UNCLASSIFIED

UNCLASSIFIED

Report No. BMI-1045
Metallurgy and Ceramics

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

CORROSION IN 650 F DEGASSED WATER OF URANIUM-MOLYBDENUM ALLOYS CONTAINING IMPURITY ADDITIONS

Contract No. W-7405-eng-92

by

Edward W. Cawthorne
Warren E. Berry
James E. Reynolds
Robert I. Jaffee
Robert S. Peoples

October 6, 1955

Photostat Price \$ 10.80

Microfilm Price \$ 3.90

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus 1, Ohio

954 001

UNCLASSIFIED

DECLASSIFIED 1 1867
1576

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DECLASSIFIED

2

3

CLASSIFICATION SECTION
James R. [Signature]
FOR THE ARMY SECRET COMMISSION
DATE FEB 18 1991
CLASSIFICATION CANCELLED

7

~~CONFIDENTIAL~~

5 and 6

5

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	8
EXPERIMENTAL TECHNIQUE	9
Preparation of Alloys	9
Testing Procedures	14
PRESENTATION AND DISCUSSION OF DATA	15
Compositional Variables	15
Melting Materials.	46
Heat Treatment	51
Additional Tests	54
CONCLUSIONS	59
REFERENCES	60
APPENDIX A	61
APPENDIX B	65

954 602

~~CONFIDENTIAL~~

DECLASSIFIED

SECRET

~~CONFIDENTIAL~~

7

CORROSION IN 650 F DEGASSED WATER OF URANIUM-MOLYBDENUM ALLOYS CONTAINING IMPURITY ADDITIONS

E. W. Cawthorne, W. E. Berry, J. E. Reynolds,
R. I. Jaffee, and R. S. Peoples

In support of the WAPD program on the pressurized water reactor, studies have been made of corrosion behavior, hardness, and metallographic structure of uranium-molybdenum alloys containing various impurities. In general, cast alloys were more corrosion resistant in 650 F degassed water than similarly heat-treated wrought alloys.

The corrosion resistance of the uranium-10.5 w/o molybdenum alloy was improved significantly by the following ternary additions:

*0.05 to 0.10 w/o silicon
0.5 to 1.0 w/o zirconium
0.25 to 1.0 w/o tin.*

Corrosion life was approximately 110 to 125 days, which is double that of the most resistant binary alloy (as-cast uranium-10.5 w/o molybdenum). Corrosion rates were as low as $-0.01 \text{ mg}/(\text{cm}^2)(\text{hr})$. Maximum corrosion resistance could not be correlated with any particular heat treatment. Silicon and zirconium additions were more potent than the tin addition, while carbon in the amount of 0.10 w/o appeared to improve corrosion behavior slightly in the alloys aged for 1 week at 400 C.

The following ternary additions appeared to have little or no effect upon corrosion resistance of the uranium-10.5 w/o molybdenum and the uranium-12.0 w/o molybdenum alloys:

*0.01 to 0.025 w/o silicon
0.001 to 0.25 w/o zirconium
0.001 to 0.10 w/o tin
1 to 10 ppm hydrogen
65 to 360 oxygen
20 to 820 nitrogen.*

The mechanism of corrosion failure was similar to that reported by WAPD. The alloys fail by cracking or disintegration. This is apparently associated with hydrogen pickup during corrosion.

In the most corrosion-resistant cast alloys, that is, those of uranium-10.5 w/o molybdenum, addition of silicon, zirconium, or tin either decreased or had no effect upon the hardness increase on aging.

Precipitation of the hydride is retarded when zirconium is added to uranium-10.5 w/o molybdenum or uranium-12.0 w/o molybdenum alloys. Above 0.5 w/o zirconium, very little hydride, if any, precipitates during corrosion.

~~CONFIDENTIAL~~

954

003

DECLASSIFIED

No significant effects of varying uranium melting stock (center-cut biscuit, vacuum-annealed center-cut biscuit, dingot, WAPD-Fernald, and electrolytic) were found on corrosion resistance of uranium-10.5 w/o molybdenum and uranium-12.0 w/o molybdenum alloys.

Melting center-cut biscuit uranium in graphite, BeO, MgO, or ZrO₂ crucibles does not affect corrosion resistance of uranium-10.5 w/o molybdenum and uranium-12.0 w/o molybdenum alloys. Pickup of beryllium, zirconium, and magnesium was negligible.

All homogenizing heat treatments and quenching rates revealed about the same corrosion behavior for the wrought alloys studied as observed with the treatment at 900 C for 12 days and water quenched.

Additional corrosion tests for studying specimen size and geometry effects are in progress. Further tests are also being made on copper, nickel, platinum, silicon, tungsten, and zirconium ternary additions, and the results of these tests will be reported in the BMI progress reports for September and October, 1955.

INTRODUCTION

At the request of WAPD, a study has been made of the effect of minor compositional variables on the corrosion behavior of uranium-molybdenum alloys in 650 F degassed water. Ternary additions of the following elements were made to both cast and wrought uranium-10.5 w/o and 12.0 w/o molybdenum alloys:

<u>Addition</u>	<u>Nominal Amount</u>
Carbon	0.01, 0.025, 0.10, 0.50 w/o
Silicon	0.01, 0.025, 0.05 w/o; 0.10, 0.25, 0.5 w/o cast alloys only
Tin	0.001, 0.01, 0.025, 0.05, 0.10, 0.25, 0.50, 1.0 w/o
Zirconium	0.001, 0.01, 0.025, 0.05, 0.10, 0.25, 0.50, 1.0 w/o; 2.0, 4.0 w/o cast alloys only
Hydrogen	1, 10, 16 ppm
Nitrogen	75, 100, 150, 200 ppm
Oxygen	50, 75, 100, 250 ppm

The effect on corrosion behavior of melting the uranium stock in beryllia, magnesia, or zirconia crucibles prior to alloying with molybdenum was also studied. A comparison was made of the corrosion behavior of alloys prepared from biscuit, dingot, WAPD-Fernald, and electrolytic uranium melting stocks.

A second phase of the program was a study of the effect on corrosion behavior of variations in homogenizing heat treatment, quenching rate, and aging treatment.

EXPERIMENTAL TECHNIQUE

Preparation of Alloys

Materials

The majority of the alloys used in this study were prepared from center-cut biscuit uranium and Westinghouse molybdenum powder. A limited amount of work was also undertaken with dingot and electrolytic uranium and with uranium furnished by WAPD. Center-cut biscuit uranium remelted in BeO, MgO, and ZrO₂ crucibles was used as melting stock to prepare alloys for investigation of the effect of contamination during crucible melting.

Ternary additions of silicon, tin, and zirconium were made by adding the desired quantities of these elements to the arc-melting charge. Carbon was added as UC₂.

Gaseous Additions

Oxygen and nitrogen additions were made by adding predetermined quantities of these gases to the uranium metal in a modified Sieverts apparatus. The gas-impregnated uranium was then used as a master alloy for preparing the ternary alloys.

The alloys containing hydrogen were prepared by hydrogenating the corrosion-test specimens in a Sieverts apparatus. These specimens were fabricated, machined to size, vacuum annealed, and then homogenized at 900 C prior to hydrogenization.

Arc-Melting Techniques

With the exception of materials supplied by WAPD for special tests, the alloys for these investigations were melted in a rocking-hearth arc-melting furnace under a total helium pressure of 15 to 20 cm of mercury. The furnace was equipped with a water-cooled tungsten electrode and a water-cooled copper crucible with a 10-cm³ capacity. Charges weighing

approximately 170 g were placed in the crucible cavity after which the furnace was evacuated to a pressure of less than 5 μ and flushed by admitting helium to a pressure of 20 cm of mercury. The system was evacuated again to less than 5 μ prior to melting and then filled with helium to a total pressure of 15 to 20 cm of mercury.

Each alloy was melted three times and was then inverted and again melted three times. Arc-amperage was maintained at approximately 300 amp, and the time of each melt was held to about 1 to 1-1/2 min. Alloys melted by these techniques were generally found to be homogeneous and of good quality. All as-cast buttons were radiographed to check homogeneity. In a few cases, where surface quality was poor or inhomogeneity was suspected, some alloys were given 1 to 3 additional melts.

Metallographic examination of cross sections of some of the arc-melted ingots showed a localized concentration of impurities and porosity at the point of arc withdrawal on the top of the ingot. This contaminated area was removed by grinding or machining before the ingots were rolled or sectioned.

Fabrication and Specimen Geometry

Wrought Alloys. Wrought alloys for corrosion tests were prepared by heating the ingots at 1000 C in an argon or helium atmosphere and rolling in air to approximately 0.090 in. with reductions of 10 to 20 per cent per pass. The rolled sheet was given a final anneal for 15 min at the rolling temperature and water quenched.

Except for some minor edge cracking, little difficulty was encountered in fabricating. The only alloys which could not be fabricated were those containing 1000 ppm of silicon and the uranium-12.0 w/o molybdenum alloy containing 5000 ppm of carbon. Excessive cracking, which was experienced with several binary and ternary alloys earlier in the program, was traced to contamination from an Inconel furnace plate and to excessive moisture in the furnace atmosphere. Identical alloys were rolled without difficulty when these conditions were corrected.

The rolled strip was cleaned by vapor blasting. For sectioning, an abrasive cutoff wheel was used to provide eight specimens measuring approximately 1.25 by 0.50 by 0.080 in. Analytical samples were taken from the middle and ends of each strip.

Cast Alloys. In preparing cast specimens for corrosion tests, about 10 mils of metal was removed from the bottom of each ingot. A minimum of 100 mils of metal was then cut from the top of the ingot to insure complete removal of the contaminated area generally present. The machined blank

was sectioned on an abrasive cutoff wheel to provide six specimens measuring 0.90 by 0.25 by 0.20 in. During the machining operation, chips were selected to provide a representative analytical sample.

Heat Treatment

Preliminary Tests. During the initial stages of this program, wrought uranium-molybdenum alloys containing 9 to 13 w/o molybdenum, and wrought uranium-10.5 and 12.0 w/o molybdenum alloys containing up to 1.0 w/o tin or zirconium were prepared and corrosion tested in the following heat-treated conditions:

- (1) 1000 C for 1/2 hr and water quenched
- (2) 1000 C for 1/2 hr and water quenched plus 400 C for 1 week and water quenched
- (3) 1000 C for 1/2 hr and water quenched plus 400 C for 3 weeks and water quenched
- (4) 1000 C for 1/2 hr and water quenched plus 400 C for 5 weeks and water quenched.

These alloys had unexpectedly poor corrosion resistance and contained considerable amounts of alpha and/or epsilon transformation products after aging for 1 to 5 weeks at 400 C (Figure 1a). The excessive transformation and poor corrosion properties of these alloys were attributed to failure to obtain homogeneity in 1/2 hr at 1000 C. Subsequent tests indicated that the extent of gamma $\rightarrow$ alpha + epsilon transformation occurring in these alloys was markedly reduced by homogenizing for 24 hr at 900 C and water quenching (Figure 1b). To insure complete homogenization, all alloys used for the study of the effects of compositional variations were heat treated for 12 days at 900 C and water quenched.

All heat treatments at 900 C were carried out with the specimens wrapped in molybdenum foil and placed in helium-filled Vycor tubes. The alloys were quenched from 900 C by plunging the tubes into water without breaking them. Specimens to be aged at 400 C were left in the original tubes and transferred to the 400 C furnace. Upon completion of the aging treatments, the specimens were water quenched without breaking the Vycor tubes.

Wrought Alloys. Wrought alloys were corrosion tested in the following heat-treated conditions:

250X

RM299

- a. Uranium-12 w/o Molybdenum, 1/2 Hour at 1000 C and WQ Plus 1 Week Aging at 400 C and WQ; Gamma Plus Transformation Product (Alpha Uranium and Epsilon); Chromic Etch

250X

RM697

- b. Uranium-12 w/o Molybdenum, 1 Day at 900 C and WQ Plus Aging at 400 C for 1 week and WQ; Retained Gamma Plus Small Amount of Transformation Product; Chromic Etch

FIGURE 1. URANIUM-12 w/o MOLYBDENUM ALLOY AFTER HEAT TREATMENT

954-008
000

- (1) 900 C for 12 days and water quenched
- (2) 900 C for 12 days and water quenched plus 400 C for 1 week and water quenched
- (3) 900 C for 12 days and water quenched plus 400 C for 3 weeks and water quenched
- (4) 900 C for 12 days and water quenched plus 400 C for 5 weeks and water quenched.

Cast Alloys. Cast alloys were corrosion tested in the following conditions:

- (1) As-melted
- (2) 900 C for 12 days and water quenched
- (3) 900 C for 12 days and water quenched plus 400 C for 1 week and water quenched.

Special Heat Treatments. In order to specifically study the effects of variations in heat treatment, the following test series were incorporated in this program:

- (1) Homogenizing heat treatments (in Vycor capsules)
 - (a) 800 C for 12 days and water quench; and preceding treatment plus effect of aging at 400 C for 1, 3, or 5 weeks and water quenching
 - (b) 900 C for 1, 2, 7, or 12 days and water quench; and preceding treatments plus 400 C for 1 or 5 weeks and water quench
 - (c) 1000 C for 1/2 or 24 hr and water quench; and preceding treatment plus 400 C for 1, 3, or 5 weeks and water quench
- (2) Quenching rates
 - (a) Water quench in Vycor capsule after homogenizing 1 or 12 days at 900 C; preceding treatment plus effect of aging at 400 C for 1, 3, or 5 weeks and water quenching

954 069

- (b) Above treatments, except Vycor capsules were broken and sample quenched directly in water after homogenization
 - (c) Water quench in Vycor capsules after homogenizing 1/2 hr at 1000 C; preceding treatment plus aging at 400 C for 1, 3, or 5 weeks and water quenching
 - (d) Above treatments except sample air cooled on metal plate after homogenization
- (3) Aging heat treatments, in which the samples were homogenized at 900 C to 12 days, water quenched, then aged 1, 3, 5, or 10 weeks at 300, 350, 400, or 500 C and water quenched.

Testing Procedures

Hardness Measurements

Transverse hardnesses were made with a Vickers hardness machine, using a 10-kg load. Specimens were mounted in Epon and wet polished through No. 2-grit emery. At least three measurements were made on each specimen and the averages were taken.

Metallographic

All metallographic specimens are transverse and were taken from the ends of the specimens used in the corrosion tests. Standard polishing procedures were used, and examinations of the structures were made within a few hours after polishing.

Corrosion Test

Corrosion tests were conducted in 650 F degassed water in 1-liter Type 316 stainless steel autoclaves. All fittings and auxiliary equipment in contact with water or steam were also of Type 316 stainless steel with the exception of nickel sealing gaskets, Chromel "A" wire baskets in which the test samples were supported, and palladium in the hydrogen diffusion valve. The latter was patterned after an early model designed by WAPD's PWR Chemistry Section⁽¹⁾ and was inserted in the vapor space of the test autoclave to release hydrogen resulting from corrosion of the test samples.

(1) References at end of report.

The valve was efficient. At no time did the pressure in the autoclaves rise above the water saturation pressure. There was no residual hydrogen pressure when the autoclaves were cooled to room temperature. Periodically, hydrogen escaping from the diffusion valve was collected and analyzed. It was found to run as high as 80 per cent of the theoretical amount evolved on the basis of the corrosion rates of test samples at the time gas samples were taken.

Test water was once distilled and passed through an ion-exchange bed. This resulted in a specific resistivity in excess of 10^6 ohm-cm. Water was boiled a minimum of 1 hr to remove dissolved gases. The test autoclave was completely filled with boiling water and quickly sealed. A measured amount of water then was boiled off to purge the autoclave of air which was trapped in fittings. Fresh water was used after each exposure period.

Test specimens were shaper finished to remove surface scale and surface irregularities. Samples were degreased in acetone, air dried, and weighed before corrosion testing. As stated before, samples were supported in Chromel "A" wire baskets which were in metallic contact with supports in the autoclave. However, samples did not touch one another. Autoclaves were opened and samples examined and weighed after 3 and 7 days of exposure and once every 7 days thereafter. Prior to weighing, samples were dried and loosely adherent oxide was removed by brushing.

PRESENTATION AND DISCUSSION OF DATA

Compositional Variables

Corrosion results, obtained in 650 F degassed water with cast and wrought alloys, showing the effects of compositional variables are presented in Tables 1, 2, and 3 along with hardnesses and microstructures. More complete chemical analyses are given in Appendixes A and B. The nitrogen content of quite a few of the uranium-12 w/o molybdenum binary and ternary alloys was unusually high, and the reason for this is not known.

Corrosion Behavior

In general, about the same corrosion behavior was observed with homogenized binary alloys regardless of composition in the range 9 to 13 w/o molybdenum. Average corrosion rates and lives were $-0.1 \text{ mg}/(\text{cm}^2)$ (hr) and 21 to 28 days for the cast alloys and $-0.2 \text{ mg}/(\text{cm}^2)$ (hr) and 14 to 21 days for the wrought alloys. Aging at 400 C lowered corrosion

TABLE 1. HARDNESSES, MICROSTRUCTURES, AND CORROSION RESULTS^(a) OBTAINED ON CAST URANIUM-MOLYBDENUM ALLOYS TESTED IN 650 F DEGASSED WATER

Testing Condition																					
Alloy Content, w/o				(1) As Cast								(2) Condition (1) Plus 12 Days at 900 C and Water Quenched				(3) Conditions (1) and (2) Plus 7 Days at 400 C and Water Quenched					
				Micro-structure ^(b)		VHN (10-Kg Load)		Corrosion Rate, mg/(cm ²)(hr)	Corrosion Life, days	Micro-structure ^(b)		VHN (10-Kg Load)		Corrosion Rate, mg/(cm ²)(hr)	Corrosion Life, days	Micro-structure ^(b)		VHN (10-Kg Load)		Corrosion Rate, mg/(cm ²)(hr)	Corrosion Life, days
Nominal	Other	Mo	Other	Before	After	Before	After			Before	After	Before	After			Before	After	Before	After		
9.0	-	8.82	-	A	A2	285	503	-0.20	42-49	B	BhHS	281	413	-0.17	14-21	BT	-	473	-	-	0-3
9.5	-	9.23	-	A	-	299	-	-0.12	49-56	B	-	289	-	-0.13	21-28	BT	-	409	-	-	0-3
10.0	-	9.96	-	A	-	283	-	-0.18	35-42	B	-	285	-	-0.17	14-21	BT	-	473	-	-0.54	14-21
10.5	-	10.28	-	A	A2h	302	417	-0.15	56-63	B	-	299	405	-0.07	35-42	BT	-	401	-	-0.07	7-14
11.0	-	10.89	-	A	A2hX	306	478	-0.16	49-56	B	-	309	-	-0.11	28-35	BT	-	360	-	-0.07	14-21
11.5	-	11.30	-	A	-	319	-	-0.16	49-56	B	-	319	-	-0.11	21-28	BT	-	342	-	-0.06	14-21
12.0	-	11.94	-	A	A2h	330	390	-0.15	42-49	BOT	BhH	319	387	-0.09	21-28	BOT	BhT	333	409	-0.08	14-21
12.5	-	12.47	-	A	-	342	-	-0.16	35-42	B	-	336	-	-0.09	28-35	BT	-	339	-	-0.11	14-21
13.0	-	12.98	-	A	A2hX	345	401	-0.12	35-42	B	BhX	342	373	-0.16	7-14	BT	Bh	336	390	-0.13	21-28
10.5	0.01Si	-	0.008Si	A2P	-	314	-	-0.15	49-56	B2P	-	306	-	-0.10	35-42	B2	-	360	-	-0.03	21-28
10.5	0.025Si	-	0.02Si	-	-	-	-	-0.11	70-84	B2P	BCh	306	401	-0.10	35-42	B2	BhX	339	530	-0.02	119-126
10.5	0.05Si	-	0.04Si	A2P	-	314	519	-0.08	98-105	B2P	-	306	-	-0.06	49-56	BC	BCh	339	-	-0.01	>133
10.5	0.10Si	-	0.110Si	-	-	-	-	-0.10	63-70	B2P	BC	314	373	-0.06	70-77	BC	BCX	333	390	-0.02	35-42
10.5	0.25Si	-	-	-	-	-	-	-0.32	7-14	-	-	-	-	-	0-3	-	-	-	-	-0.05	7-14
10.5	0.50Si	-	-	-	-	-	-	-0.32	7-14	-	-	-	-	-0.36	14-21	-	-	-	-	-0.11	7-14
12.0	0.01Si	-	0.012Si	A2P	-	333	-	-0.17	49-56	B2P	-	327	-	-0.08	28-35	B2	-	339	-	-0.04	21-28
12.0	0.025Si	-	0.025Si	-	-	-	-	-0.15	49-56	B2P	-	336	-	-0.22	42-49	B2	-	333	-	-0.06	49-63
12.0	0.05Si	-	0.035Si	A2P	-	330	-	-0.11	49-56	B2P	-	336	-	-0.07	21-28	BC	-	339	-	-0.07	21-28
12.0	0.10Si	-	0.090Si	-	A2hX	-	483	-0.13	63-70	B2P	BCh	333	387	-0.08	42-49	B2	BhC	339	409	-0.09	35-42
12.0	0.25Si	-	-	-	-	-	-	-0.30	21-28	-	-	-	-	-	0-3	-	-	-	-	-0.08	3-7
12.0	0.50Si	-	-	-	-	-	-	-0.28	7-14	-	-	-	-	-0.32	21-28	-	-	-	-	-0.12	14-21
10.5	0.01C	-	0.015C	AC	-	306	-	-0.47	28-35	BC	-	309	-	-0.16	28-35	BT	-	468	-	-0.09	7-14
10.5	0.025C	-	0.034C	-	-	-	-	-0.44	28-35	BCT	-	304	-	-0.15	28-35	BT	-	421	-	-0.10	14-21
10.5	0.10C	-	0.110C	AC	-	317	-	-0.67	21-28	BC	BCh	314	405	-0.25	28-35	BT	BChX	455	525	-0.13	21-28
10.5	0.50C	-	0.460C	-	-	-	-	-1.18	14-21	BC	BCh	357	417	-0.47	7-14	BCT	BCh	409	498	-0.78	3-7
12.0	0.01C	-	0.015C	AC	-	327	-	-0.35	28-35	BC	-	327	-	-0.15	7-14	BT	-	373	-	-0.10	14-21
12.0	0.025C	-	0.034C	-	-	-	-	-0.51	28-35	BC	-	330	-	-0.30	14-21	BCT	-	354	-	-0.33	7-14
12.0	0.10C	-	0.120C	AC	-	339	-	-0.68	21-28	BC	BCTh	339	405	-0.25	21-28	BT	BCh	366	468	-0.20	28-35
12.0	0.50C	-	0.50C	-	-	-	-	-1.12	14-21	BC	-	387	-	-0.49	3-7	BCSP	BCh	394	417	-0.61	14-21
10.5	0.001Sn	-	0.001Sn	-	-	-	-	-0.26	28-35	B	-	306	-	-0.14	21-28	BT	-	383	-	-0.11	7-14
10.5	0.01Sn	-	0.005Sn	ACP	-	299	-	-0.34	35-42	B	-	314	-	-0.14	21-28	BT	-	376	-	-0.07	7-14
10.5	0.025Sn	-	0.015Sn	-	-	-	-	-0.29	28-35	B	-	306	-	-0.12	21-28	-	-	366	-	-0.07	7-14
10.5	0.05Sn	-	0.03Sn	ACP	-	304	-	-0.16	49-56	B	BChX	317	488	-0.10	28-35	BT	BhX	376	498	-0.09	7-14
10.5	0.10Sn	-	0.095Sn	-	-	-	-	-0.29	35-42	B	-	317	-	-0.12	21-28	BT	-	383	-	-0.07	7-14
10.5	0.25Sn	-	0.22Sn	ACP	-	304	-	-0.12	77-84	BC	-	317	-	-0.10	21-28	BT	-	401	-	-0.07	7-14
10.5	0.50Sn	-	0.50Sn	-	A2h	-	503	-0.08	98-105	BC	-	314	-	-0.18	21-28	BCT	BhTX	397	-	-0.17	7-14
10.5	1.0Sn	-	0.97Sn	ACP	-	317	-	-0.20	28-35	BC	BCh	312	401	-0.35	21-28	BCT	BChX	401	488	-0.34	14-21
12.0	0.001Sn	-	0.002Sn	-	-	-	-	-0.31	28-35	B	-	333	-	-0.15	21-28	BT	-	351	-	-0.08	21-28
12.0	0.01Sn	-	0.005Sn	ACP	-	322	-	-0.34	28-35	B	-	336	-	-0.11	21-28	BT	-	351	-	-0.16	14-21
12.0	0.025Sn	-	0.015Sn	-	-	-	-	-0.21	42-49	B	-	339	-	-0.10	28-35	BT	-	345	-	-0.07	21-28
12.0	0.05Sn	-	0.035Sn	ACP	-	322	-	-0.31	28-35	B	BChX	345	366	-0.16	14-21	BT	BChS	348	429	-0.13	21-28
12.0	0.10Sn	-	0.060Sn	-	-	-	-	-0.22	42-49	B	-	342	-	-0.13	21-28	BT	-	348	-	-0.08	21-28
12.0	0.25Sn	-	0.24Sn	ACP	-	319	-	-0.24	42-49	BC	-	342	-	-0.20	14-21	BT	-	360	-	-0.09	21-28
12.0	0.50Sn	-	0.51Sn	-	-	-	-	-0.16	49-56	BC	-	333	-	-0.34	7-14	BCT	-	354	-	-0.35	14-21
12.0	1.0Sn	-	0.91Sn	AC	ACh	336	464	-0.23	49-56	BC	-	330	-	-0.32	21-35	BCT	-	366	-	-0.56	7-14
10.5	0.001Zr	-	-	A	-	312	-	-0.26	21-35	-	-	319	-	-0.13	28-35	-	-	401	-	-0.13	7-21
10.5	0.01Zr	-	0.01Zr	A2	-	302	-	-0.31	21-28	BP	-	319	-	-0.14	21-28	BT	-	401	-	-0.26	3-7
10.5	0.025Zr	-	-	A0	-	304	-	-0.24	35-42	-	-	306	-	-0.15	28-35	-	-	417	-	-0.15	7-21
10.5	0.05Zr	-	0.049Zr	A2	-	304	-	-0.36	21-28	BP	-	309	-	-0.20	21-28	BT	-	405	-	-0.20	3-7
10.5	0.10Zr	-	0.096Zr	A2	-	297	-	-0.33	21-28	BP	-	299	-	-0.16	21-28	BT	-	401	-	-0.19	3-7
10.5	0.25Zr	-	-	A	-	304	-	-0.20	42-49	-	BTS	314	473	-0.10	35-42	-	-	421	-	-1.81	3-7
10.5	0.50Zr	-	0.53Zr	A2T	-	312	-	-0.14	77-84	BT	B	312	380	-0.13	42-49	BT	BShX	390	525	-0.28	3-7
10.5	1.0Zr	-	0.92Zr	A2	-	312	-	-0.13	63-70	BP	BX	325	380	-0.15	28-35	BT	-	405	-	-	0-3
10.5	2.0Zr	-	-	-	-	-	-	-0.17	14-21	-	-	-	-	-0.93	7-14	-	-	-	-	-	0-3
10.5	4.0Zr	-	-	-	-	-	-	-0.22	7-14	-	-	-	-	-	0-3	-	-	-	-	-	0-3
12.0	0.001Zr	-	-	A0	-	327	-	-0.24	35-42	-	-	333	-	-0.11	21-28	BT	-	348	-	-0.12	7-21
12.0	0.01Zr	-	0.01Zr	A	-	322	-	-0.33	21-28	BP	-	325	-	-0.12	21-28	-	-	357	-	-0.08	21-35
12.0	0.025Zr	-	0.021Zr	AN	-	319	-	-0.37	28-35	-	-	339	-	-0.20	14-21	-	-	363	-	-0.15	14-21
12.0	0.05Zr	-	0.042Zr	A2	-	327	-	-0.24	28-35	BP	-	327	-	-0.23	14-21	BT	-	354	-	-0.10	21-35
12.0	0.10Zr	-	0.09Zr	A	-	325	-	-0.34	28-35	BP	-	333	-	-0.22	21-28	BT	-	357	-	-0.13	14-21
12.0	0.25Zr	-	-	A0	-	333	-	-0.21	42-49	-	BhT	336	498	-0.10	35-42	-	-	376	-	-0.18	7-21
12.0	0.50Zr	-	0.53Zr	A2	A2X	327	468	-0.16	4												

TABLE 1. (Continued)

Alloy Content, w/o				Testing Condition															
				(1) As Cast				(2) Condition (1) Plus 12 Days at 900 C and Water Quenched				(3) Conditions (1) and (2) Plus 7 Days at 400 C and Water Quenched							
				Micro-structure ^(b)		VHN (10-Kg Load)		Corrosion Rate, mg/(cm ²)(hr)		Corrosion Life, days		Micro-structure ^(b)		VHN (10-Kg Load)		Corrosion Rate, mg/(cm ²)(hr)		Corrosion Life, days	
Nominal	Mo	Other	Analyzed	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
10.5	1 ppm H	-	0.6 ppm H	A	-	309	-	-0.16	-	28-35	-	B	BSh	312	488	-0.12	-	21-28	-
10.5	10 ppm H	-	5.3 ppm H	A	-	312	-	-0.16	-	21-28	-	B	-	314	508	-0.14	-	14-21	-
10.5	16 ppm H	-	9.3 ppm H	A	-	314	-	-0.38	-	14-21	-	B	-	322	-	-0.27	-	14-21	-
12.0	1 ppm H	-	1.1 ppm H	A	-	-	-	-0.17	-	21-28	-	B	-	-	-	-0.12	-	28-35	-
12.0	10 ppm H	-	5.7 ppm H	A	-	-	-	-0.30	-	7-14	-	B	-	-	405	-0.17	-	14-21	-
12.0	16 ppm H	-	7.7 ppm H	A	-	-	-	-0.29	-	14-21	-	B	-	-	-	-0.30	-	14-21	-
10.5	75 ppm N	-	60 ppm N	AN	-	302	-	-	-	-	-	BN	-	322	-	-	-	-	-
10.5	100 ppm N	-	110 ppm N	AN	-	297	-	-	-	-	-	BN	-	314	-	-	-	-	-
10.5	150 ppm N	-	130 ppm N	AN	-	302	-	-	-	-	-	BN	-	312	-	-	-	-	-
10.5	200 ppm N	-	170 ppm N	AN	-	302	-	-	-	-	-	BN	BNh	322	-	-	-	-	-
12.0	75 ppm N	-	70 ppm N	AN	-	333	-	-	-	-	-	BN	BNh	348	-	-	-	-	-
12.0	100 ppm N	-	70 ppm N	AN	-	325	-	-	-	-	-	BN	-	345	-	-	-	-	-
12.0	150 ppm N	-	130 ppm N	AN	-	322	-	-	-	-	-	BN	BhX	357	-	-	-	-	-
12.0	200 ppm N	-	170 ppm N	AN	-	319	-	-	-	-	-	BN	BNh	342	-	-	-	-	-
10.5	Base	-	<0.4 ppm H	A2	-	-	-	-	-	-	-	BO	-	-	-	-	-	-	-
12.0	Base	-	<0.4 ppm H	A2	-	-	-	-	-	-	-	BO	-	-	-	-	-	-	-

(a) Corrosion rates given are the lowest observed rates. The times given are the times required for cracking or disintegration (complete oxidation).

(b) Code for microstructures:

A, typical as-cast cored structure

B, homogeneous gamma

C, compound

T, transformation product, usually precipitate in grain boundary

P, microporosity

2, second constituent, unidentified

h, fine Widmannstätten hydride needles

H, coarse Widmannstätten hydride needles

O, oxides

N, nitrides

X, intercrystalline and transcrystalline cracks

S, subgrain boundaries.

TABLE 2. HARDNESS, MICROSTRUCTURE, AND CORROSION RESULTS^(a) OBTAINED ON WROUGHT URANIUM-MOLYBDENUM ALLOYS TESTED IN 450 F DEGASSED WATER

Alloy Content, w/o		Testing Conditions																							
		(1) 12 Days at 900 C and Water Quenched				(2) Condition (1) Plus 1 Week at 400 C and Water Quenched				(3) Condition (1) Plus 3 Weeks at 400 C and Water Quenched				(4) Condition (1) Plus 5 Weeks at 400 C and Water Quenched											
		Micro-structure ^(b)	VHN (10-Kg Load)		Corrosion Rate, mg/(cm ² ·hr)	Corrosion Life, days	Micro-structure ^(b)	VHN (10-Kg Load)		Corrosion Rate, mg/(cm ² ·hr)	Corrosion Life, days	Micro-structure ^(b)	VHN (10-Kg Load)		Corrosion Rate, mg/(cm ² ·hr)	Corrosion Life, days	Micro-structure ^(b)	VHN (10-Kg Load)		Corrosion Rate, mg/(cm ² ·hr)	Corrosion Life, days				
			Before	After				Before	After				Before	After				Before	After			Before	After	Before	After
Nominal	Other	Mo	Other	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After				
9.0	-	8.94	-	BNO	287	579	-	-0.13	21-28	BT	542	-	-	0-3	BT	560	-	-	0-3	BT	572	-	-	0-3	
9.5	-	9.49	-	B	289	-	-	-0.15	14-21	BT	542	-	-	0-3	BT	606	-	-	0-3	BT	554	-	-	0-3	
10.0	-	10.0	-	BNO	297	-	-	-0.20	21-28	BT	455	-	-0.34	7-14	BT	548	-	-0.32	3-7	BT	548	-	-	0-3	
10.5	-	10.4	-	B	312	508	-	-0.14	21-28	BTNO	401	514	-0.20	3-7	BT	575	-	-	0-3	BT	536	-	-	No Test	
11.0	-	10.9	-	B	317	-	-	-0.21	14-21	BT	376	-	-0.22	3-7	BT	529	-	-0.29	3-7	BT	519	-	-	0-3	
11.5	-	11.3	-	BNO	322	-	-	-0.30	14-21	BTNO	380	-	-0.23	7-14	BT	464	-	-0.23	7-14	BT	493	-	-0.23	7-14	
12.0	-	11.8	-	BNO	336	-	-	-0.38	14-21	BTNO	357	-	-	No Test	BT	429	-	-0.15	7-14	BT	468	536	-	-0.15	7-14
12.5	-	12.3	-	BNO	333	-	-	-0.54	7-14	BTNO	354	-	-0.33	7-14	BT	390	-	-0.17	14-21	BT	401	-	-0.17	14-21	
13.0	-	12.9	-	BNO	345	-	-	-0.46	7-14	BTNO	348	-	-0.38	7-14	BT	370	-	-0.23	14-21	BT	373	-	-0.23	14-21	
14.0	-	14.0	-	BNO	357	-	-	-0.31	7-14	BTNO	373	-	-0.38	7-14	BT	363	-	-0.34	7-14	BT	342	-	-0.34	7-14	
15.0	-	15.0	-	BNO	360	-	-	-0.84	3-7	BTNO	363	-	-0.49	7-14	BT	342	417	-0.68	7-14	BT	345	-	-0.68	7-14	
16.0	-	16.0	-	BNOT	383	-	-	0-3	BTNO	373	-	-	0-3	BT	370	-	-0.33	7-14	-	357	-	-0.33	7-14		
10.5	0.01 Si	-	0.01 Si	BNO	306	-	-	-0.31	14-21	B	390	-	-0.06	21-28	B2	514	-	-0.20	21-28	BNOn	530	-	-1.24	3-7	
10.5	0.025 Si	-	0.03 Si	BNO	314	-	-	-0.32	14-21	B	366	-	-0.04	21-28	B2	514	-	-0.13	21-28	BNOn	519	-	-0.34	14-21	
10.5	0.05 Si	-	0.05 Si	BNO	317	483	-	-0.16	28-35	B	357	566	-0.03	112-119	B2	503	-	-0.08	28-35	B2	548	566	-0.31	7-14	
12.0	0.01 Si	-	0.01 Si	BNO	336	-	-	-0.45	7-14	B	354	-	-0.12	21-28	BT	401	-	-0.10	28-35	B2	468	-	-0.18	28-35	
12.0	0.025 Si	-	0.02 Si	BNO	336	-	-	-0.31	7-14	B	342	-	-0.18	21-28	B2T	387	-	-0.23	7-14	B2	429	-	-0.16	7-14	
12.0	0.05 Si	-	0.05 Si	BNO	333	-	-	-0.25	7-14	B	339	-	-0.10	42-49	BT	370	468	-0.08	21-28	B2	394	508	-0.07	21-28	
10.5	0.01 C	-	0.017 C	BCNO	306	-	-	-0.41	14-21	BT	401	-	-0.14	7-14	BTn	536	-	-0.50	14-21	BTCN	548	-	-1.58	3-7	
10.5	0.025 C	-	0.034 C	BC	306	-	-	-0.50	7-14	BT	387	-	-0.14	7-14	BTn	514	-	-0.71	7-14	BTCN	542	-	-1.31	3-7	
10.5	0.10 C	-	0.10 C	B2	306	-	-	-0.42	7-14	BT	429	-	-0.15	21-28	BTn	503	-	-0.64	7-14	BTCN	530	-	-1.70	3-7	
10.5	0.50 C	-	0.47 C	B2	348	-	-	0-3	BTn	409	-	-3.52	3-7	BCT	464	-	-2.29	3-7	BTCN	514	-	-	0-3		
12.0	0.01 C	-	0.018 C	BCNO	325	-	-	-0.56	7-14	BTn	363	-	-0.12	21-28	BT	401	-	-0.19	14-21	BTCN	455	-	-0.28	14-21	
12.0	0.025 C	-	0.033 C	BC	330	-	-	-0.46	7-14	BT	373	-	-0.16	21-28	BT	394	-	-0.17	21-28	BTCN	468	-	-0.28	14-21	
12.0	0.10 C	-	0.110 C	B2	327	-	-	-0.49	7-14	BTn	373	442	-0.20	21-28	BT	409	525	-0.21	21-28	BTCN	464	-	-0.22	14-21	
10.5	0.001 Sn	-	0.001 Sn	-	319	-	-	-0.25	14-21	-	407	-	-0.11	14-21	BT	514	-	-0.28	7-14	BT	548	-	-1.87	7-14	
10.5	0.01 Sn	-	0.009 Sn	BC	304	-	-	-0.26	14-21	BCT	397	-	-0.07	14-21	BT	514	-	-	0-3	BT	525	-	-1.05	7-14	
10.5	0.025 Sn	-	0.020 Sn	-	306	-	-	-0.25	14-21	-	378	-	-0.10	14-21	BT	514	-	-0.83	3-7	BT	525	-	-	0-3	
10.5	0.05 Sn	-	0.030 Sn	BC	306	-	-	-0.23	14-21	BCT	390	-	-0.11	7-14	BTn	514	-	-0.64	14-21	BT	525	-	-0.71	7-14	
10.5	0.10 Sn	-	0.080 Sn	-	309	-	-	-0.09	21-28	-	380	-	-0.09	7-14	BT	519	-	-0.32	3-7	Bn	536	-	-0.26	7-14	
10.5	0.25 Sn	-	0.23 Sn	BNC	314	-	-	-0.07	21-28	BCT	390	-	-0.09	7-14	BT	525	-	-	0-3	B	554	-	-	0-3	
10.5	0.50 Sn	-	0.47 Sn	-	312	-	-	-0.11	42-49	-	397	-	-0.08	63-70	BT	508	566	-0.82	3-7	BT	548	-	-0.60	7-14	
10.5	1.0 Sn	-	0.88 Sn	BC	309	-	-	-0.24	21-28	BCT	413	-	-0.13	56-63	BTn	493	-	-0.62	7-14	BCT	519	-	-0.61	7-14	
12	0.001 Sn	-	0.001 Sn	-	339	-	-	-0.37	14-21	-	351	-	-0.24	7-14	BT	413	-	-0.17	7-14	BT	483	-	-0.17	7-14	
12	0.01 Sn	-	0.008 Sn	BCN	333	-	-	-0.23	7-14	BNT	351	-	-0.14	7-14	BT	397	-	-0.15	7-14	BT	468	-	-0.19	7-14	
12	0.025 Sn	-	0.017 Sn	-	336	-	-	-0.47	7-14	-	354	-	-0.24	7-14	BT	397	-	-0.16	7-14	BT	473	-	-3.41	3-7	
12	0.05 Sn	-	0.03 Sn	BC	333	-	-	-0.62	7-14	BT	370	541	-0.18	28-35	BTS	417	-	-0.20	21-35	BT	459	-	-0.17	35-42	
12	0.10 Sn	-	0.06 Sn	-	348	-	-	-0.33	7-14	-	366	-	-0.17	7-14	BT	405	-	-0.20	3-7	BT	478	-	-0.18	7-14	
12	0.25 Sn	-	0.25 Sn	BCN	336	-	-	-0.17	14-21	BNT	348	-	-0.15	7-14	BT	450	-	-0.20	7-14	BT	478	-	-0.39	7-14	
12	0.50 Sn	-	0.54 Sn	-	345	-	-	-0.27	14-21	-	366	-	-0.14	7-14	BT	417	-	-0.18	7-14	BT	464	488	-0.23	3-7	
12	1.0 Sn	-	0.98 Sn	BC	339	525	-	-0.39	7-14	BCT	366	554	-0.24	28-35	BT	394	-	-0.23	21-35	BT	455	-	-0.28	35-42	
10.5	0.001 Zr	-	-	-	314	-	-	-0.27	14-21	-	390	-	-0.09	21-28	-	514	-	-0.87	7-14	BT	536	-	-0.60	7-14	
10.5	0.01 Zr	-	0.008 Zr	-	317	-	-	-0.40	7-14	BNT	409	-	-0.18	3-7	-	514	-	-0.32	3-7	BT	530	-	-	0-3	
10.5	0.025 Zr	-	0.02 Zr	-	317	-	-	-0.63	7-14	-	425	-	-	0-3	-	525	-	-	0-3	BT	536	-	-	0-3	
10.5	0.05 Zr	-	0.058 Zr	-	312	-	-	-0.35	7-14	BT	409	-	-0.24	3-7	-	519	-	-	0-3	BT	514	498	-	0-3	
10.5	0.10 Zr	-	0.10 Zr	-	322	-	-	-0.51	7-14	-	390	-	-0.10	7-14	-	525	-	-0.68	3-7	BT	548	-	-	0-3	
10.5	0.25 Zr	-	0.25 Zr	-	309	-	-	-0.34	14-21	-	409	-	-0.13	3-7	-	530	-	-	0-3	BT	548	-	-	0-3	
10.5	0.50 Zr	-	0.51 Zr	-	325	-	-	-0.25	21-28	-	413	-	-0.17	3-7	-	525	-	-	0-3	BT	536	572	-0.57	7-14	
10.5	1.0 Zr	-	0.97 Zr	BN	319	-	-	-0.07	>133	BNT	397	-	-	0-3	-	548	566	-	0-3	BT	548	-	-	0-3	
12.0	0.001 Zr	-	<0.0005 Zr	-	342	-	-	-0.20	14-21	-	342	-	-0.15	7-14	-	397	-	-0.16	7-14	BT	459	-	-0.29	7-14	
12.0	0.01 Zr	-	0.007 Zr	BN	330	-	-	-0.47	7-14	BNT	351	-	-0.18	7-14	-	409	-	-0.26	7-14	BT	459	-	-0.10	7-14	
12.0	0.025 Zr	-	0.03 Zr	-	345	-	-	-0.32	7-14	-	347	-	-0.17	7-14	-	397	-	-0.27	3-7	B	473	-	-0.25	7-14	
12.0	0.05 Zr	-	0.05 Zr	-	342	-	-	-0.37	7-14	BT	366	-	-0.19	14-21	-	409	-	-0.40	7-14	BT	455	-	-0.15	14-21	
12.0																									

TABLE 3. MICROSTRUCTURES OF WROUGHT URANIUM-MOLYBDENUM ALLOYS AFTER CORROSION TESTING IN 650 F DEGASSED WATER

All specimens treated originally at 900 C for 12 days and water quenched.

Alloy Content, w/o		Alloy Content, w/o		Aging Time, weeks				Microstructure(a)	Corrosion Test Time, hr
Nominal	Other	Mo	Other	0	1	3	5		
9.0		8.94			x			Bh	672
10.5		10.4			x			BhX	672
12.0		11.8					x	BhX	336
15.0		15.0				x		BTh	168
10.5	0.05Si		0.05Si		x			BTh	336
10.5	0.05Si		0.05Si		x			BCh	2856
10.5	0.05Si		0.05Si	x				BHC	840
12.0	0.05Si		0.05Si			x		Bh	672
12.0	0.05Si		0.05Si				x	BhX	672
12.0	0.1C		0.11C			x		BTh	672
10.5	0.5Sn		0.47Sn			x		BCh	168
12.0	0.05Sn		0.03Sn		x			Bh	336
12.0	0.05Sn		0.03Sn		x			BCh	840
12.0	0.5Sn		0.54Sn				x	BhX	168
10.5	0.5Zr		0.51Zr				x	BHX	168
10.5	1.0Zr		0.97Zr			x		BC	72
12.0	1.0Zr		1.01Zr		x			BhS	1008
10.5	250 ppm O ₂		190 ppm O ₂				x	BhX	336
12.0	250 ppm O ₂		160 ppm O ₂		x			BThX	336

(a) Code for microstructure

B, homogeneous gamma

H, coarse Widmanstätten hydride

h, fine Widmanstätten hydride

X, intercrystalline and transcrystalline cracks

C, compound

T, transformation product, usually precipitate in grain boundaries

S, subgrain boundaries.

resistance. As aging time increased, alloys of higher molybdenum content failed, and after a 5-week anneal at 400 C only those containing more than 11 w/o molybdenum exhibited a corrosion life longer than 3 days. It was noted also that cast binary alloys were more resistant than similar wrought alloys, and, in general, as-melted (no heat treatment) alloys were the most resistant of all tested. With several exceptions this was also true of the ternary alloys in the compositional studies. This effect is discussed in more detail in the section on heat treatment.

A marked improvement in corrosion resistance was observed with the addition of approximately 0.05 to 0.10 w/o silicon, 0.5 to 1.0 w/o zirconium, or 0.25 to 1.0 w/o tin to the uranium-10.5 w/o molybdenum alloy. The corrosion life of these alloys was approximately double the 56 to 63 days obtained on the most resistant binary (as-melted 10.5 w/o alloy). Corrosion rates were as low as $-0.01 \text{ mg}/(\text{cm}^2)(\text{hr})$. Maximum corrosion resistance could not be correlated with any given heat treatment, i. e., the most resistant 0.05 w/o silicon sample was cast, homogenized, and aged 1 week, the most resistant 0.5 w/o tin sample was as-melted, and the most resistant 1.0 w/o zirconium sample was wrought and homogenized. The beneficial effects of 0.05 to 0.10 w/o silicon and 0.5 to 1.0 w/o zirconium additions were more pronounced than those of 0.25 to 1.0 w/o tin. However, additions of greater than 0.25 w/o silicon or 2.0 w/o zirconium lowered corrosion resistance. Alloys containing more than 1.0 w/o tin were not investigated. Plots of maximum corrosion life versus silicon or zirconium content are presented in Figures 2 through 9.

Addition of 0.5 w/o carbon to the 10.5 and 12.0 w/o molybdenum alloys not only increased corrosion rates but reduced corrosion life. On the other hand, addition of 0.10 w/o carbon appeared to improve corrosion behavior slightly in the alloys aged 1 week at 400 C. Carbon additions of less than 0.10 w/o had little effect on corrosion behavior.

The following ternary additions appeared to have little or no effect on the corrosion behavior of the 10.5 and 12.0 w/o molybdenum alloys: 0.01 to 0.025 w/o silicon, 0.001 to 0.25 w/o and 2.0 to 4.0 w/o zirconium, 0.001 to 0.10 w/o tin, 1 to 10 ppm hydrogen, 65 to 360 ppm oxygen, and 20 to 820 ppm nitrogen.

Alloys corroded to form loosely adherent uranium dioxide with corrosion rates varying from $-0.01 \text{ mg}/(\text{cm}^2)(\text{hr})$ for uranium-10.5 w/o molybdenum -0.05 w/o silicon alloy to in excess of $-1.00 \text{ mg}/(\text{cm}^2)(\text{hr})$ for the 0.5 w/o carbon additions to the 10.5 and 12.0 w/o binaries. Weight loss-time curves for the more resistant silicon and zirconium ternary alloys are presented in Figures 10 through 14. It can be seen that the less resistant alloys corrode at an ever increasing rate. The more resistant alloys corrode at a linear rate until several exposure periods before cracking or disintegration occurs, at which time their rates accelerated.

21

FIGURE 2. CORROSION LIFE OF CAST URANIUM-10.5 w/o MOLYBDENUM-0.01 to 0.50 w/o SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16142

CONFIDENTIAL

CONFIDENTIAL

95440017

CONFIDENTIAL

CONFIDENTIAL

22

FIGURE 3. CORROSION LIFE OF CAST URANIUM-12.0 w/o MOLYBDENUM-0.01 TO 0.50 w/o SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16143

FIGURE 4. CORROSION LIFE OF WROUGHT URANIUM—10.5 w/o MOLYBDENUM—0.01 TO 0.05 w/o SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16144

CONFIDENTIAL

23

CONFIDENTIAL

619 756 619

CONFIDENTIAL

CONFIDENTIAL

954-020

34

FIGURE 5. CORROSION LIFE OF WROUGHT URANIUM-12.0 w/o MOLYBDENUM-0.01 TO 0.05 w/o SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16145

CONFIDENTIAL

FIGURE 6. CORROSION LIFE OF CAST URANIUM-10.5 w/o MOLYBDENUM-0.001 TO 4.0 w/o ZIRCONIUM ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16146

CONFIDENTIAL

CONFIDENTIAL

CONFIDENTIAL

954-022

CONFIDENTIAL

CONFIDENTIAL

26

FIGURE 7. CORROSION LIFE OF CAST URANIUM-12.0 w/o MOLYBDENUM-0.001 TO 4.0 w/o ZIRCONIUM ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16147

FIGURE 8. CORROSION LIFE OF WROUGHT URANIUM-10.5 w/o MOLYBDENUM-0.001 TO 1.0 w/o ZIRCONIUM ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16148

CONFIDENTIAL

CONFIDENTIAL

0000000000

954-023

CONFIDENTIAL

CONFIDENTIAL

CONFIDENTIAL

FIGURE 9. CORROSION LIFE OF WROUGHT URANIUM-12.0 w/o MOLYBDENUM-0.001 TO 1.0 w/o ZIRCONIUM ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16149

954-024

954-024

CONFIDENTIAL

29

FIGURE 10. WEIGHT LOSS OF URANIUM-10.5 w/o MOLYBDENUM-SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16150

CONFIDENTIAL

954

126

DECLASSIFIED

CONFIDENTIAL

30

FIGURE II. WEIGHT LOSS OF URANIUM-12.0 w/o MOLYBDENUM-SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16151

CONFIDENTIAL

03712281030

FIGURE 12. WEIGHT LOSS OF URANIUM-10.5 w/o MOLYBDENUM-SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16152

FIGURE 13. WEIGHT LOSS OF URANIUM-12.0 w/o MOLYBDENUM-SILICON ALLOYS EXPOSED TO 650 F DEGASSED WATER

A-16153

954

028

037028.030

FIGURE 14. WEIGHT LOSS OF URANIUM-MOLYBDENUM-ZIRCONIUM ALLOYS EXPOSED TO 650 F DEGASSED WATER

As reported by WAPD(3, 4, 5, 6, 7), cracking (and undoubtedly disintegration, i. e., complete oxidation) is associated with hydrogen penetration at the grain boundaries and the formation of hydride platelets both at the grain boundaries and across the grains.

Hardness and Microstructure

Hardness is plotted in Figures 15 and 16 as a function of molybdenum content for the uranium-molybdenum binary alloys. It is seen that the hardness of the gamma-quenched alloys (both wrought and as cast) increases linearly with weight percentage molybdenum. The aging treatment increases the hardness considerably with a maximum increase of about 275 Vickers points for the low-molybdenum wrought alloys and 190 Vickers points for the low-molybdenum as-cast alloys. Figure 15 also contains the hardness curve for the wrought binary alloys aged for 1 week for comparison with the cast alloys. The wrought alloys aged for 1 week are between 15 to 70 Vickers points harder than similarly aged as-cast alloys. This is probably due to nucleation being favored in the worked material and the availability of more sites for precipitation.

The ternary additions did not significantly affect the hardness values in the as-cast condition or the as-cast gamma-quenched specimens. Some effects were noted, however, in the as-cast aged condition, and these effects are noted below:

<u>Ternary Addition</u>	<u>Effect on Hardness Increase on Aging Cast Alloys</u>	
	<u>Uranium-10.5 w/o Molybdenum</u>	<u>Uranium-12 w/o Molybdenum</u>
Silicon	Decreases	No effect
Carbon	Increases	Increases
<0.1 w/o tin	Decreases	Increases slightly
0.1-1 w/o tin	No effect	Increases slightly
Zirconium	No effect	Increases slightly
Oxygen	No effect	No effect
Hydrogen	Increases slightly	No data
Nitrogen	No effect	Increases

It is observed that the best corrosion resistant alloys, i. e., uranium-10.5 w/o molybdenum-silicon, zirconium, or tin, all decrease the aging response or have no effect upon it.

For the alloys in the wrought series, the ternary additions have no noticeable effects in the gamma-quenched condition, but some effects are shown for the 1-, 3-, and 5-week aging treatments at 400 C. Silicon tends to decrease the aging response for both the uranium-10.5 and 12 w/o

954 - 030

0372291030

FIGURE 15. HARDNESS VERSUS w/o MOLYBDENUM FOR HEAT-TREATED AS-CAST URANIUM-MOLYBDENUM ALLOYS

A-16155

FIGURE 16. HARDNESS VERSUS w/o MOLYBDENUM WROUGHT URANIUM-MOLYBDENUM ALLOYS

A-16156

molybdenum alloys. Carbon decreased the aging response slightly in the uranium-10.5 w/o molybdenum alloy. Tin seemed to affect 1-week aging treatment of the uranium-10.5 w/o molybdenum alloy by first decreasing the aging response with an opposite effect as the tin was increased above approximately 0.1 w/o. This reversal seems to coincide with the minimum corrosion life, but this result may be fortuitous. Zirconium also showed such a reversal in the uranium-10.5 w/o molybdenum alloy aged for 3 weeks, but there is no apparent correlation with corrosion behavior.

Some representative microstructures are shown in Figures 17 through 31 to supplement the structures tabulated in Tables 1, 2, and 3. Figures 17, 18, and 19 illustrate typical structures of the as-cast group before corrosion tests. Microstructures after corrosion tests of specimens in the as-cast series are presented in Figures 20 through 29 and two of the wrought series in Figures 30 and 31.

The effect of zirconium additions upon microstructure are of special interest since zirconium improves the corrosion resistance appreciably. When 0.25 w/o zirconium is added (Figure 21) to a base uranium-12 w/o molybdenum alloy (Figure 20), the coarse hydride which forms in the binary alloy is formed as finer needles. The zirconium has also reduced the grain size appreciably. Increasing zirconium to 0.5 w/o in a base uranium-12 w/o molybdenum alloy affects the microstructure of aged specimens after corrosion. At the 0.5 w/o zirconium level, the formation of hydride needles has been suppressed (see Figure 23), while the binary alloy (Figure 22) contains abundant fine Widmanstätten hydride.

The effect of aging upon microstructure is illustrated in Figures 24 and 25. Coarse hydrides form during corrosion of the gamma-quenched specimen, while finer hydrides occur in the same alloy with prior aging treatment.

Figures 26 and 27 show carbon alloys before and after corrosion test. In the uranium-12 w/o molybdenum-0.1 w/o carbon alloy (Figure 27), there seems to be both coarse and fine hydride formation. There was no evidence of selective corrosion at or in the carbides.

The hydrides in the corrosion-tested as-cast uranium-10.5 w/o molybdenum-0.5 w/o tin alloy are extremely fine and are associated with the dark-etching constituent (Figure 28). As shown in Figure 29, coarse hydrides are formed in the corrosion test of a uranium-10.5 w/o molybdenum-1 tin as-cast gamma-quenched alloy which corroded at a rate of $-0.35 \text{ mg}/(\text{cm}^2)(\text{hr})$ with a corrosion life of 21 to 28 days. Other tin alloys in the as-cast series which had fine hydrides (see Figure 28) had a lower corrosion rate, $\sim 0.1 \text{ mg}/(\text{cm}^2)(\text{hr})$, and a longer life (up to 105 days). This points toward the deleterious effects of coarse hydrides, compared with finer ones, although the quantity of hydrides is probably a very important factor also.

250X

RM2526

FIGURE 17. URANIUM-12 w/o MOLYBDENUM ALLOY BEFORE CORROSION TESTING

As Cast, Showing Cored Gamma; Chromic Acetic Etch

250X

RM2524

FIGURE 18. URANIUM-10.5 w/o MOLYBDENUM AS-CAST ALLOY BEFORE CORROSION TESTING

Heat Treatment; 900 C for 12 Days and WQ; Homogeneous Gamma; Chromic Acetic Etch

954 034

03712281030

250X

RM2525

FIGURE 19. URANIUM-10.5 w/o MOLYBDENUM CAST ALLOY BEFORE CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Gamma and Transformation Product; Chromic Acetic Etch

CONFIDENTIAL

40

250X

RM2690

FIGURE 20. URANIUM-12 w/o MOLYBDENUM CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ; Coarse Hydrides in Gamma Matrix; Chromic Etch

250X

RM2631

FIGURE 21. URANIUM-12 w/o MOLYBDENUM-0.25 w/o ZIRCONIUM CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ; Fine Hydride Needles in Gamma; Some Transformation Product in Grain Boundaries; Chromic Etch

954-036

CONFIDENTIAL

037122A.030

250X

RM2691

FIGURE 22. URANIUM-12 w/o MOLYBDENUM CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Fine Widmanstätten Hydride in Gamma; Some Grain-Boundary Transformation; Chromic Etch.

250X

RM2679

FIGURE 23. URANIUM-12 w/o MOLYBDENUM-0.5 w/o ZIRCONIUM CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Gamma With Some Transformation Product; Chromic Etch; Note the Absence of Hydrides

954 037

250X

RM2669

FIGURE 24. URANIUM-12 w/o MOLYBDENUM-75 ppm NITROGEN CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ; Coarse Hydrides in Gamma Matrix; Chromic Etch

250X

RM2670

FIGURE 25. URANIUM-12 w/o MOLYBDENUM-75 ppm NITROGEN CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Fine Widmanstätten Hydrides in Gamma Matrix; Some Grain-Boundary Transformation and Cracks; Chromic Etch

250X

RM2539

FIGURE 26. URANIUM-12 w/o MOLYBDENUM-0.5 w/o CARBON CAST ALLOY BEFORE CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Gamma, Carbide and Porosity; $\text{NH}_4\text{OH} + \text{H}_2\text{O}_2$ Etch

250X

RM2683

FIGURE 27. URANIUM-12 w/o MOLYBDENUM-0.1 w/o CARBON CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ; Carbides and Coarse Hydrides in Gamma Matrix; Chromic Etch

250X

RM2675

FIGURE 28. URANIUM-10.5 w/o MOLYBDENUM-0.5 w/o TIN CAST ALLOY AFTER CORROSION TESTING

Dark-Etching Phase Contains Some Fine Hydride Needles; the Lighter Phase is Gamma; Chromic Etch

250X

RM2673

FIGURE 29. URANIUM-10.5 w/o MOLYBDENUM-1 w/o TIN CAST ALLOY AFTER CORROSION TESTING

Original Heat Treatment; 900 C for 12 Days and WQ; Coarse Hydride Needles in Gamma; Dark Globules are Probably U_5Sn_4 ; Chromic Etch

250X

RM2881

FIGURE 30. URANIUM-9 w/o MOLYBDENUM WROUGHT ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 1 Week at 400 C and WQ; Gamma Matrix With Widmanstätten Transformation Product and Hydrides; Note the Nitride Spheroids; Chromic Etch

250X

RM2882

FIGURE 31. URANIUM-10.5 w/o MOLYBDENUM-0.5 w/o TIN WROUGHT ALLOY AFTER CORROSION TESTING

Original Heat Treatment: 900 C for 12 Days and WQ Plus Aged 3 Weeks at 400 C and WQ; Dark Tin Compound in Gamma Matrix; Light Gray is Believed to be Transformation Product Containing Hydride Needles; Chromic Etch

Two examples of microstructures of wrought alloys after corrosion testing are included in Figures 30 and 31 to illustrate the appearance of the fine transformation product. As indicated in Table 3, the hydrides formed during the corrosion of aged specimens from the wrought series are usually fine. Perhaps the hydrides are present in larger quantities than in the cast alloys, and this could account for the poorer corrosion resistance of the wrought alloys.

Melting Materials

Uranium Melting Stock

It can be seen from Tables 4 and 5 that preparing the binary 10.5 and 12 w/o molybdenum alloys from dingot, WAPD-Fernald, electrolytic, center-cut biscuit, or vacuum-annealed center-cut biscuit (vacuum annealed at 640 C after alloying) uranium melting stocks did not result in any marked difference in corrosion behavior. However, it should be noted that as little as 0.05 w/o silicon improved the corrosion resistance of the binaries and that individual melts high in such an element could exhibit unusual corrosion properties. There was also very little variation in hardness or microstructure (Tables 4 and 5) for the various uranium melting stocks. Chemical analyses are given in Appendixes A and B.

Variation in Crucible Composition

Corrosion, microstructure, and hardness data resulting from melting the uranium stock in various crucible materials [graphite (biscuit), BeO, MgO, and ZrO₂] are presented in Table 6 and some of the chemical analyses in Appendixes A and B. The pickup of zirconium, beryllium, and magnesium appears insignificant and is summarized as follows:

<u>Crucible</u>	Nominal	<u>Analysis, ppm</u>		
	<u>Molybdenum, w/o</u>	<u>Zirconium</u>	<u>Beryllium</u>	<u>Magnesium</u>
<u>Cast Alloy</u>				
BeO	12.0		<2	
MgO	12.0			<2
ZrO ₂	12.0	<10		
<u>Wrought Alloy</u>				
BeO	10.5	<5	<2	<2
BeO	12.0	<5	<2	<2
MgO	10.5	10	<2	<2
MgO	12.0	10	<2	<2
ZrO ₂	10.5	<5	<2	<2
ZrO ₂	12.0	<5	<2	<2

954 042

47

TABLE 4. EFFECT OF URANIUM MELTING STOCK ON CORROSION BEHAVIOR, MICROSTRUCTURE, AND HARDNESS OF BINARY WROUGHT URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

All specimens given 12 days at 900 C and water quenched and aged at 400 C for various times as indicated.

Uranium Melting Stock	Aging Time ^(a) , weeks	Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
		VHN (10-Kg Load)	Microstructure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Microstructure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days
Center-cut biscuit	0	312	B	-0.14	21-28	336	BNO	-0.38	14-21
Vacuum-annealed center-cut biscuit	0	309	B2	-0.14	21-28	322	BNO	-0.14	21-28
Dingot	0	302	BNO	-0.46	14-21	333	BNO	-0.27	14-21
WAPD-Fernald	0	314	BNO	-0.58	7-14	330	BNO	-0.26	14-21
Electrolytic	0	304	BNO	-0.28	7-14	330	BNO	-0.42	7-14
Center-cut biscuit	1	401	BTNO	-0.20	3-7	357	BTNO	No Test	
Vacuum-annealed center-cut biscuit	1	387	BTS2	-0.06	7-21	345	BTNO	-0.09	21-28
Dingot	1	397	BT	-0.26	7-14	360	BT	-0.23	14-21
WAPD-Fernald	1	397	BT	-0.26	14-21	351	BT	-0.24	14-21
Electrolytic	1	390	BT	-0.11	35-42	363	BT	-0.26	7-14
Center-cut biscuit	3	579	BT	--	0-3	429	BT	-0.15	7-14
Vacuum-annealed center-cut biscuit	3	519	BTn	-0.11	3-7	363	BT	-0.10	7-21
Dingot	3	508	BT	-0.68	7-14	401	BT	-0.10	14-21
WAPD-Fernald	3	508	BT	-1.11	7-14	405	BT	-0.10	14-21
Electrolytic	3	514	BT	-0.26	3-7	387	BT	-0.13	28-35
Center-cut biscuit	5	536	BT	No Test		468	BT	-0.15	7-14
Vacuum-annealed center-cut biscuit	5	536	BTn	-0.58	7-21	478	BTn	-0.20	7-21
Dingot	5	548	BTNO	-0.45	14-21	459	BTNO	-0.23	14-21
WAPD-Fernald	5	560	BTNO	-0.76	7-14	478	BTNO	-0.14	21-28
Electrolytic	5	519	BTn	-0.84	7-14	464	BTn	-0.25	14-21

Footnotes appear on following page.

~~CONFIDENTIAL~~

Footnotes to Table 4

- (a) Samples sealed in Vycor capsules during heat treatment. Water quenched after homogenizing and after aging.
- (b) Microstructure before corrosion testing. See Table 1 or 2 for identification of symbols used.
- (c) Lowest observed rate.
- (d) Time to cracking or disintegration (complete oxidation).
- (e) Vacuum annealed at 640 C after alloy melted and before heat treatment.

954-044
044

~~CONFIDENTIAL~~

037122A1030

49

TABLE 5. EFFECT OF URANIUM MELTING STOCK ON CORROSION BEHAVIOR, MICROSTRUCTURE, AND HARDNESS OF BINARY CAST URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

Uranium Melting Stock	Heat Treat- ment ^(a)	Uranium 10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
		VHN (10-Kg Load)	Microstructure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Microstructure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days
Center-cut biscuit	As cast	302	A	-0.15	56-63	330	A	-0.15	42-49
Vacuum-annealed									
center-cut biscuit ^(e)	As cast	287	A2	-0.25	35-42	314	A2	-0.27	28-35
Dingot	As cast	299	A2	-0.20	42-49	325	A2	-0.23	28-35
WAPD-Fernald	As cast	--	--	No test		330	A2	-0.22	42-49
Center-cut biscuit	f	299	B	-0.07	35-42	319	BOT	-0.09	21-28
Vacuum-annealed									
center-cut biscuit	f	302	BNO	-0.13	28-35	327	BNO	-0.09	28-35
Dingot	f	309	B	-0.09	35-42	339	BC	-0.16	21-35
WAPD-Fernald	f	--	--	No test		339	BNOC	-0.16	21-35
Center-cut biscuit	g	401	BT	-0.07	7-14	333	BOT	-0.08	14-21
Vacuum-annealed									
center-cut biscuit	g	373	BTS	-0.12	7-14	333	BTS	-0.13	7-14
Dingot	g	394		-0.11	3-7	342	BT	-0.11	7-21
WAPD-Fernald	g	--	--	No test		351	BTNO	-0.14	7-21

(a) Samples sealed in Vycor capsules during heat treatment. Water quenched after homogenizing and after aging.

(b) Microstructure before corrosion testing. For identification of symbols, see footnotes of Table 1 or 2.

(c) Lowest observed rate.

(d) Time to cracking or disintegration (complete oxidation).

(e) Vacuum annealed at 640 C after alloy melted and before heat treatment.

(f) Held 12 days at 900 C and water quenched.

(g) Held 12 days at 900 C and water quenched, aged 1 week at 400 C and water quenched.

CONFIDENTIAL

CONFIDENTIAL

49

954

048

45

TABLE 6. EFFECT OF MELTING URANIUM STOCK IN SEVERAL CRUCIBLES ON MICROSTRUCTURE, HARDNESS, AND CORROSION BEHAVIOR OF URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

Crucible In Which Uranium Stock Melted ^(a)	Heat Treatment ^(b)				Cast Alloys								Wrought Alloys							
	Homogenizing		Aging		Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum				Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
	Temp, C		Time, days		VHN	Micro-	Corrosion	Corrosion	VHN	Micro-	Corrosion	Corrosion	VHN	Micro-	Corrosion	Corrosion	VHN	Micro-	Corrosion	Corrosion
	Temp, C	Time, days	Temp, C	Time, weeks	(10-Kg Load)	structure ^(c)	Rate ^(d) , mg/(cm ²)(hr)	Life ^(e) , days	(10-Kg Load)	structure ^(c)	Rate ^(d) , mg/(cm ²)(hr)	Life ^(e) , days	(10-Kg Load)	structure ^(c)	Rate ^(d) , mg/(cm ²)(hr)	Life ^(e) , days	(10-Kg Load)	structure ^(c)	Rate ^(d) , mg/(cm ²)(hr)	Life ^(e) , days
Graphite (biscuit)	None				302	A	-0.15	56-63	330	A	-0.15	42-49	No test				No test			
BeO					304	A2	-0.13	49-63	330	A2	-0.20	49-63	No test				No test			
MgO					304	A2NO	-0.21	42-49	330	A2NO	-0.27	28-35	No test				No test			
ZrO ₂					304	A2NO	-0.26	28-35	330	A2NO	-0.33	35-42	No test				No test			
Graphite (biscuit)	900	12	None		299	B	-0.07	35-42	319	BOT	-0.09	21-28	312	B	-0.14	21-28	336	BNO	-0.21	14-21
BeO					314	B2NO	-0.13	28-35	333	B2NO	-0.13	21-28	299	Bd	-0.39	14-21	333	Bd	-0.49	7-14
MgO					312	Bd	-0.17	21-28	330	Bd	-0.18	21-28	319	Bd	-0.33	7-14	333	Bd	-0.58	7-14
ZrO ₂					309	Bd	-0.15	28-35	342	Bd	-0.14	21-28	306	Bd	-0.52	14-21	330	Bd	-0.63	7-14
Graphite (biscuit)	900	12	400	1	401	BT	-0.07	7-14	333	BOT	-0.08	14-21	401	BTNO	-0.20	3-7	357	BTNO	No data	
BeO					468	BTS	-0.06	14-21	363	BT	-0.10	14-21	387	BdT	-0.13	14-21	360	BT	-0.16	14-21
MgO					366	B	-0.08	14-21	363	B	-0.14	21-35	401	-	-0.08	28-35	363	BdT	-0.14	28-35
ZrO ₂					421	BT	-0.08	14-21	363	BT	-0.10	14-21	401	BT	-0.14	7-14	370	BT	-0.22	14-21
Graphite (biscuit)	900	12	400	3	No test				No test				579	BT	-	0-3	429	BT	-0.15	7-14
BeO					No test				No test				503	BTn	-0.48	7-14	405	BT	-0.16	14-21
MgO					No test				No test				514	BTn	-0.32	14-21	401	BT	-0.08	28-35
ZrO ₂					No test				No test				514	BTn	-0.84	7-14	401	BT	-0.13	21-28
Graphite (biscuit)	900	12	400	5	No test				No test				536	BT	No data		468	BT	-0.15	7-14
BeO					No test				No test				530	BTNO	-2.28	7-14	473	BTNO	-0.40	14-21
MgO					No test				No test				554	BTNO	-	0-3	473	BTNO	-0.25	7-14
ZrO ₂					No test				No test				542	BTNO	-1.08	7-14	464	BTNO	-0.21	7-14

(a) Biscuit uranium employed as stock for melting in BeO, MgO, and ZrO₂ crucibles. All melts bottom poured into graphite molds.

(b) Samples sealed in Vycor capsules during heat treatment, water quenched after homogenizing and after aging.

(c) Microstructure before corrosion testing. For identification of symbols, see footnotes of Table 1 or 2 (I, dirty structure, probably excessive oxides, nitrides and/or carbides).

(d) Lowest observed rate.

(e) Time to cracking or disintegration (complete oxidation).

In both the cast and the wrought alloys the carbon increased 40 to 50 ppm and the iron increased from 20 to 100 ppm. Oxygen and nitrogen increased somewhat in the cast alloys. No corresponding changes were noted, however, in the corrosion behavior (Table 6), and these pickups, as well as those of zirconium, beryllium, and magnesium (if any), do not appear to affect corrosion resistance.

Heat Treatment

Because of the importance of heat treatment in determining corrosion resistance, further examinations of heat-treatment variables were made. It has already been noted (see Tables 1 and 2) that samples from any one alloy were, in general, more resistant in the as-cast than in the as-cast gamma-quenched condition, and the latter were more resistant than those samples aged at 400 C. To explore this more carefully, several experiments were conducted to determine the effect on corrosion behavior of time, temperature, and quenching rate during homogenization and the effect of time and temperature on aging treatment.

Homogenization

The following homogenizing heat treatments were investigated: 800 C for 12 days, 900 C for 1, 2, 7, or 12 days, and 1000 C for 1/2 or 24 hr. Wrought samples of the 10.5 and 12 w/o molybdenum binaries were sealed in Vycor capsules under a partial pressure of helium, and the capsules were not broken when water quenched after the homogenizing treatment. The effect of each of the above treatments on subsequent aging also was investigated with treatments of 1, 3, or 5 weeks at 400 C followed by a water quench. Corrosion data are presented in Table 7 and, in general, all homogenizing treatments reveal about the same corrosion behavior as observed with the treatment of holding at 900 C for 12 days and water quenching employed in the compositional-variable studies. No significant variations were observed in the hardnesses or microstructures.

Quenching Rate

The following variations in quenching rate of wrought binary alloys were studied:

- (1) Held at 900 C for 1 or 12 days and water quenched in sealed Vycor capsules or from broken capsules (direct quench)

954 - 047

TABLE 7. EFFECT OF HOMOGENIZATION TIME AND TEMPERATURE ON HARDNESS, MICROSTRUCTURE, AND CORROSION BEHAVIOR OF WROUGHT URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

Heat Treatment(a)				Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
Homogenizing		Aging		VHN	Microstructure(b)	Corrosion	Corrosion	VHN	Microstructure(b)	Corrosion	Corrosion
Temp, C	Time, days	Temp, C	Time, weeks	(10-Kg Load)		Rate(c), mg/(cm ²)(hr)	Life(d), days	(10-Kg Load)		Rate(c), mg/(cm ²)(hr)	Life(d), days
800	12	none	none	314		-0.22	14-21	333		-0.30	14-21
800	12	400	1	394	BT	-0.24	3-7	360	BT	-0.21	7-14
800	12	400	3	514		--	0-3	394		-0.20	7-14
800	12	400	5	554	BT	--	0-3	468	BT	-0.68	3-7
900	1	none	none	306		-0.15	21-28	330		-0.21	14-21
900	2	none	none	309		-0.14	21-28	330		-0.34	14-21
900	7	none	none	309		-0.14	21-28	327		-0.34	14-21
900	12	none	none	314	B	-0.14	21-28	336	BNO	-0.38	14-21
900	1	400	1	394	BT	-0.13	3-7	360	BT	-0.10	14-21
900	2	400	1	393		-0.11	3-7	351		-0.14	7-14
900	7	400	1	397		-0.32	3-7	351		-0.14	7-14
900	12	400	1	401	BTNO	-0.20	3-7	357	BTNO	No data	
900	1	400	5	554	BT	--	0-3	503	BT	-0.32	3-7
900	2	400	5	566			0-3	503		--	0-3
900	7	400	5	579			0-3	508		-0.30	3-7
900	12	400	5	536	BT	No test		468	BT	-0.15	7-14
1000	1/2 hr	none	none	312		-0.19	21-28	339		-0.26	21-28
1000	24 hr	none	none	319		--	0-3	339		-0.30	14-21
1000	1/2 hr	400	1	409	BTNO	-0.68	3-7	354	BT	-0.21	7-14
1000	24 hr	400	1	394	BTNO	-0.21	7-14	357	BTNO	-0.23	7-14
1000	1/2 hr	400	3	536		--	0-3	413		-0.19	7-14
1000	24 hr	400	3	519		-3.06	7-14	394		-0.20	3-7

53

TABLE 7. (Continued)

Heat Treatment ^(a)				Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
Homogenizing		Aging		VHN	Microstructure ^(b)	Corrosion	Corrosion	VHN	Microstructure ^(b)	Corrosion	Corrosion
Temp, C	Time, days	Temp, C	Time, weeks	(10-Kg Load)		Rate ^(c) , mg/(cm ²)(hr)	Life ^(d) , days	(10-Kg Load)		Rate ^(c) , mg/(cm ²)(hr)	Life ^(d) , days
1000	1/2 hr	400	5	554	BT	--	0-3	473	BT	-0.61	7-14
1000	24 hr	400	5	560		--	0-3	468		-0.20	3-7

(a) Sample sealed in Vycor capsules during heat treatment. Water quenched after homogenizing and after aging.

(b) Microstructure before corrosion testing. For identification of symbols, see Table 1 or 2.

(c) Lowest observed rate.

(d) Time to cracking or disintegration (complete oxidation).

- (2) Held 1/2 hr at 1000 C and either air cooled on a metal plate or water quenched in sealed Vycor capsules.

Aging at 400 C for 1, 3, or 5 weeks after each of the above treatments also was investigated. It can be seen from Table 8 that the above variations in quenching did not have a marked effect on the corrosion behavior, hardness, or microstructure of the uranium-molybdenum alloys.

Aging

The effect on corrosion behavior of long-time aging (up to 10 weeks) at low temperatures (300 and 350 C) was determined on both cast and wrought binary alloys. Also investigated were aging treatments up to 10 weeks at 500 C. In Table 9 the corrosion and metallographic data for the above samples are compared with those obtained on the alloy series which was aged at 400 C. Lowering the aging temperature and lengthening the aging time did not improve the corrosion resistance of the binaries beyond that obtained by gamma quenching. As expected, aging at 500 C destroyed the corrosion resistance of the binary alloys and all disintegrated within the initial 3-day exposure. As indicated in Table 9, the gamma-phase transformation to the less-resistant alpha uranium plus epsilon structure is up to 90 per cent complete in some alloys aged at 500 C.

Additional Tests

Size Effects

Because of the shape and larger dimensions of the as-cast alloys, there was some question as to whether or not these factors were responsible for the differences in corrosion resistance in comparison with wrought sheet. Wrought specimens have a much higher surface to volume ratio than the cast series, and it is well known that contamination by diffusion is extremely sensitive to geometry. A series of corrosion tests are now under way to check this point, but the results are not yet available. The variables introduced are outlined in Table 10.

Ternary Additions

Table 11 contains an outline of additional ternary alloys now in corrosion testing. It was of interest to test smaller amounts of platinum and nickel than had been used in WAPD studies for possible depolarization effects leading to a decrease in hydrogen pickup. Copper and tungsten ternary additions were made on the basis that these are contaminants often introduced

55

TABLE 8. EFFECT OF QUENCHING RATE AFTER HOMOGENIZATION ON HARDNESS, MICROSTRUCTURE, AND CORROSION BEHAVIOR OF WROUGHT URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

Heat Treatment ^(a)				Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum				
Homogenizing			Aging		VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)(hr)	Corrosion Life ^(d) , days
Temp, C	Time, days	Type of Quench	Temp, C	Time, weeks								
900	1	Vycor capsule intact; water quench	None		312	—	−0.15	21-28	330	—	−0.21	14-21
900	12		None		314	B	−0.14	21-28	336	BNO	−0.38	14-21
900	1	Vycor capsule broken; water quench	None		309	—	−0.22	14-21	339	—	−0.29	14-21
900	12		None		309	—	−0.17	14-21	336	—	−0.32	7-14
1000	1/2 hr	Air cool on metal plate	None		292	B	−0.21	7-14	314	B	−0.27	14-21
1000	1/2 hr	Vycor capsule intact; water quench	None		312	—	−0.19	21-28	339	—	−0.26	21-28
900	1	Vycor capsule intact; water quench	400	1	394	—	−0.13	3-7	360	—	−0.10	14-21
900	12		400	1	401	BTNO	−0.20	3-7	357	BTNO	No data	
900	1	Vycor capsule broken; water quench	400	1	421	—	−0.15	21-28	357	—	−0.19	7-14
900	12		400	1	383	BT	−0.07	7-14	363	BTNO	−0.24	7-14
1000	1/2 hr	Air cool on metal plate	400	1	373	BT	−0.17	7-14	351	BT	−0.13	21-28
1000	1/2 hr	Vycor capsule intact, water quench	400	1	409	BTNO	−0.68	3-7	354	BT	−0.21	7-14
900	1	Vycor capsule intact; water quench	400	3	—	—	No data		—	—	No data	
900	12		400	3	579	BT	—	0-3	429	BT	−0.15	7-14
900	1	Vycor capsule broken; water quench	400	3	542	—	−1.27	3-7	405	—	−0.21	7-14
900	12		400	3	525	—	—	0-3	421	—	−0.20	14-21
1000	1/2 hr	Air cool on metal plate	400	3	530	BT	−0.16	14-21	405	BT	−0.22	14-21
1000	1/2 hr	Vycor capsule intact; water quench	400	3	536	—	—	0-3	413	—	−0.19	7-14
900	1	Vycor capsule intact; water quench	400	5	554	—	—	0-3	503	—	−0.32	3-7
900	12		400	5	536	BT	No data		468	BT	−0.15	7-14
900	1	Vycor capsule broken; water quench	400	5	566	—	−1.04	3-7	498	—	−0.12	7-14
900	12		400	5	560	BT	−0.84	3-7	478	BT	−0.14	21-35
1000	1/2 hr	Air cool on metal plate	400	5	542	BT	−2.52	3-7	462	BT	−0.19	14-21
1000	1/2 hr	Vycor capsule intact; water quench	400	5	554	—	—	0-3	473	—	−0.20	3-7

(a) All aging treatments carried out in sealed Vycor capsules.

(b) Microstructure before corrosion test. For identification of symbols, see Table 1 or 2.

(c) Lowest observed rate.

(d) Time to cracking or disintegration (complete oxidation).

TABLE 9. EFFECT OF AGING TREATMENT ON HARDNESS, MICROSTRUCTURE, AND CORROSION BEHAVIOR OF URANIUM-MOLYBDENUM ALLOYS IN 650 F DEGASSED WATER

Cast Alloys										Wrought Alloys							
Uranium-10.5 w/o Molybdenum					Uranium-12 w/o Molybdenum					Uranium-10.5 w/o Molybdenum				Uranium-12 w/o Molybdenum			
Aging Treatment ^(a)		VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)hr	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)hr	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)hr	Corrosion Life ^(d) , days	VHN (10-Kg Load)	Micro- structure ^(b)	Corrosion Rate ^(c) , mg/(cm ²)hr	Corrosion Life ^(d) , days
Temp, C	Time, weeks																
300	0	299	B	-0.07	35-42	319	BOT	-0.09	21-28	312	B	-0.14	21-28	336	BNO	-0.38	14-21
300	1	312	B	-0.14	14-21	322	B	-0.15	14-21	297	B	-0.16	21-35	333	B	-0.21	14-21
300	5	302	-	-0.12	21-28	322	-	-0.20	21-28	304	-	-0.14	28-35	314	-	-0.19	14-21
300	10	302	B	-0.17	21-28	317	B	-0.16	14-21	299	BT	-0.17	14-21	322	B	-0.21	7-14
350	0	299	B	-0.07	35-42	319	BOT	-0.09	21-28	312	B	-0.14	21-28	336	BNO	-0.38	14-21
350	1	319	B	-0.16	14-21	339	B	-0.21	14-21	325	B	-0.12	21-35	322	B	-0.26	7-14
350	5	508	-	-0.10	7-14	339	-	-0.14	21-28	478	-	-0.09	7-14	322	-	-0.17	14-21
350	10	514	BT	-0.12	7-14	348	BT	-0.17	14-21	508	BT	-0.13	3-7	373	BT	-0.08	14-21
400	0	299	B	-0.07	35-42	319	BOT	-0.09	21-28	312	B	-0.14	21-28	336	BNO	-0.38	14-21
400	1	401	BT	-0.07	7-14	333	BOT	-0.08	14-21	401	BTNO	-0.20	3-7	357	BTNO	No test	
400	3		No test				No test			579	BT	-	0-3	429	BT	-0.15	7-14
400	5		No test				No test			536	BT	No test		468	BT	-0.15	7-14
500	0	299	B	-0.07	35-42	319	BOT	-0.09	21-28	312	B	-0.14	21-28	336	BNO	-0.38	14-21
500	1	446	90% T, B	-	0-3	339	BT	-	0-3	390	50% T, B	-	0-3	333	10% T, B	-	0-3
500	3	433	-	-	0-3	351	-	-	0-3	421	-	-	0-3	345	-	-	0-3
500	5	336	-	-	0-3	376	-	-	0-3	421	-	-	0-3	327	-	-	0-3

(a) All specimens held 12 days at 900 C and water quenched prior to aging.

(b) Microstructure before corrosion testing. For identification of symbols, see Table 1 or 2.

(c) Lowest observed rate.

(d) Time to cracking or disintegration (complete oxidation).

TABLE 10. OUTLINE OF TEST VARIABLES FOR SIZE AND SHAPE EFFECTS

Nominal Molybdenum Content, w/o	Description of Alloy
12.0	Duplex melted, forged at 1850 F, rolled at 1800 F, and air cooled; cut into sections measuring about 7/16 by 3/4 by 1/2 in.
10.5	1/2 by 1/2 by 0.080-in. specimens cut from scrap end sections of rolled alloys
12.0	1/2 by 1/2 by 0.080-in. specimens cut from scrap end sections of rolled alloys
10.5	Arc-melted button forged to 3/8-in.-square rod; cut to give sections 3/8 by 3/8 by 5/8 in.
12.0	Arc-melted button forged to 3/8-in.-square rod; cut to give sections 3/8 by 3/8 by 5/8 in.

TABLE 11. OUTLINE OF ADDITIONAL TERNARY ALLOYS (CAST SERIES)

Nominal Addition Element	Nominal Molybdenum Content, w/o	Vickers Hardness Number (10-Kg Load)		
		As Melted	900 C for 1 Day and Water Quenched	900 C for 1 Day and Water Quenched plus 400 C for 1 Week and Water Quenched
Cu 0.05 w/o	12.0			
Cu 0.10 w/o	12.0	327	339	405
W 0.05 w/o	12.0			
W 0.10 w/o	12.0	336	339	342
Pt 0.05 w/o	12.0			
Pt 0.10 w/o	12.0	342	339	339
Ni 0.05 w/o	12.0			
Ni 0.10 w/o	12.0	336	339	
Si 0.25 w/o	10.5	383	357	
Si 0.25 w/o	12.0	413	373	433
Si 0.50 w/o	10.5	342		397
Si 0.50 w/o	12.0	366	351	390
Zr 2 w/o	10.5	421		
Zr 2 w/o	12.0			514
Zr 4 w/o	10.5	339		634
Zr 4 w/o	12.0			620

954 054

from the electrodes and crucibles in arc melting. Higher levels of silicon and zirconium additions than previously reported are also being studied. The results of these additional tests will be reported in the September and October, 1955, BMI progress reports.

CONCLUSIONS

- (1) A marked increase in corrosion resistance was found in the uranium-10.5 w/o molybdenum alloys with ternary additions of

0.05 to 0.10 w/o silicon
0.5 to 1.0 w/o zirconium
0.25 to 1.0 w/o tin.

Corrosion rates were as low as $-0.01 \text{ mg}/(\text{cm}^2)(\text{hr})$, and the corrosion life was approximately 110 to 125 days which was double that observed for the most resistant binary (as-melted uranium-10.5 w/o molybdenum).

- (2) The following ternary additions had little or no effect on corrosion behavior of the alloys studied:

0.01 to 0.025 w/o silicon
0.001 to 0.25 w/o zirconium
0.001 to 0.10 w/o tin
1 to 10 ppm hydrogen
65 to 360 ppm oxygen
20 to 820 ppm nitrogen.

- (3) Maximum corrosion resistance could not be correlated with any given heat treatment, but, in general, aging was found to decrease corrosion resistance drastically when large quantities of gamma transformed to alpha uranium and epsilon. On the other hand, some of the as-cast alloys with rather large amounts of transformation products showed up well in corrosion tests.
- (4) The discontinuous failures in corrosion tests are associated with hydrogen contamination during corrosion and its subsequent precipitation as needles or plates. Zirconium in excess of about 0.5 w/o appears to suppress the hydride precipitation during corrosion of uranium-10.5 w/o molybdenum-0.5 w/o zirconium and uranium-12 w/o molybdenum-0.5 w/o zirconium alloys (see Figure 23).

- (5) In the cast series of alloys, it was observed that the greatest improvement in corrosion resistance could be associated with the elements (silicon, tin, and zirconium) which decreased the aging response or had no effect upon it.
- (6) There was no indication that corrosion behavior was sensitive to the uranium melting stock, the type of crucible in which the biscuit was melted, the quenching rate, or the homogenization treatment.

REFERENCES

- (1) Bostrum, W. A., Internal Memorandum to B. Lustman, PWR Metallurgy Subdivision, WAPD (October 30, 1954).
- (2) Personal communication with S. A. Weber, PWR Chemistry Subdivision, WAPD.
- (3) Lustman, B., "Résumé of Uranium Alloy Data-I", WAPD-MM-287 (February 19, 1954).
- (4) Thomas, D. E., and Lustman, B., "Résumé of Uranium Alloy Data-II", WAPD-MM-413 (April 15, 1954).
- (5) Castleman, L. S., Lustman, B., and Thomas, D. E., "Résumé of Uranium Alloy Data-III", WAPD-MM-429 (June 3, 1954).
- (6) Lustman, B., "Résumé of Uranium Alloy Data-IV", WAPD-MM-451 (August 9, 1954).
- (7) Lustman, B., "Résumé of Uranium Alloy Data-V" WAPD-MM-475 (October 20, 1954).

954 056

APPENDIX A

TABLE A-1. CHEMICAL ANALYSES OF URANIUM-MOLYBDENUM AS-CAST ALLOYS

Addition Element, nominal w/o	Nominal Molybdenum Content, w/o	Analysis								
		Weight Per Cent			PPM					
		Mo	Sn	Zr	C	Si	Fe	O	N	H
	9.0	8.82	-	-	40	40	300	24	30	1.5
	9.5	9.23	-	-	50	30	150	-	20	-
	10.0	9.96	-	-	30	30	200	-	20	-
	10.5	10.28	-	-	30	40	200	21	20	1.4
	11.0	10.89	-	-	40	40	400	-	30	-
	11.5	11.30	-	-	40	40	150	-	20	-
	12.0	11.94	-	-	20	20	100	27	30	1.6
	12.5	12.47	-	-	20	30	100	-	20	-
	13.0	12.98	-	-	40	30	100	-	30	-
Tin	1.0	10.5	-	0.97	-	-	-	-	30	-
	0.5	10.5	-	0.50	-	-	-	-	-	-
	0.25	10.5	-	0.22	-	-	-	-	-	-
	0.10	10.5	-	0.095	-	-	-	-	30	-
	0.05	10.5	-	0.03	-	-	-	-	-	-
	0.025	10.5	-	0.015	-	-	-	-	-	-
	0.01	10.5	-	0.005	-	-	-	-	-	-
	0.001	10.5	-	0.001	-	-	-	-	-	-
	1.0	12.0	-	0.91	-	-	-	-	30	-
	0.5	12.0	-	0.51	-	-	-	-	-	-
	0.25	12.0	-	0.24	-	-	-	-	-	-
	0.10	12.0	-	0.060	-	-	-	-	20	-
	0.05	12.0	-	0.035	-	-	-	-	-	-
	0.025	12.0	-	0.015	-	-	-	-	-	-
	0.01	12.0	-	0.005	-	-	-	-	-	-
	0.001	12.0	-	0.002	-	-	-	-	-	-
Zirconium	1.0	10.5	-	-	0.97	-	-	-	30	-
	0.5	10.5	-	-	0.53	-	-	-	-	-
	0.25	10.5	-	-	0.25	-	-	-	-	-
	0.1	10.5	-	-	0.096	-	-	-	20	-
	0.05	10.5	-	-	0.049	-	-	-	-	-
	0.025	10.5	-	-	0.023	-	-	-	-	-
	0.01	10.5	-	-	0.01	-	-	-	-	-
	0.001	10.5	-	-	0.0015	-	-	-	-	-
	1.0	12.0	-	-	1.01	-	-	-	30	-
	0.5	12.0	-	-	0.53	-	-	-	-	-
	0.25	12.0	-	-	0.24	-	-	-	-	-
	0.1	12.0	-	-	0.09	-	-	-	30	-
	0.05	12.0	-	-	0.042	-	-	-	-	-
	0.025	12.0	-	-	0.021	-	-	-	-	-
	0.01	12.0	-	-	0.01	-	-	-	-	-
	0.001	12.0	-	-	0.001	-	-	-	-	-
Hydrogen	(a)	10.5	-	-	-	-	-	-	-	<0.4
	1.0 ppm	10.5	-	-	-	-	-	-	-	0.6

TABLE A-1. (Continued)

Addition Element, nominal w/o			Nominal Molybdenum Content, w/o	Analysis								
				Weight Per Cent			PPM					
							Mo	Sn	Zr	C	Si	Fe
Hydrogen	10	ppm	10.5	-	-	-	-	-	-	-	-	5.3
	16	ppm	10.5	-	-	-	-	-	-	-	-	9.3
	(b)		12.0	-	-	-	-	-	-	-	-	<0.4
	1	ppm	12.0	-	-	-	-	-	-	-	-	1.1
	10	ppm	12.0	-	-	-	-	-	-	-	-	5.7
	16	ppm	12.0	-	-	-	-	-	-	-	-	7.7
Silicon	100	ppm	10.5	-	-	-	-	80	-	-	20	-
	250	ppm	10.5	-	-	-	-	200	-	-	-	-
	500	ppm	10.5	-	-	-	-	400	-	-	-	-
	1000	ppm	10.5	-	-	-	-	1100	-	-	-	-
	100	ppm	12.0	-	-	-	-	120	-	-	20	-
	250	ppm	12.0	-	-	-	-	250	-	-	-	-
	500	ppm	12.0	-	-	-	-	350	-	-	-	-
	1000	ppm	12.0	-	-	-	-	900	-	-	-	-
Carbon	100	ppm	10.5	-	-	-	150	-	-	-	20	-
	250	ppm	10.5	-	-	-	340	-	-	-	-	-
	1000	ppm	10.5	-	-	-	1100	-	-	-	-	-
	5000	ppm	10.5	-	-	-	4600	-	-	-	-	-
	100	ppm	12.0	-	-	-	150	-	-	-	20	-
	250	ppm	12.0	-	-	-	340	-	-	-	-	-
	1000	ppm	12.0	-	-	-	1200	-	-	-	-	-
	5000	ppm	12.0	-	-	-	5000	-	-	-	-	-
Oxygen	50	ppm	10.5	-	-	-	-	-	-	65	-	1.2
	75	ppm	10.5	-	-	-	-	-	-	86	-	1.2
	100	ppm	10.5	-	-	-	-	-	-	363	-	2.0
	250	ppm	10.5	-	-	-	-	-	-	112	-	1.3
	50	ppm	12.0	-	-	-	-	-	-	67	-	1.3
	75	ppm	12.0	-	-	-	-	-	-	84	-	1.1
	100	ppm	12.0	-	-	-	-	-	-	98	-	1.4
	250	ppm	12.0	-	-	-	-	-	-	130	-	1.5
Nitrogen	75	ppm	10.5	-	-	-	-	-	-	-	60	-
	100	ppm	10.5	-	-	-	-	-	-	-	110	-
	150	ppm	10.5	-	-	-	-	-	-	-	130	-
	200	ppm	10.5	-	-	-	-	-	-	-	170	-
	75	ppm	12.0	-	-	-	-	-	-	-	70	-
	100	ppm	12.0	-	-	-	-	-	-	-	70	-
	150	ppm	12.0	-	-	-	-	-	-	-	130	-
	200	ppm	12.0	-	-	-	-	-	-	-	170	-
BeO crucible ^(b)			10.5	-	-	-	-	-	-	-	-	-
BeO crucible			12.0	-	-	-	60	-	160	32	30	1.3
MgO crucible			10.5	-	-	-	-	-	-	-	-	-
MgO crucible			12.0	-	-	-	70	-	120	75	100	1.4
ZrO ₂ crucible			10.5	-	-	-	-	-	-	-	-	-
ZrO ₂ crucible			12.0	-	-	<0.001	70	-	120	33	40	0.8

954-058

CONFIDENTIAL

~~CONFIDENTIAL~~

63 63 and 64

TABLE A-1. (Continued)

Addition Element, nominal w/o	Nominal Molybdenum Content, w/o	Analysis								
		Weight Per Cent			PPM					
		Mo	Sn	Zr	C	Si	Fe	O	N	H
Dingot uranium ^(c)	10.5	-	-	-	-	-	-	-	-	-
Dingot uranium	12.0	-	-	-	50	-	80	19	30	1.3
WAPD uranium	12.0	-	-	-	100	-	110	27	50	1.4

(a) Vacuum annealed.

(b) Crucible material is variable.

(c) Uranium melting stock is variable.

~~CONFIDENTIAL~~

RECEIVED

954 059

49

DECLASSIFIED

954 060

090-756

CONFIDENTIAL

65

APPENDIX B

TABLE B-1. CHEMICAL ANALYSES OF WROUGHT URANIUM-MOLYBDENUM ALLOYS

Addition Element, nominal w/o	Nominal Molybdenum Content, w/o	Analysis								
		Weight Per Cent			PPM					
		Mo	Sn	Zr	C	Si	Fe	O	N	H
	9.0	8.94	-	-	20	30	120	-	260	-
	9.5	9.49	-	-	20	20	100	-	40	-
	10.0	10.0	-	-	30	40	150	-	280	-
	10.5	10.4	-	-	10	20	120	-	30	-
	11.0	10.9	-	-	20	30	120	-	30	-
	11.5	11.3	-	-	30	30	150	-	300	-
	12.0	11.8	-	-	30	40	100	-	160	-
	12.5	12.3	-	-	20	40	120	-	240	-
	13.0	12.9	-	-	30	40	100	-	220	-
	14.0	14.0	-	-	30	5	100	-	180	-
	15.0	15.0	-	-	60	15	150	-	130	-
	16.0	16.0	-	-	50	15	150	-	170	-
Tin	1.0	10.5	-	0.88	-	-	-	-	50	-
	0.5	10.5	-	0.47	-	-	-	-	-	-
	0.25	10.5	-	0.23	-	-	-	-	-	-
	0.1	10.5	-	0.08	-	-	-	-	40	-
	0.05	10.5	-	0.03	-	-	-	-	-	-
	0.025	10.5	-	0.02	-	-	-	-	-	-
	0.01	10.5	-	0.009	-	-	-	-	-	-
	0.001	10.5	-	0.001	-	-	-	-	-	-
	1.0	12.0	-	0.98	-	-	-	-	50	-
	0.5	12.0	-	0.54	-	-	-	-	-	-
	0.25	12.0	-	0.25	-	-	-	-	-	-
	0.1	12.0	-	0.06	-	-	-	-	40	-
	0.05	12.0	-	0.03	-	-	-	-	-	-
	0.025	12.0	-	0.017	-	-	-	-	-	-
	0.01	12.0	-	0.008	-	-	-	-	-	-
	0.001	12.0	-	0.001	-	-	-	-	-	-
Zirconium	1.0	10.5	-	-	0.97	-	-	-	120	-
	0.5	10.5	-	-	0.51	-	-	-	-	-
	0.25	10.5	-	-	0.25	-	-	-	-	-
	0.10	10.5	-	-	0.1	-	-	-	40	-
	0.05	10.5	-	-	0.058	-	-	-	-	-
	0.025	10.5	-	-	0.02	-	-	-	-	-
	0.01	10.5	-	-	0.008	-	-	-	-	-
	0.001	10.5	-	-	-	-	-	-	-	-
	1.0	12.0	-	-	1.01	-	-	-	50	-
	0.5	12.0	-	-	0.5	10	15	100	310	-
	0.25	12.0	-	-	0.25	10	20	80	480	-
	0.10	12.0	-	-	0.10	-	-	-	40	-
	0.05	12.0	-	-	0.05	-	-	-	-	-
	0.025	12.0	-	-	0.03	-	-	-	-	-
	0.01	12.0	-	-	0.007	-	-	-	-	-
	0.001	12.0	-	-	<0.0005	-	-	-	-	-

CONFIDENTIAL

DECLASSIFIED

954 061

CONFIDENTIAL

TABLE B-1. (Continued)

Addition Element, nominal w/o			Nominal Molybdenum Content, w/o	Analysis								
				Weight Per Cent			PPM					
				Mo	Sn	Zr	C	Si	Fe	O	N	H
Hydrogen	(a)		10.5	-	-	-	-	-	-	-	-	1.2
	1.0 ppm		10.5	-	-	-	-	-	-	-	-	0.6
	10.0 ppm		10.5	-	-	-	-	-	-	-	-	5.3
	16.0 ppm		10.5	-	-	-	-	-	-	-	-	9.3
	(a)		12.0	-	-	-	-	-	-	-	-	0.9
	1.0 ppm		12.0	-	-	-	-	-	-	-	-	1.1
	10.0 ppm		12.0	-	-	-	-	-	-	-	-	5.7
	16.0 ppm		12.0	-	-	-	-	-	-	-	-	7.7
Silicon	100 ppm		10.5	-	-	-	-	100	200	-	450	-
	250 ppm		10.5	-	-	-	-	300	100	-	-	-
	500 ppm		10.5	-	-	-	-	500	100	-	-	-
	1000 ppm		10.5	-	-	-	-	-	-	-	-	-
	100 ppm		12.0	-	-	-	-	100	200	-	300	-
	250 ppm		12.0	-	-	-	-	200	-	-	-	-
	500 ppm		12.0	-	-	-	-	500	-	-	-	-
	1000 ppm		12.0	-	-	-	-	-	-	-	-	-
Carbon	100 ppm		10.5	-	-	-	170	10	200	-	230	-
	250 ppm		10.5	-	-	-	340	20	250	-	570	-
	1000 ppm		10.5	-	-	-	1000	30	250	-	820	-
	5000 ppm		10.5	-	-	-	4700	40	200	-	500	-
	100 ppm		12.0	-	-	-	180	40	150	-	430	-
	250 ppm		12.0	-	-	-	330	40	150	-	440	-
	1000 ppm		12.0	-	-	-	1100	20	200	-	450	-
	5000 ppm		12.0	-	-	-	-	-	-	-	-	-
Oxygen	50 ppm		10.5	-	-	-	-	-	-	120	-	0.4
	75 ppm		10.5	-	-	-	-	-	-	120	-	0.5
	100 ppm		10.5	-	-	-	-	-	-	115	-	0.8
	250 ppm		10.5	-	-	-	-	-	-	190	-	0.3
	50 ppm		12.0	-	-	-	-	-	-	110	-	0.4
	75 ppm		12.0	-	-	-	-	-	-	120	-	0.4
	100 ppm		12.0	-	-	-	-	-	-	100	-	1.1
	250 ppm		12.0	-	-	-	-	-	-	160	-	0.4
Nitrogen	75 ppm		10.5	-	-	-	-	-	-	-	70	-
	100 ppm		10.5	-	-	-	-	-	-	-	60	-
	150 ppm		10.5	-	-	-	-	-	-	-	360	-
	200 ppm		10.5	-	-	-	-	-	-	-	520	-
	75 ppm		12.0	-	-	-	-	-	-	-	370	-
	100 ppm		12.0	-	-	-	-	-	-	-	300	-
	150 ppm		12.0	-	-	-	-	-	-	-	250	-
	200 ppm		12.0	-	-	-	-	-	-	-	130	-
BeO crucible ^(b)			10.5	-	-	-	60	30	150	170	250	0.6
BeO crucible			12.0	-	-	-	50	40	200	150	170	0.5
MgO crucible			10.5	-	-	-	70	50	200	120	450	0.4
MgO crucible			12.0	-	-	-	60	50	200	130	330	0.3

CONFIDENTIAL

954-062

0375081033

~~CONFIDENTIAL~~

67 and 68

67

TABLE B-1. (Continued)

Addition Element, nominal w/o	Nominal Molybdenum Content, w/o	Analysis								
		Weight Per Cent			PPM					
		Mo	Sn	Zr	C	Si	Fe	O	N	H
ZrO ₂ crucible	10.5	-	-	<0.0005	70	20	200	110	340	0.8
ZrO ₂ crucible	12.0	-	-	<0.0005	70	20	200	110	280	0.7
Dingot uranium ^(c)	10.5	-	-	-	30	20	150	130	160	<0.5
Dingot uranium	12.0	-	-	-	30	15	150	76	260	0.2
Electrolytic uranium	10.5	-	-	-	-	-	-	160	-	1.4
Electrolytic uranium	12.0	-	-	-	-	-	-	110	-	2.0
WAPD uranium	10.5	-	-	-	80	30	150	260	-	<0.3
WAPD uranium	12.0	-	-	-	100	20	200	110	330	0.9

(a) Vacuum annealed.

(b) The variable introduced here is one of melting in various types of crucibles.

(c) Melting stock is the variable.

~~CONFIDENTIAL~~

RECEIVED

954

063