵
Mo3a9-8e	0.000056	13.5 Mo, 5 U ²³⁵

TABLE VI
ANALYTICAL AND ASSAY DATA

<u>Rod No.</u>	<u>Mo Top</u>	<u>Mo Bottom</u>	<u>C Top</u>	<u>C Bottom</u>	<u>U²³⁵ Top</u>	<u>U²³⁵ Bottom</u>
Mo3a9-1e	9.1	9.2	0.030	0.025	4.96	4.95
Mo3a9-2e	8.8	9.1	0.048	0.034	5.08	5.00
Mo3a9-3e	10.2	10.3	0.040	0.033	4.96	4.99
Mo3a9-4e	10.5	10.5	0.040	0.032	4.90	4.97
Mo3a9-5e	12.1	12.1	0.046	0.043	4.84	4.91
Mo3a9-6e	12.2	12.1	0.046	0.043	4.80	4.86
Mo3a9-7e	13.4	13.2	0.029	0.031	4.89	4.90
Mo3a9-8e	13.5	13.4	0.038	0.037	4.89	4.88
Mo3a9-1	10.6	10.5	0.044	0.036		
Mo3a9-2	10.6	10.5	0.044	0.036		
Mo3a9-4	13.3	12.6	0.018	0.010		
Mo3a9-5	8.8	8.8	0.055	0.049		
Mo3a9-6	8.8	8.8	0.055	0.049		
Mo3a9-7	12.1	11.8	0.047	0.038		
Mo3a9-8	12.1	11.8	0.047	0.038		
Mo3a9-10	13.7	13.3	0.015	0.018		
	<u>Nb Top</u>	<u>Nb Bottom</u>				
Mo3a9-11	9.8	10.3	0.034	0.033		
Mo3a9-12	9.8	10.3	0.034	0.033		
Mo3a9-13	9.8	10.3	0.034	0.033		

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EXTRUSION ASSEMBLY

FIG. 1

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SPECIMEN A
IN PILE SPECIMEN

SPECIMEN B
CORROSION SPECIMEN

SPECIMEN C
METALLOGRAPHIC SPECIMEN

SPECIMEN D
SPECIAL U-10%Nb SPECIMEN

FIGURE 17

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Fig. 18a

Fig. 18b

Fig. 19a

Fig. 19b

Fig. 18a

Rod Mo3a9-5. U-9 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 18b

Rod Mo3a9-5. Zircaloy-2 cladding on left, U-9 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 19a

Rod Mo3a9-6. U-9 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 19b

Rod Mo3a9-6. Zircaloy-2 cladding on left, U-9 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 20a

Fig. 20b

Fig. 21a

Fig. 21b

Fig. 20a

Rod Mo3a9-1. U-10.5 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 20b

Rod Mo3a9-1. Zircaloy-2 cladding on left, U-10.5 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 21a

Rod Mo3a9-2. U-10.5 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 21b

Rod Mo3a9-2. Zircaloy-2 cladding on left, U-10.5 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 22a

Fig. 22b

Fig. 23a

Fig. 23b

Fig. 22a

Rod Mo3a9-7. U-12 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 22b

Rod Mo3a9-7. Zircaloy-2 cladding on left, U-12 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 23a

Rod Mo3a9-8. U-12 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 23b

Rod Mo3a9-8. Zircaloy-2 cladding on left, U-12 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 25a

Fig. 21a

Fig. 25b

Fig. 21b

Fig. 24a

Rod Mo3a9-4. U-13.5 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 24b

Rod Mo3a9-4. Zircaloy-2 cladding on left, U-13.5 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 25a

Rod Mo3a9-10. U-13.5 w/o Mo fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 25b

Rod Mo3a9-10. Zircaloy-2 cladding on left, U-13.5 w/o Mo fuel on right. Bright field illumination, cathodic vacuum etched, magnification.

Fig. 26a

Fig. 26b

Fig. 27a

Fig. 27b

Fig. 26a

Rod Mo3a9-11. U-10 w/o Nb fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 26b

Rod Mo3a9-11. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 27a

Rod Mo3a9-12. U-10 w/o Nb fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 27b

Rod Mo3a9-12. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 28a

Fig. 28b

Fig. 28a

Rod Mo3a9-13. U-10 w/o Nb fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 28b

Rod Mo3a9-13. Zircaloy-2 cladding on left, U-10 w/o Nb fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

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Fig. 29 a

Fig. 29b

Fig. 30a

Fig. 30b

Fig. 29a

Rod Mo3a9-1e. U-9 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 29b

Rod Mo3a9-1e. Zircaloy-2 cladding on left, U-9 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 30a

Rod Mo3a9-2e. U-9 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 30b

Rod Mo3a9-2e. Zircaloy-2 cladding on left, U-9 w/o Mo-5 w/o U²³⁵ on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 31a

Fig. 31b

Fig. 32a

Fig. 32b

Fig. 31a

Rod Mo3a9-3e. U-10.5 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 31b

Rod Mo3a9-3e. Zircaloy-2 cladding on left, U-10.5 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 32a

Rod Mo3a9-4e. U-10.5 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 32b

Rod Mo3a9-4e. Zircaloy-2 cladding on left, U-10.5 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 33a

Fig. 33b

Fig. 34a

Fig. 34b

Fig. 33a

Rod Mo3a9-5e. U-12 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 33b

Rod Mo3a9-5e. Zircaloy-2 cladding on left, U-12 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination cathodic vacuum etched, magnification 1000X.

Fig. 34a

Rod Mo3a9-6e. U-12 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 34b

Rod Mo3a9-6e. Zircaloy-2 cladding on left, U-12 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 35a

Fig. 35b

Fig. 36a

Fig. 36b

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Fig. 35a

Rod Mo3a9-7e. U-13.5 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etch.

Fig. 35b

Rod Mo3a9-7e. Zircaloy-2 cladding on left, U-13.5 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

Fig. 36a

Rod Mo3a9-8e. U-13.5 w/o Mo-5 w/o U²³⁵ fuel, Zircaloy-2 cladding. Magnification 7X, chemical etched.

Fig. 36b

Rod Mo3a9-8e. Zircaloy-2 cladding on left, U-13.5 w/o Mo-5 w/o U²³⁵ fuel on right. Bright field illumination, cathodic vacuum etched, magnification 1000X.

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