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CORROSION OF URANIUM ALLOYS IN HIGH-TEMPERATURE WATER

by

H. A. Pray
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CORROSION OF URANIUM ALLOYS IN HIGH-TEMPERATURE WATER

by

H. A. Pray and W. E. Berry

In the search for a corrosion-resistant high-uranium-content alloy for use as core material in high-temperature-water-moderated reactors, the corrosion of binary and ternary uranium alloys was studied in water at 500 and 600 F. Alloys containing less than 40 wt % zirconium additions completely oxidized upon short exposure at 600 F, whereas 50 plus wt % alloys exhibited relatively low corrosion rates. Alloys were sensitive to heat treatment and were most resistant in the quenched condition. The corrosion rates of zirconium alloys were linear to slightly accelerated with respect to time. Alloys containing 40, 50, and 60 wt % zirconium were resistant to water at 500 F.

Molybdenum additions (arc-melted alloys) in the range of 10 to 15 wt % improved the resistance of uranium to 600 F water but did not result in corrosion-resistant alloys, probably because of inhomogeneity of the alloys studied.

The addition of molybdenum, niobium, thorium, tin, and titanium to uranium-20 wt % zirconium resulted in several promising alloys: uranium-20 zirconium-5 molybdenum and uranium-20 zirconium-10 niobium. Additions of up to 5 wt % molybdenum did not improve the resistance of 40 and 50% zirconium alloys to 600 F water.

A uranium-30 zirconium-5.6 tantalum alloy also exhibited promising resistance to 600 F water. Other additions (2 and 5 at.%) which did not improve the resistance of uranium-30 wt % zirconium were: antimony, bismuth, cerium, chromium, cobalt, iron, lead, nickel, niobium, silicon, thorium, titanium, and tungsten.

INTRODUCTION

This report is one of a series of five, dealing with alloys of the uranium-zirconium series. The complete series includes:

BMI-877, "Processing of Uranium-Zirconium Alloys"

BMI-878, "Examination and Properties of Uranium Alloys" (Heat treatment, microstructure, hardness, density)

BMI-879, "Mechanical Properties of Alloys of Uranium-Zirconium System"

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BMI-833, "A Hot-Hardness Survey of the Zirconium-Uranium System"

BMI-874, "Corrosion of Uranium Alloys in High-Temperature Water"

If additional information is desired about the fabrication or properties of the alloys described in this report, it can be found in one of the other four reports of the series. This work was a part of the studies of CVR (Carrier Vessel Reactor) fuel elements performed by Battelle for Westinghouse Atomic Power Division.

High-uranium-content alloys are now being sought for use as core material in high-temperature-water-moderated reactors. In case of defects in the cladding material, a core material which exhibits good corrosion resistance for the life of the reactor would be desirable. Since the addition of as little as 5 wt % zirconium to uranium is known to increase greatly its resistance to boiling water, a program was initiated to study the corrosion properties of uranium alloys, with zirconium as the major alloying agent, in high-temperature water.

The corrosion data presented below have not been reduced to corrosion rates. In general, however, the term "corrosion-resistant" is applied to alloy compositions for which the corrosion rate is in the range from 0.01 to 0.05 mg/(sq cm) (hr).

EXPERIMENTAL WORK

Test Procedures

Sample Preparation

Samples were shaper finished to remove all scale from heat-treating operations. Before testing, the specimens were degreased in acetone, rinsed, pickled 1.5 minutes in 1:1 nitric acid water (by volume), rinsed 30 min in tap water, dipped in acetone, air dried, and put on test as soon as possible. Pickling in nitric acid did not remove any appreciable amount of metal, but did brighten the samples (particularly those of low alloy content).

Test Conditions

Alloy samples were exposed under static conditions to high-temperature water in Type 316 stainless steel autoclaves. Temperature control was

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±5 F. The test water was distilled once and then passed through an ion-exchange column to give specific resistivity of approximately 1,000,000 ohm-cm. Autoclaves were filled with sufficient water to give a 10 per cent head space at temperature. This represents initial dissolved-oxygen concentrations (from air trapped in head space) of 60 ml/liter at 600 F and 30 ml/liter at 500 F. Samples were supported on Chromel A wire hooks. Samples were not electrically insulated from the hooks, but were supported so they did not touch each other, the walls, or the bottom of the autoclave.

Because of the large number of alloys tested, it was impossible to test each alloy composition by itself in a separate autoclave. To avoid the build-up of large quantities of hydrogen in the autoclave, alloys were screened and those suspected of having poor resistance were tested in separate autoclaves.

Before weighing, samples were scrubbed to remove loose oxide. No attempt was made to remove adherent oxide films. However, the samples having the latter were scrubbed as soon as the adherent films began to break down and flake off.

Test Results

Uranium-Zirconium Alloys

Induction Melts. Results are presented in Table 1 for an induction-melted uranium-zirconium-alloy series exposed to water at 600 F. Samples were tested in 5 heat-treated conditions. All alloys corroded uniformly, indicating homogeneous melts. Samples containing less than 50 wt % zirconium completely oxidized within 24 hr. In general, increasing zirconium content resulted in increased corrosion resistance. The effect of heat treatment on corrosion resistance was most pronounced in the high-zirconium-content alloys, with the quenched samples being the most resistant. It is interesting to note the remarkable resistance of the quenched 90 per cent zirconium-alloy sample.

Arc Melts. Corrosion data are summarized in Table 2 for a double-arc-melted uranium-zirconium-alloy series exposed to water at 600 F. Almost all the samples corroded in localized areas, indicating segregation of the alloying agent in the melt. In general, the alloys developed an adherent oxide film which eventually flaked off at a uniform rate (see Figure 1). The behavior of the arc-melted alloys paralleled that of induction-melted alloys, i. e., alloys containing less than 50 wt % zirconium completely oxidized within 24 hr, increasing zirconium content increased the corrosion resistance, and the quenched high-zirconium-content alloys were the most

TABLE 1. INDUCTION-MELTED URANIUM-ZIRCONIUM ALLOYS EXPOSED TO WATER AT 600 F
(Melted in Graphite From Grade I Crystal-Bar Zirconium and Fernald Grade Uranium)

Sample	Analysis, wt %			Total Weight Gain, mg/sq cm, at Hours Indicated												Remarks
	U	C	N	24	48	96	168	336	504	672	1344	2016	2688	3360		
1 Hr at 800 C - Water Quenched																
1	None	0.28	0.002	0.03	0.02	0.07	-0.37	-2.38	-4.50	-6.36	-10.8	-14.7	-15.9	-17.2	Uniform powdery white oxide	
2	9.99	0.24	0.002	0.01	-0.01	0.05	0.01	0.05	0.02	0.04	0.12	0.14	0.14	0.13	Adherent dark oxide; yellow flecks	
3	19.2	0.56	0.004	0	0	0.04	0.07	0.05	0.05	0.05	-0.97	-2.95	-5.11	-9.58	Uniform powdery yellow oxide	
4	28.3	0.96	0.006	-0.18	-0.20	-0.28	-0.52	-1.74	-3.97	-6.87	-25.0	--			Edge erupted, 1848 hr	
15	40.5	0.71	0.006	-0.15	-0.19	-0.27	-0.58	-1.69	-3.80	-6.60	-25.0	(a)			Uniform powdery yellow oxide	
6	49.9	0.66	0.005	-0.52	-0.78	-1.32	-2.82	-6.50	--						One-third disintegrated, 504 hr	
24 Hr at 575 C - Furnace Cooled																
1	None	0.28	0.002	0.04	0.07	0.04	-0.20	-0.82	-1.23	-1.92	-2.49	-2.80	-2.80	-2.90	Uniform powdery white oxide	
2	9.99	0.24	0.002	0.04	0.06	0.10	0.08	0.01	-0.04	-0.06	-0.60	-4.10	-6.50	-12.4	Uniform powdery yellow oxide	
3	19.2	0.56	0.004	0.05	0.07	0.02	-0.13	-0.39	-0.95	-2.22	-11.0	-19.8	-28.7	-40.1	Uniform powdery yellow oxide	
4	28.3	0.96	0.006	-0.19	-0.16	-0.28	-0.48	-1.73	-3.91	-7.03	-21.9	-36.3	-49.1	-64.7	Uniform powdery yellow oxide	
15	40.5	0.71	0.006	-0.13	-0.22	-0.32	-0.91	-1.96	-3.62	-5.80	-22.2	(a)			Uniform powdery yellow oxide	
6	49.9	0.66	0.005	-0.54	-0.81	-1.60	-3.17	-7.10	-13.6	-21.4	-59.7	(a)			Uniform powdery yellow oxide	
1 Hr at 800 C - Water Quenched Plus 24 Hr at 575 C - Furnace Cooled ^(b)																
1	None	0.28	0.002	0.02	-0.01	-0.33	-1.22	-3.82	-6.53	-8.76	-13.9	-15.9	-16.9	-16.7	Uniform powdery white oxide	
2	9.99	0.24	0.002	0.01	0.03	0.09	0.04	-0.07	-0.29	-0.90	-6.49	-14.0	-19.9	-29.1	Uniform powdery yellow oxide	
3	19.2	0.56	0.004	0	0.03	-0.01	-0.15	-0.44	-1.24	-2.87	-9.96	-16.4	-22.1	-31.7	Uniform powdery yellow oxide	
4	28.3	0.96	0.006	-0.67	-0.97	-1.82	-3.20	-6.88	-10.0	-14.1	-30.9	-47.3	-79.2	--	Edge erupted, 3024 hr	
1 Hr at 800 C - Quenched to 550 C - 2 Hr at 550 C - Air Cooled ^(b)																
1	None	0.28	0.002	0.03	0.05	-0.46	-1.62	-4.65	-7.77	-10.1	-16.6	-20.0	-21.2	-22.9	Uniform powdery white oxide	
4	28.3	0.96	0.006	-0.15	-0.15	-0.24	-0.28	-2.95	-2.35	-6.17	-21.3	-34.0	-45.6	-61.1	Uniform powdery yellow oxide	
1 Hr at 800 C - Water Quenched Plus 2 Hr at 650 C - Water Quenched ^(b)																
1	None	0.28	0.002	-0.01	0.09	-0.25	-0.87	-5.02	-4.58	-5.77	-8.48	-9.48	-10.1	-10.3	Uniform powdery white oxide	
2	9.99	0.24	0.002	0.02	0.05	0.07	0.11	-0.01	-0.07	-0.52	-4.72	-10.6	-15.9	-24.9	Uniform powdery yellow oxide	
3	19.2	0.56	0.004	0	0.01	-0.08	-0.10	-1.10	-3.05	-5.81	-18.1	-31.0	-41.7	-55.5	Uniform powdery yellow oxide	
4	28.3	0.96	0.006	-0.25	-0.27	-0.47	-0.63	-2.64	-18.2	--					Edge erupted, 504 hr	

Note: 60, 70, and 80 wt % uranium alloys disintegrated within 24 hr.

(a) Test started at later date.

(b) Only alloys containing up to 30 wt % uranium were tested.

TABLE 2. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM ALLOYS EXPOSED TO WATER AT 600 F
(Base Material - Grade I Crystal-Bar Zirconium and Biscuit Grade Uranium)

Sample	Analysis, wt %			Total Weight Gain, mg/sq cm, at Hours Indicated										Remarks ^(b)
	U	C	N	24	48	96	168	336	504	672	1344	2016	2688	
1 Hr at 800 C – Water Quenched ^(a)														
21	None	0.01	0.001	0.04	0.06	0.09	0.08	0.08	0.13	0.12	0.93	1.40	1.60	Adherent white oxide, 1008 hr
22	10.6	0.01	0.002	0.05	0.08	0.12	0.12	0.15	0.20	0.19	0.23	0.28	0.28	Adherent dark film
23	20.0	0.02	0.004	0.07	0.13	0.16	0.21	0.27	0.37	0.38	0.98	2.05	3.30	Dark coating with yellow streaks
24	29.6	0.02	0.004	0.13	0.19	0.30	0.64	1.76	2.72	3.65	3.96	--	--	Severe cracking, 2016 hr
25	39.4	0.02	0.004	0.15	0.18	0.30	0.57	1.74	1.24	-3.41	-26.0	-55.4	--	Severe cracking, 2016 hr
26	49.5	0.03	0.005	0.12	-0.95	-1.37	-1.60	-2.89	-4.98	-8.52	--	--	--	Erupted, 1176 hr
24 Hr at 575 C – Furnace Cooled ^(c)														
21	None	0.01	0.001	0.04	0.02	0.04	0.05	0.01	0.05	0.06	0.08	0.10	0.13	Adherent dark film
24	29.6	0.02	0.004	0.06	0.07	0.29	0.23	1.52	2.01	-8.17	-26.0	-41.6	-63.0	Flaky green-yellow oxide
25	39.4	0.02	0.004	0.16	0.19	0.27	0.40	0.78	0.89	1.00	-19.1	-38.8	-61.7	Flaky green-yellow oxide
26	49.5	0.03	0.005	0.21	0.23	0.31	0.41	-0.72	-3.33	-8.28	-40.0	-69.9	-107.0	Flaky green-yellow oxide
1 Hr at 800 C – Water Quenched Plus 24 Hr at 575 C – Furnace Cooled ^(c)														
21	None	0.01	0.001	0.05	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.10	0.11	Adherent dark film
24	29.6	0.02	0.004	0.11	0.17	0.30	0.62	1.50	2.49	3.68	2.08	-18.6	-37.9	Flaky green-yellow oxide
25	39.4	0.02	0.004	0.05	0.08	0.18	0.36	0.50	0.07	0.37	-18.4	-37.1	-65.4	Flaky green-yellow oxide
26	49.5	0.03	0.005	-0.34	-0.38	-0.37	-0.35	-0.56	-1.66	-2.73	-13.0	-27.9	-57.7	Flaky green-yellow oxide
1 Hr at 800 C – Quenched to 550 C – 2 Hr at 550 C – Air Cooled ^(c)														
21	None	0.01	0.001	0.07	0.05	0.06	0.06	0.07	0.07	0.11	0.87	1.57	2.06	Adherent white oxide, 1008 hr
24	29.6	0.02	0.004	0.17	0.18	0.25	0.41	0.96	1.81	2.99	8.04	12.1	-33.3	Flaky green-yellow oxide
25	39.4	0.02	0.004	0.15	0.18	0.26	0.35	0.59	0.57	0.81	-8.06	-25.0	-51.3	Flaky green-yellow oxide
26	49.5	0.03	0.005	0.06	0.04	0.10	0.15	-0.26	-1.49	-3.47	-22.8	-49.7	-86.5	Flaky green-yellow oxide
1 Hr at 800 C – Water Quenched Plus 2 Hr at 650 C – Water Quenched ^(a)														
21	None	0.01	0.001	0.08	0.04	0.05	0.05	0.08	0.06	0.08	0.09	0.14	0.18	Adherent dark film
24	29.6	0.02	0.004	0.17	0.14	0.22	0.40	0.94	-2.70	-2.11	-12.1	-21.8	-44.6	Flaky green-yellow oxide
25	39.4	0.02	0.004	0.19	0.10	0.29	0.37	0.64	0.53	-0.49	-15.4	-30.4	-49.9	Flaky green-yellow oxide
26	49.5	0.03	0.005	0.24	0.20	0.29	0.36	-0.65	-2.81	-6.04	-34.2	-78.4	--	Severe cracking, 2016 hr

(a) 60, 70, and 80 wt % uranium alloys disintegrated within 24 hr.

(b) All samples except 100 wt % zirconium alloy exhibit some segregation.

(c) Only those alloys listed were tested.

FIGURE 1. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM ALLOY SERIES EXPOSED TO WATER AT 600 F; SAMPLES QUENCHED FROM 800 C

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resistant. These results agree with those for 1 week's exposure of a uranium-zirconium-alloy series reported by Lustman of WAPD. (1)*

Triple-arc-melted alloys containing 20, 40, 50, and 60 wt % zirconium additions corroded more uniformly than the double-arc-melted samples, but still exhibited large weight changes. The 40 per cent alloy did not disintegrate within 24 hr as the induction-melted and double-arc-melted 40 per cent alloys had. The 50 per cent alloy appeared more resistant than the 40 or 60 per cent alloys.

This phenomenon was not observed with other zirconium series and, as yet, is unexplained. Data for these alloys are presented in Table 3.

The triple-arc-melted samples exhibit good resistance to 500 F water, as illustrated in Table 4. A comparison of 500 F- and 600 F-water results for a uranium-50 wt % zirconium alloy is presented in Figure 2.

Corrosion data are presented in Table 5 for triple-arc-melted uranium-40 per cent zirconium alloys melted from crystal-bar zirconium and sponge zirconium. After 2 months' exposure, those with crystal-bar additions appear slightly more resistant than those melted from sponge.

Justusson and McGeary⁽²⁾ and Lustman, et al.⁽⁴⁾, of WAPD report an accelerated corrosion rate for uranium-molybdenum alloys at 56 days' exposure to 600 F water. To date, this phenomenon has not been observed for uranium-zirconium alloys whose corrosion rates are essentially linear, as illustrated in Figure 2.

Uranium-Molybdenum Alloys

Corrosion results are presented in Table 6 for both induction-melted and arc-melted uranium-molybdenum alloys exposed to water at 600 F. Although the addition of molybdenum above 8 to 10 per cent resulted in an alloy much more resistant than unalloyed uranium, the alloy still corroded severely. Since considerable difficulty was encountered in alloying the molybdenum, the resulting alloys were probably inhomogeneous. This could account for the poor resistance of these alloys, in contrast to results reported by Justusson and McGeary⁽²⁾ and Lustman, et al.⁽⁴⁾, of WAPD, who find 9.5 to 12 wt % molybdenum alloys resistant to 600 F water.

Ternary Uranium Alloys

Double Arc Melted. Double-arc-melted alloys consisting of additions of molybdenum, niobium, thorium, tin, and titanium to a uranium-20 wt % zirconium base were exposed to water at 600 F to determine whether the

*References are given at the end of report.

TABLE 3. TRIPLE-ARC-MELTED URANIUM-ZIRCONIUM ALLOYS EXPOSED TO WATER AT 600 F
(Melted From Grade I Crystal-Bar Zirconium and Biscuit Grade Uranium)

Sample	Analysis, wt %			Total Weight Gain, mg/sq cm, at Hours Indicated										Remarks
	Zr	C	N	24	48	96	168	336	504	672	1008	1344	1512	
1 Hr at 800 C - Water Quenched														
40	60(39.3U)	0.02	0.006	0.15	0.25	0.26	0.43	-3.50	-13.6	-25.9	-57.5	-90.9	-109.0	Uniform flaky yellow oxide
39	47.3	0.02	0.008	-0.02	-0.06	-0.18	-0.39	-1.60	-3.30	-4.80	-11.3	-21.4	-27.8	Uniform flaky yellow oxide
38	40.2	0.02	0.006	5.50	22.6	--	--	--	--	--	--	--	--	Disintegrated, 96 hr
24 Hr at 575 C - Furnace Cooled														
40	60(39.3U)	0.02	0.006	0.18	0.37	1.02	2.30	-12.7	-27.5	-36.8	-66.0	-96.5	-112.0	Uniform flaky yellow oxide
39	47.3	0.02	0.008	0.15	0.21	0.23	-0.20	-2.40	-5.30	-8.10	-20.2	-36.3	-45.6	Uniform flaky yellow oxide
38	40.2	0.02	0.006	-0.15	-1.50	-4.90	-9.90	-21.2	-32.4	-40.9	-69.8	-102.0	-120.0	Uniform flaky yellow oxide
1 Hr at 800 C - Water Quenched - 24 Hr at 575 C - Furnace Cooled														
40	60(39.3U)	0.02	0.006	0.14	0.34	0.94	1.70	-10.0	-26.8	-38.1	-71.7	-106.0	-124.0	Uniform flaky yellow oxide
39	47.3	0.02	0.008	-0.03	-0.01	-0.03	-0.41	-2.50	-5.60	-8.90	-24.1	-42.3	-52.7	Uniform flaky yellow oxide
38	40.2	0.02	0.006	-0.10	-0.97	-3.00	-6.20	-14.2	-22.5	-28.9	-50.6	-74.7	-87.3	Uniform flaky yellow oxide
1 Hr at 800 C - Quenched to 550 C - 2 Hr at 550 C - Air Cooled														
40	60(39.3U)	0.02	0.006	0.10	0.36	0.90	-0.85	-9.20	-18.1	-29.8	-57.6	-87.0	-101.0	Uniform flaky yellow oxide
39	47.3	0.02	0.008	0.01	0.02	-0.47	-1.50	-5.50	-10.5	-15.1	-31.8	-50.7	-60.3	Uniform flaky yellow oxide
38	40.2	0.02	0.006	0.16	-0.27	-1.30	-3.70	-9.90	-16.3	-21.3	-39.9	-61.1	-72.7	Uniform flaky yellow oxide
1 Hr at 800 C - Water Quenched - 2 Hr at 650 C - Water Quenched														
40	60(39.3U)	0.02	0.006	0.13	0.27	0.21	-1.40	-8.80	-18.7	-28.3	-56.2	-86.7	-102.0	Uniform flaky yellow oxide
39	47.3	0.02	0.008	0.15	0.21	0.16	-0.75	-3.60	-7.20	-10.3	-23.1	-38.9	-47.8	Uniform flaky yellow oxide
38	40.2	0.02	0.006	0.13	-0.10	-1.00	-2.80	-7.60	-13.4	-16.9	--	--	--	Erupted at 1 corner, 840 hr
1 Hr at 800 C - Furnace Cooled														
40	60(39.3U)	0.02	0.006	--	0.41	0.91	0.45	-8.80	-23.8	-26.9	-59.4	--	--	Uniform flaky yellow oxide
39	47.3	0.02	0.008	--	-0.43	-1.00	-2.40	-5.80	-11.8	-18.1	-32.5	-50.6	-61.5	Uniform flaky yellow oxide
38	40.2	0.02	0.006	--	-0.42	-1.59	-4.00	-8.5	-14.8	-21.0	-34.4	-52.2	-62.2	Uniform flaky yellow oxide
1 Hr at 800 C - Quenched to 550 C - 10 Min at 550 C - Air Cooled														
40	60(39.3U)	0.02	0.006	--	0.21	0.87	2.00	-6.00	-21.4	-37.1	-63.9	--	--	Uniform flaky yellow oxide
39	47.3	0.02	0.008	--	0.17	0.23	0.01	-0.10	-3.40	-6.30	-14.6	-28.0	-35.8	Uniform flaky yellow oxide
38	40.2	0.02	0.006	--	-0.10	-0.70	-2.40	-5.80	-10.3	-15.3	-25.9	-41.7	-50.8	Uniform flaky yellow oxide

Note: 20 wt % zirconium alloys disintegrated within 24 hr.

TABLE 4. TRIPLE-ARC-MELTED URANIUM-ZIRCONIUM ALLOYS EXPOSED TO WATER AT 500 F

Analysis, wt %			Total Weight Gain, mg/sq cm, at Hours Indicated									Remarks
Zr	C	N	24	48	96	168	336	504	672	840	1008	
1 Hr at 800 C - Water Quenched												
21.3	0.02	0.007	-26.0	-30.1	--	--	--	--	--	--	--	Erupted along one edge; cracked, 96 hr
40.2	0.02	0.006	0.05	0.05	-0.04	0.03	0.05	-0.06	0.05	3.50	9.09	Dark film. Sample bowed, 1008 hr
47.3	0.02	0.008	0.07	0.07	-0.15	0.01	-0.01	-0.07	-0.18	-0.41	-0.63	Dark film
60 (39.3U)	0.02	0.006	0.09	0.10	0.10	0.09	0.19	0.28	0.42	0.64	0.77	Adherent dark film
24 Hr at 575 C - Furnace Cooled												
21.3	0.02	0.007	--	--	--	--	--	--	--	--	--	Disintegrated, 24 hr
40.2	0.02	0.006	0.06	0.06	-0.04	-0.03	-0.70	-1.54	-2.42	-3.67	-4.73	Dark film
47.3	0.02	0.008	0.10	0.10	-0.04	-0.11	0.15	0.19	0.20	0.19	-0.01	Adherent dark film
60 (39.3U)	0.02	0.006	0.08	0.09	-0.19	0.13	0.33	0.59	0.94	1.24	1.59	Adherent dark film
1 Hr at 800 C - 2 Hr at 550 C - Air Cooled												
21.3	0.02	0.007	-799.0	--	--	--	--	--	--	--	--	Oxidized to thin wafer, 24 hr
40.2	0.02	0.006	0.18	0.23	0.28	0.38	0.24	-0.11	-0.34	-0.83	-1.30	Dark film
47.3	0.02	0.008	0.02	0.02	0.01	0.01	0.05	0.08	0.09	0.01	-0.29	Adherent dark film
60 (39.3U)	0.02	0.006	0.09	0.09	0.02	0.15	0.38	0.61	0.80	0.46	-0.16	Adherent dark film

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FIGURE 2. TRIPLE-ARC-MELTED URANIUM-50 WT % ZIRCONIUM ALLOYS EXPOSED TO HIGH-TEMPERATURE WATER

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TABLE 5. TRIPLE-ARC-MELTED URANIUM-40 WT % ZIRCONIUM ALLOYS EXPOSED TO WATER AT 600 F
(Biscuit Uranium, Sponge Zirconium, and Crystal-Bar Zirconium)

Heat Treatment ^(a)	Analysis, wt %			Weight Gain, mg/sq cm, at Hours Indicated													Remarks
	Zr	C	N	24	48	96	168	336	504	672	840	1008	1176	1344	1512	1680	
Crystal-Bar Zirconium																	
A1	40.2	0.02	0.006	--	-0.42	-1.59	-4.00	-5.70	-14.8	-21.0	-26.2	-34.4	-43.3	-52.2	-62.2	-72.5	Uniform flaky tan oxide
D1	40.2	0.02	0.006	--	-0.10	-0.70	-2.40	-5.80	-10.3	-15.3	-19.0	-25.9	-33.7	-41.7	-50.8	-60.5	Uniform flaky tan oxide
D2	40.2	0.02	0.006	0.17	0.19	-0.34	-1.18	-4.80	-9.10	-12.4	-18.4	-25.5	-32.6	-40.4	-48.9	--	Uniform flaky tan oxide
D3	40.2	0.02	0.006	0.12	0.11	-0.37	-1.48	-5.80	-11.3	-15.5	-23.3	-31.7	-40.6	-50.3	-60.3	--	Uniform flaky tan oxide
D4	40.2	0.02	0.006	0.13	-0.16	-1.20	-3.30	-11.9	-20.7	-27.1	-37.7	-48.8	-60.1	-72.3	-84.9	--	Uniform flaky tan oxide
D5	40.2	0.02	0.006	0.14	0.14	-0.29	-1.12	-5.00	-9.50	-13.1	-19.7	-27.2	-35.1	-43.8	-53.2	--	Uniform flaky tan oxide
Sponge Zirconium																	
A	40.9	0.02	0.007	--	-0.33	-1.50	-3.50	-8.70	-16.0	-24.0	-29.7	-39.9	-52.2	-60.5	-72.9	-84.6	Uniform flaky tan oxide
B	40.9	0.02	0.007	--	0.08	-0.81	-2.20	-5.30	-11.0	-18.2	-23.5	-32.6	-42.7	-52.9	-64.3	-75.6	Uniform flaky tan oxide
D2	40.9	0.02	0.007	0.12	0.12	-0.40	-1.66	-6.10	-12.8	-18.3	-26.8	-36.8	-46.8	-57.7	-68.8	--	Uniform flaky tan oxide
D3	40.9	0.02	0.007	0.19	0.11	-0.32	-1.29	-5.10	-11.2	-16.3	-24.8	-34.4	-44.4	-55.2	-65.8	--	Uniform flaky tan oxide
D4	40.9	0.02	0.007	-0.19	-0.79	-2.30	-5.60	-13.1	-25.7	-32.9	-45.4	-60.1	-75.7	-90.4	-107.0	--	Uniform flaky tan oxide
D5	40.9	0.02	0.007	0.18	0.95	-0.46	-1.73	-5.70	-11.8	-16.1	-25.1	-34.6	-44.2	-54.7	-65.6	--	Uniform flaky tan oxide

- (a) A - 1 hr at 800 C, water quenched.
A1 - 1 hr at 800 C, furnace cooled.
B - 24 hr at 575 C, furnace cooled.
D1 - 1 hr at 800 C, 10 min at 550 C, air cooled.
D2 - 1 hr at 800 C, 10 sec at 550 C, air cooled.
D3 - 1 hr at 800 C, 60 sec at 550 C, air cooled.
D4 - 1 hr at 800 C, 10 min at 550 C, air cooled.
D5 - 1 hr at 800 C, 20 hr at 550 C, air cooled.

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TABLE 6. DOUBLE-ARC-MELTED URANIUM-MOLYBDENUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment ^(a)	Analysis, wt %			Total Weight Gain, mg/sq cm, at Hours Indicated									Remarks	
	Mo	C	N	6	12	18	24	48	96	168	336	504		
Induction Melted														
A	10 (Intended)	--	--	--	--	--	-2.10	-14.5	-22.6	-32.1	-49.1	-70.7	Uniform loose dark oxide	
B	10 (Intended)	--	--	--	--	--	--	--	--	--	--	--	Disintegrated in 24 hr	
D4	10 (Intended)	--	--	--	--	--	-18.6	-26.7	-37.6	-51.1	-82.9	-138.0	Uniform loose dark oxide	
Arc Melted														
A	7.4	0.02	0.010	--	--	--	--	--	--	--	--	--	Disintegrated in 6 hr	
B	7.4	0.02	0.010	--	--	--	--	--	--	--	--	--	Disintegrated in 6 hr	
D4	7.4	0.02	0.010	--	--	--	--	--	--	--	--	--	Disintegrated in 6 hr	
A	8.7	0.03	0.011	-27.5	-30.7	-34.5	-38.0	-43.8	-57.1	-95.7	--	--	Uniform loose dark oxide	
B	8.7	0.03	0.011	-26.8	-30.2	-34.2	-38.0	-44.4	-60.3	-113.0	--	--	Uniform loose dark oxide	
D4	8.7	0.03	0.011	--	--	--	--	--	--	--	--	--	Disintegrated in 6 hr	
A	15 (Intended)	--	--	-6.10	-10.0	-12.5	-14.1	-18.2	-22.9	-27.6	--	--	Uniform loose dark oxide	
B	15 (Intended)	--	--	-3.80	-6.41	-8.22	-9.42	-12.4	-16.0	-19.5	--	--	Uniform loose dark oxide	
D4	15 (Intended)	--	--	-10.5	-17.4	-24.2	-30.6	-62.2	--	--	--	--	Two corners corroded away	

(a) A 1 hr at 800 C, water quenched.

B 24 hr at 575 C, furnace cooled.

D4 1 hr at 800 C, quenched to 550 C, 10 min. at 550 C, air cooled.

addition of a third element would lower the total amount of alloying elements required for corrosion resistance. The results of these tests are presented in Tables 7 through 11. In general, all the alloys were segregated. Only samples of uranium-20 zirconium-5 molybdenum and uranium-20 zirconium-10 niobium alloys were promising, and those either disintegrated or cracked upon extended exposure. Additional heat treatment of several alloys failed to improve their corrosion resistance (Table 12). The results for several of these alloys are in agreement with those obtained by Justusson and McGeary⁽²⁾, who found uranium-molybdenum-zirconium and uranium-zirconium-niobium alloys (probably low total alloy content) did not exhibit exceptional resistance to 600 F water. McGeary⁽³⁾ also reports the addition of up to 20 per cent zirconium does not improve the resistance of uranium-8 to 15 wt % molybdenum alloys.

Several of the above alloys exhibited some resistance to 500 F water, but failed upon extended exposure (see Tables 13 through 16).

Triple Arc Melted. Corrosion results are summarized in Tables 17 and 18 for triple-arc-melted uranium-zirconium-molybdenum and uranium-zirconium-niobium alloys exposed to water at 600 F. The addition of molybdenum and niobium to low-zirconium-content alloys improved their resistance somewhat. The addition of molybdenum did not improve the resistance of uranium-40 and 50 per cent zirconium alloys.

Multiple Arc Melted. As part of the survey, multiple-arc-melted uranium-30 wt % zirconium alloys with 2 and 5 at. % additions of antimony, bismuth, cerium, chromium, cobalt, iron, lead, nickel, niobium, silicon, tantalum, thorium, titanium, and tungsten were exposed to water at 600 F. Alloys were examined every 6 hr during the first 24 hr of exposure to determine any beneficial trends due to alloy additions. The results of these tests are summarized in Tables 19, 20, and 21. In general, alloys in the annealed condition exhibited the poorest resistance, while those which were isothermally annealed were the best. Only one alloy, uranium-20 zirconium-5.6 tantalum showed a vast improvement in resistance over that of the uranium-30 zirconium base.

CONCLUSIONS

The development of corrosion-resistant uranium alloys, which, when used as reactor fuel-element cores, would allow minor defects to coexist in the cladding without catastrophic failure, has indicated a number of potentially useful compositions. Evaluation and rating as corrosion resistant are based on a corrosion rate in the range from 0.01 to 0.05 mg/(sq cm) (hr). Although not completely resistant, several high-uranium-content

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TABLE 7. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-MOLYBDENUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment ^(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated						Remarks
	Zr	Mo	C	N	24	48	96	168	336		
A	19.8	0.89	0.03	0.006	--						Partially disintegrated, 24 hr
B	19.8	0.89	0.03	0.006	--						Disintegrated
C	19.8	0.89	0.03	0.006	--						"
D	19.8	0.89	0.03	0.006	--						"
E	19.8	0.89	0.03	0.006	--						"
A	20.2	1.82	0.02	0.007	--						Partially disintegrated, 24 hr
B	20.2	1.82	0.02	0.007	--						Disintegrated
C	20.2	1.82	0.02	0.007	--						"
D	20.2	1.82	0.02	0.007	--						"
E	20.2	1.82	0.02	0.007	--						"
A	20.2	4.77	0.03	0.013	-0.11	-0.89	-2.50				Corner corroded away at 168 hr
B						Not tested					
C	20.2	4.77	0.03	0.013	-12.4						Loose yellow oxide
D	20.2	4.77	0.03	0.013	0.14	0.26	0.27	0.20	-1.80		
					Hr: <u>504</u>	<u>672</u>	<u>840</u>	<u>1008</u>	<u>1176</u>	<u>1344</u>	Cracked and blistered, 504 hr; corner erupted, 1344 hr
					Wt Gain: -5.10	-9.07	-12.7	-20.3	-64.3	-300.0	Partially disintegrated, 48 hr
E	20.2	4.77	0.03	0.013	-0.18	--					

(a) A - 1 hr at 800 C, water quenched.

B - 24 hr at 575 C, furnace cooled.

C - 1 hr at 800 C, water quenched, 24 hr at 575, furnace cooled.

D - 1 hr at 800 C, 2 hr at 550 C, air cooled

E - 1 hr at 800 C, water quenched, 2 hr at 650 C, water quenched.

TABLE 8. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-NIOBIUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment ^(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated				Remarks
	Zr	Nb	C	N	24	48	96	168	
A	19.1	1.01	0.02	0.008	-4.89	--			Large hole corroded out, 48 hr
B	19.1	1.01	0.02	0.008	--				Partially disintegrated, 24 hr
C	19.1	1.01	0.02	0.008	--				Ditto
D	19.1	1.01	0.02	0.008	--				"
E	19.1	1.01	0.02	0.008	--				"
A	21.0	2.01	0.02	0.009	--				Disintegrated, 24 hr
B	21.0	2.01	0.02	0.009	--				Ditto
C	21.0	2.01	0.02	0.009	--				"
D	21.0	2.01	0.02	0.009	--				"
E	21.0	2.01	0.02	0.009	--				"
A	20.7	4.09	0.02	0.015	-1.63				Disintegrated, 48 hr
B	20.7	4.09	0.02	0.015	--				Disintegrated, 24 hr
C	20.7	4.09	0.02	0.015	--				Ditto
D	20.7	4.09	0.02	0.015	--				"
E	20.7	4.09	0.02	0.015	--				"
A	21.4	8.33	0.03	0.011	0.13	0.04	0.64	--	Disintegrated, 168 hr
B	21.4	8.33	0.03	0.011	--				Partially disintegrated, 168 hr
C	21.4	8.33	0.03	0.011	-130.0				Severe cracking
D	21.4	8.33	0.03	0.011	-1.00	-7.00	--		Severe cracking, 96 hr
E	21.4	8.33	0.03	0.011	0.20	1.60	--		Ditto

- (a) A - 1 hr at 800 C, water quenched.
 B - 24 hr at 575 C, furnace cooled.
 C - 1 hr at 800 C, water quenched, 24 hr at 575 C, furnace cooled.
 D - 1 hr at 800 C, 2 hr at 550 C, air cooled.
 E - 1 hr at 800 C, water quenched, 2 hr at 650 C, water quenched.

TABLE 9. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-THORIUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated		Remarks
	Zr	Th	C	N	24	48	
A	31.0	9.7	0.01	0.008			Disintegrated, 24 hr
B	31.0	9.7	0.01	0.008	--		Ditto
C	31.0	9.7	0.01	0.008	--		"
D	31.0	9.7	0.01	0.008	--		"
E	31.0	9.7	0.01	0.008	--		"
A	20.8	1.1	0.02	0.013	-9.18	--	Partially disintegrated, 48 hr
B	20.8	1.1	0.02	0.013	--		Disintegrated
C	20.8	1.1	0.02	0.013	--		"
D	20.8	1.1	0.02	0.013	--		"
E	20.8	1.1	0.02	0.013	--		"
A	21.5	5.0	0.02	0.013	-19.7	--	Partially disintegrated, 48 hr.
B	21.5	5.0	0.02	0.013	--		Disintegrated
C	21.5	5.0	0.02	0.013	--		"
D	21.5	5.0	0.02	0.013	--		"
E					--		"
A	21.9	10.0	0.01	0.014	-321.0		Loose yellow oxide
B	21.9	10.0	0.01	0.014	--		Disintegrated, 24 hr
C	21.9	10.0	0.01	0.014	-244.0		Loose yellow oxide
D	21.9	10.0	0.01	0.014	-202.0		Ditto
E	21.9	10.0	0.01	0.014	-152.0		"
A	23.0	31.7	0.04	0.008	--		Disintegrated, 24 hr
B	23.0	31.7	0.04	0.008	--		Ditto
C	23.0	31.7	0.04	0.008	--		"
D	23.0	31.7	0.04	0.008	--		"
E	23.0	31.7	0.04	0.008	--		"

- (a) A - 1 hr at 800 C, water quenched.
 B - 24 hr at 575 C, furnace cooled.
 C - 1 hr at 800 C, water quenched, 2 hr at 575 C, furnace cooled.
 D - 1 hr at 800 C, 2 hr at 550 C, air cooled.
 E - 1 hr at 800 C, water quenched, 2 hr at 650 C, water quenched.

TABLE 10. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-TIN ALLOYS
EXPOSED TO WATER AT 600 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated		Remarks
	Zn	Sn	C	N	24	48	
A	22.6	1.14	0.02	0.012	-4.11	--	Disintegrated, 48 hr
B	22.6	1.14	0.02	0.012	-266		Loose yellow oxide
C	22.6	1.14	0.02	0.012	-234		Ditto
D	22.6	1.14	0.02	0.012	-160		"
E	22.6	1.14	0.02	0.012	-104		"
A	23.0	2.04	0.02	0.012	-8.49		Badly cracked
B	23.0	2.04	0.02	0.012	-355		Loose yellow oxide
C	23.0	2.04	0.02	0.012	-352		Ditto
D	23.0	2.04	0.02	0.012	-200		"
E	23.0	2.04	0.02	0.012	-229		"

- (a) A - 1 hr at 800 C, water quenched.
 B - 24 hr at 575 C, furnace cooled.
 C - 1 hr at 800 C, water quenched, 2 hr at 575 C, furnace cooled.
 D - 1 hr at 800 C, 2 hr at 550 C, air cooled.
 E - 1 hr at 800 C, water quenched, 2 hr at 650 C, water quenched.

TABLE 11. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-TITANIUM ALLOYS
EXPOSED TO WATER AT 600 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated		Remarks
	Zr	Ti	C	N	24	48	
A	21.1	1.15	0.03	0.008	--		Disintegrated, 24 hr
B	21.1	1.15	0.03	0.008	--		Ditto
C	21.1	1.15	0.03	0.008	--		"
D	21.1	1.15	0.03	0.008	--		"
E	21.1	1.15	0.03	0.008	--		"
A	21.2	2.15	0.02	0.011	--		Disintegrated, 24 hr
B	21.2	2.15	0.02	0.011	--		Ditto
C	21.2	2.15	0.02	0.011	--		"
D	21.2	2.15	0.02	0.011	--		"
E	21.2	2.15	0.02	0.011	--		"

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 C 1 hr at 800 C, water quenched, 2 hr at 575 C, furnace cooled.
 D 1 hr at 800 C, 2 hr at 550 C, air cooled.
 E 1 hr at 800 C, water quenched, 2 hr at 650 C, water quenched.

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TABLE 12. TERNARY URANIUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated					Remarks
	Zr	Other	C	N	24	48	96	168	336	
A3	21.4	8.33 Nb	0.03	0.011	1.02	--				Partially disintegrated, 48 hr
A7	21.4	8.33 Nb	0.03	0.011	0.18	-0.18	-0.59	-1.10	-25.3	Partially disintegrated, 336 hr
A3	20.4	1.1 Th	0.02	0.013	--					Disintegrated, 24 hr
A7	20.4	1.1 Th	0.02	0.013	--					Ditto
A3	21.5	5.0 Th	0.02	0.013	-6.70	--				Severe cracking, 48 hr
A7	21.5	5.0 Th	0.02	0.013	--					Disintegrated, 24 hr
A3	21.9	10.0 Th	0.01	0.014	-26.9	--				Disintegrated, 48 hr
A7	21.9	10.0 Th	0.01	0.014	--					Disintegrated, 24 hr

(a) A3 1 hr at 1000 C, water quenched.

A7 1 hr at 1000 C, furnace cooled.

TABLE 13. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-MOLYBDENUM ALLOYS EXPOSED TO WATER AT 500 F

Heat Treatment ^(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated				Remarks
	Zr	Mo	C	N	12	24	48	96	
A	19.8	0.89	0.03	0.006	-0.19	-1.20	-2.6	-2.1	Large crack, 168 hr
B	19.8	0.89	0.03	0.006	-212.0				Uniform loose dark oxide
D	19.8	0.89	0.03	0.006	-76.1				Ditto
A	20.2	1.82	0.02	0.007	0.10	-0.01	-0.89		Large crack, 96 hr
B	20.2	1.82	0.02	0.007	-67.8	-322.0			Uniform loose dark oxide
D	20.2	1.82	0.02	0.007	-15.1	-180.0			Ditto

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 D 1 hr at 800 C, 2 hr at 550 C, air cooled.

TABLE 14. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-NIOBIUM ALLOYS EXPOSED TO WATER AT 500 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated							Remarks
	Zr	Nb	C	N	12	24	48	96	168	336	504	
A	19.1	1.01	0.02	0.008	-0.12	-0.44	-0.81	-0.42	-13.8			Erupted one corner, 168 hr
B	19.1	1.01	0.02	0.008	-90.4	-288.0						Flaky yellow oxide
D	19.1	1.01	0.02	0.008	-228.0	-528.0						Ditto
A	21.0	2.01	0.02	0.009	-0.08	-0.37	-1.10					Cracking, 96 hr
B	21.0	2.01	0.02	0.009	-46.2	-200.0						Flaky yellow oxide
D	21.0	2.01	0.02	0.009	-37.4	-168.7						Ditto
A	20.7	4.09	0.02	0.015	0.04	0.03	0.04	-0.02	-0.83	-4.70	-68.1	Erupted and cracked in two, 504 hr
B	20.7	4.09	0.02	0.015	-10.0	-72.6						Flaky yellow oxide
D	20.7	4.09	0.02	0.015	-0.26	-2.00	-10.5	-60.3				Ditto

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 D 1 hr at 800 C, 2 hr at 550 C, air cooled.

TABLE 15. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-THORIUM ALLOYS EXPOSED TO WATER AT 500 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated					Remarks
	Zr	Th	C	N	12	24	48	96	168	
A	20.8	1.1	0.02	0.013	-0.93	-1.70	-3.5	-6.0	-11.5	Chipped and cracked, 168 hr
B	20.8	1.1	0.02	0.013	-526.0	--				Flaky yellow oxide
D	20.8	1.1	0.02	0.013	--					Disintegrated, 24 hr
A	21.5	5.0	0.02	0.013	-0.82	-2.80	-7.0	-16.4	-32.5	Chipped and cracked, 168 hr
B	21.5	5.0	0.02	0.013	-187.0	-556.0				Flaky yellow oxide
D	21.5	5.0	0.02	0.013	-172.0	-793.0				Ditto

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 D 1 hr at 800 C, 2 hr at 550 C, air cooled.

TABLE 16. DOUBLE-ARC-MELTED URANIUM-ZIRCONIUM-TITANIUM
ALLOYS EXPOSED TO WATER AT 500 F

Heat Treatment(a)	Analysis, wt %				Weight Gain, mg/sq cm, at Hours Indicated		Remarks
	Zr	Ti	C	N	12	24	
A	21.1	1.15	0.03	0.008	-9.30	--	Cracked, 24 hr
B	21.1	1.15	0.03	0.008	-31.4	-108.0	Loose dark oxide
D	21.1	1.15	0.03	0.008	-8.80	--	Cracked, 24 hr
A	21.2	2.15	0.02	0.011	-53.4		Loose dark oxide
B	21.2	2.15	0.02	0.011	Not tested		
D	21.2	2.15	0.02	0.011	-13.6		Ditto

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 D 1 hr at 800 C, 2 hr at 550 C, air cooled.

TABLE 17. TRIPLE-ARC-MELTED URANIUM-ZIRCONIUM-MOLYBDENUM ALLOYS EXPOSED TO WATER AT 600 F

Heat Treatment ^(a)	Nominal Alloy Additions, wt %		Weight Gain, mg/sq cm, at Hours Indicated										Remarks
	Zr	Mo	24	48	96	168	336	504	672	840	1008		
A	10	5	-10.4	--	--	--	--	--	--	--	--	Metal split and peeling, 24 hr	
B	10	5	--	--	--	--	--	--	--	--	--	Disintegrated, 24 hr	
D4	10	5	-4.82	--	--	--	--	--	--	--	--	Metal split and peeling, 24 hr	
A	20	5	-1.07	-2.30	-5.29	--	--	--	--	--	--	Disintegrated, 168 hr	
B	20	5	-470.0	--	--	--	--	--	--	--	--	Loose dark oxide	
D4	20	5	-0.25	-2.10	-5.27	-8.00	--	--	--	--	--	Partially disintegrated, 336 hr	
A	30	1	--	--	--	--	--	--	--	--	--	Disintegrated, 24 hr	
B	30	1	-165.0	-368.0	--	--	--	--	--	--	--	Excessive oxide	
D4	30	1	-2.60	-6.50	-14.5	-27.4	-50.8	-83.7	--	--	--	Uniform tan oxide	
A	30	3	0.10	--	--	--	--	--	--	--	--	Erupted, 48 hr	
B	30	3	-3.20	-11.6	--	--	--	--	--	--	--	Disintegrated, 96 hr	
D4	30	3	-0.05	-0.36	-2.05	-6.53	-16.8	-30.4	--	--	--	Some segregated oxide	
A	30	5	-0.13	-59.4	--	--	--	--	--	--	--	Erupted at 2 corners, 96 hr	
B	30	5	-0.23	-4.30	-22.7	-70.0	-184.0	-305.0	--	--	--	Excessive loose dark oxide	
D4	30	5	-0.23	-0.41	-1.16	-2.30	--	--	--	--	--	Partially disintegrated, 336 hr	
A	40	1	0.29	6.60	--	--	--	--	--	--	--	Erupted, 96 hr	
B	40	1	-0.09	-1.10	-5.80	-14.4	-37.0	-62.2	--	--	--	Uniform tan oxide	
D4	40	1	-5.60	-6.70	-12.1	-16.2	-41.0	-66.0	--	--	--	Dark oxide	
A	40	3	-0.32	-0.72	-1.75	--	--	--	--	--	--	1/4 of sample disintegrated, 168 hr	
B	40	3	-4.10	-13.1	-30.8	-61.0	-125.0	-189.0	-261.0	-314.0	-404.0	Erupted across top of sample, 1008 hr	
D4	40	3	-0.09	-0.75	-2.53	-4.50	-10.6	-17.3	-24.1	-31.6	-39.9	Uniform tan oxide	
A	40	5	-0.47	-0.85	-1.63	-6.30	--	--	--	--	--	Erupted one corner, 336 hr	
B	40	5	-0.93	-2.20	-5.49	-13.6	-34.8	-55.9	-77.8	-96.1	-120.0	Uniform tan oxide	
D4	40	5	-1.30	-1.80	-3.32	-5.20	-11.2	-17.0	-20.9	--	--	Corners erupted, 840 hr	
A	50	1	0.26	-0.16	-0.99	-2.50	-6.00	-10.2	-14.8	-19.2	-24.5	Uniform tan oxide	
B	50	1	0.03	-0.38	-1.39	-3.80	-10.9	-18.7	-26.8	-33.7	-42.3	Uniform tan oxide	
D4	50	1	0.23	-0.17	-1.10	-2.30	-6.40	-10.8	-15.5	-20.7	-26.3	Uniform tan oxide	
A	50	3	0.01	-0.68	-1.92	-4.00	-9.30	-14.5	-19.8	-24.0	-29.6	Uniform tan oxide	
B	50	3	0.16	-0.65	-2.47	-6.30	-13.4	-23.3	-30.1	-35.3	-43.2	Small blisters on one face, 1008 hr	
D4	50	3	0.17	-0.47	-2.01	-3.60	-8.80	-13.80	-18.9	-23.2	-28.8	Uniform tan oxide	

(a) A - 1 hr at 800 C, water quenched. B - 24 hr at 575 C, furnace cooled. D4 - 1 hr at 800 C, quench to 550 C, 10 min at 550 C air cooled.

TABLE 18. TRIPLE-ARC-MELTED URANIUM-ZIRCONIUM-NIOBIUM ALLOYS EXPOSED
TO WATER AT 600 F

Heat Treatment(a)	Nominal Alloy Additions, wt %		Weight Gain, mg/sq cm, at Hours Indicated							Remarks
	Zr	Nb	24	48	96	168	336	504	672	
A	20	5	0.02	-0.96	--					Disintegrated, 96 hr
B	20	5	-103.8							Loose dark oxide and cracks, 336 hr
D4	20	5	-0.01	-0.49	-2.53	-6.40	--			Hole through sample
A	20	10	0.14	0.14	-0.40	-0.88	--			Erupted at sample hole, 336 hr
B	20	10	-0.27	-2.40	-7.76	-34.6	--			Piece cracked off, 336 hr
D4	20	10	0.17	0.28	0.14	-0.09	-1.00	--		Erupted at 2 corners, 504 hr
A	30	5	-2.30	-8.00	-22.4	-44.6	--			Erupted on 1 edge, 336 hr
B	30	5	-32.4	-93.5	-207.0	-20.3	-44.1			Covered with yellow oxide, 96 hr
D4	30	5	-1.80	-6.50	-20.3	-44.1	-109.0	--		Erupted at 2 corners, 504 hr

- (a) A 1 hr at 800 C, water quenched.
 B 24 hr at 575 C, furnace cooled.
 D4 1 hr at 800 C, quenched to 550 C, 10 min at 550 C, air cooled.

TABLE 19. TERNARY URANIUM-30 WT % ZIRCONIUM ALLOYS EXPOSED
TO WATER AT 600 F

(Samples Arc Melted Minimum of Five Times, Heated to 800 C and Water Quenched)

Sample	Intended Composition, Wt % Alloy	Weight Gain, mg/sq cm, at Hours Indicated						Remarks
		6	12	18	24	48	96	
100	None	-30.3	-63.5	-107.0	-141.0	-307.0	--	Disintegrated, 96 hr
101	"	-1.70	-2.20	-3.60	-11.1			Cracked and segregated, 24 hr
102	"	-42.6	-96.3	-173.0	-285.0			Cracked, 24 hr
103	0.75 Sb	-28.6						Erupted and cracked, 6 hr
104	3.74 Sb	Not tested						
105	0.36 Ni	-1.40	-2.00	-4.30				Corner corroded away, 18 hr
106	1.8 Ni	--						Disintegrated, 6 hr
107	0.36 Co	-28.2	-57.5	-90.7	-121.0	--		Disintegrated, 48 hr
108	1.8 Co	-46.7	-92.5	-123.0	-150.0	--		Disintegrated, 48 hr
109	1.28 Bi	--						Disintegrated, 6 hr
110	6.4 Bi	-18.6						Erupted and cracked, 6 hr
111	0.16 Si	-83.2	-161.5	-250.0	-336.0	-667.0		Uniform loose dark oxide
112	0.8 Si	-4.00	-8.70	-17.2	-23.0			Cracked and erupted at 1 corner, 24 hr
113	0.35 Fe	-0.08	-1.70	-29.8				Erupted and cracked, 18 hr
114	1.72 Fe	-2.00	-15.4					Cracked, 12 hr
115	0.32 Cr	-6.60						Cracked and erupted, 6 hr
116	1.6 Cr	-70.2	-132.0	-227.0	-305.0			Pieces chipped off, 24 hr
117	0.3 Ti	--						Disintegrated, 6 hr
118	1.48 Ti	-46.6	-87.3	-259.0				Portion corroded away, 18 hr
119	1.12 Ta	-0.06	-5.30	-24.8				Cracked and erupted, 18 hr
120	5.6 Ta	0.03	0.01	0.01	-0.02	-14.9		Erupted, 48 hr
121	0.86 Ce	-71.4						Erupted and cracked, 6 hr
122	0.57 Nb	3.10	--					Disintegrated, 12 hr
123	2.87 Nb	-3.30	-10.1	-20.7	-32.4	-73.2	-172.0	Cracked and peeling, 96 hr
124	1.26 Pb	-65.2						Erupted and cracked, 6 hr
125	2.52 Pb	-17.2						Ditto
126	1.12 W	-0.59	-1.10	-2.00	-2.70	-146.0		Erupted on 1 face, 48 hr
127	5.66 W	-0.44	-0.92	-1.70	-2.50	-14.1	-76.8	Erupted at 1 corner, 96 hr
128	1.44 Th	--						Disintegrated, 6 hr
129	7.6 Th	-7.30	--					Disintegrated, 12 hr

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TABLE 20. TERNARY URANIUM-30 WT % ZIRCONIUM ALLOYS EXPOSED TO WATER
AT 600 F

(Samples Arc Melted Minimum of Five Times, Held 24 Hr at 575 C, and Furnace Cooled)

Sample	Intended Composition, Wt % Alloy	Weight Gain, mg/sq cm, at Hours Indicated						Remarks
		6	12	18	24	48	96	
100	None	-95.5	-215.0	-361.0	--			Loose dark oxide
101	None	--						Cracked into 3 pieces, 6 hr
102	None	-96.2	-186.0	-312.0	-433.0	--		Disintegrated, 48 hr
103	0.75 Sb	-150.0	-334.0	-503.0	-662.0	--		Ditto
104	3.74 Sb	Not tested						
105	0.36 Ni	--						Disintegrated, 6 hr
106	1.8 Ni	--						Ditto
107	0.36 Co	-94.8	-309.0	--				Corner corroded away, 18 hr
108	1.8 Co	--						Broke in two, 6 hr
109	1.28 Bi	-210.0	-521.0					Broke in two, 18 hr
110	6.4 Bi							Broke in two, 6 hr
111	0.16 Si	-214.0	-396.0	-552.0	-697.0	--		Disintegrated, 48 hr
112	0.8 Si	--						Erupted at 1 corner 6 hr
113	0.35 Fe	-94.4	-224.0	-341.0	-453.0	--		Disintegrated, 48 hr
114	1.72 Fe	-43.1	-107.0	-171.0	-256.0	--		Ditto
115	0.35 Cr	-119.0	-251.0	-360.0	-558.0	--		"
116	1.6 Cr	-152.0	-336.0	-502.0	-602.0	--		"
117	0.3 Ti	-89.2	-153.0	-251.0				Piece broke off 1 corner, 18 hr
118	1.48 Ti	-41.1	-95.9	-171.0	--			Erupted at 1 edge, 18 hr
119	1.12 Ta	-38.6	-85.0	-127.0	-213.0	--		Disintegrated, 48 hr
120(a)	5.6 Ta	0.49	0.12	0	-0.12	-1.71	-3.84	
121	0.86 Ce	--						Erupted on 1 face, 6 hr
122	0.57 Nb	-79.7	-163.0	-243.0	-323.0			Disintegrated, 48 hr
123	2.87 Nb	-50.7	-103.0	-168.0	-209.0			Ditto
124	1.26 Pb	--						Piece chipped off 1 face, 6 hr
125	2.52 Pb	-113.0	-543.0					Ditto
126	1.12 W	--						Piece chipped off 1 face, 6 hr
127	5.66 W	Not tested						
128	1.44 Th	-23.0	229.0	-354.0	--			Portion corroded away
129	7.6 Th	--						Disintegrated, 6 hr

(a) Specimen 120: weight gain - 7.19 mg/sq cm at 168 hr, dark film.

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TABLE 21. TERNARY URANIUM-30 WT % ZIRCONIUM ALLOYS EXPOSED TO WATER AT 600 F
(Samples Arc Melted Minimum of Five Times, Held 1 Hr at 800 C, Quenched to 550 C, 10 Min at 550 C, Air Cooled)

Sample	Intended Composition, wt %	Weight Gain, mg/sq cm, at Hours Indicated							Remarks
	Alloy	6	12	18	24	48	96	168	
100	None	-0.95	-2.45	-4.22	-6.34	-15.4	-35.3	-64.0	Loose tan oxide
101	None	-0.19	-0.57	-1.17	-1.97	-4.82	-10.6	-19.2	Loose tan oxide
102	None	-0.20	-0.87	-1.66	-2.83	-6.76	-15.2	-27.8	Loose tan oxide
103	0.75 Sb	-0.55	-4.77	-7.97	-19.5	-232.0	--	--	Excessive general attack, 48 hr
104	3.74 Sb	-25.8	-47.2	-67.2	-87.7	--	--	--	Piece corroded away, 24 hr
105	0.36 Ni	-0.06	-1.69	-3.31	-4.67	-8.93	-16.0	-22.0	Slightly bowed, loose oxide
106	1.8 Ni	-0.04	-26.1	-30.7	-34.0	-84.1	--	--	Broke into small pieces, 96 hr
107	0.36 Co	0	-0.50	-1.37	-2.28	-6.37	-16.7	-33.0	Loose tan oxide
108	1.8 Co	-0.34	-1.36	-3.39	-6.35	-15.0	-30.5	-51.8	Dark area over tan color and oxide
109	1.28 Bi	-0.77	-2.09	-3.79	-5.95	-16.8	-62.8	--	Erupted at one corner, 96 hr
110	6.4 Bi	-0.54	-1.96	-3.71	-5.93	-15.1	-37.5	-373.0	Partially disintegrated, 168 hr
111	0.16 Si	-0.72	-2.53	-4.55	-6.78	-16.3	-37.9	-102.0	Cracked, 168 hr
112	0.8 Si	-6.70	-11.3	-15.9	-20.2	-46.6	-87.4	-178.0	Dark area over tan color and oxide
113	0.35 Fe	-0.19	-0.29	-0.76	-1.60	-5.63	-15.8	--	Edge broken off, 96 hr
114	1.72 Fe	-0.28	-0.81	-1.39	-2.29	-13.2	--	--	Corner corroded away, 48 hr
115	0.35 Cr	-2.68	-34.1	--	--	--	--	--	Erupted top edge, 12 hr
116	1.6 Cr	-0.73	-2.86	-6.26	-9.18	-52.9	--	--	Portion corroded away, 48 hr
117	0.3 Ti	-4.33	-10.6	-16.6	-22.3	-48.1	-171.0	--	Erupted at one corner
118	1.48 Ti	-22.5	-103.0	--	--	--	--	--	One corner corroded away, 12 hr
119	1.12 Ta	-0.12	-0.55	-0.99	-1.64	-3.63	-7.38	-11.9	Loose tan oxide
120	5.6 Ta	0.09	-0.15	-0.32	-0.58	-1.83	-4.44	-210.0	Partially disintegrated, 168 hr
121	0.86 Ce	-0.52	-1.87	-3.59	-5.81	-88.9	--	--	Erupted at one edge, 48 hr
122	0.57 Nb	-0.58	-2.03	-3.13	-4.19	-8.01	-15.6	-26.8	Loose tan oxide
123	2.87 Nb	-0.76	-3.08	-5.32	-7.43	-16.2	-35.5	-64.5	Loose dark oxide
124	1.26 Pb	-1.14	-2.59	-4.21	-6.01	-12.6	-32.2	-54.2	Erupting along one edge, 168 hr
125	2.52 Pb	-1.56	-3.35	-5.54	-7.68	-16.5	-35.8	-64.5	Loose tan oxide
126	1.12 W	-0.08	-0.91	-1.48	-2.55	-6.52	-15.5	-28.9	Cracked in two, 168 hr
127	5.66 W	-0.68	-1.79	-2.45	-3.52	-8.00	-91.3	--	Broke in two, 96 hr
128	1.44 Th	0	-11.0	--	--	--	--	--	One corner corroded away, 12 hr
129	7.6 Th	-7.71	-24.9	-31.4	-72.3	--	--	--	Cracked into pieces, 48 hr

alloys (uranium-20 wt % zirconium-10 wt % niobium and uranium-30 wt % zirconium-5.6 wt % tantalum, in particular) tested in 600 F water appear promising, with respect to corrosion resistance, as possible core materials. These alloys, together with uranium-zirconium-molybdenum alloys, should be investigated further, with emphasis placed on obtaining uniform melts.

The addition of 50 wt % or more of zirconium to uranium results in alloys which exhibit no warping and a relatively low corrosion rate upon extended exposure at 600 F.

Uranium-40 plus wt % zirconium alloys are resistant to 500 F water. It is possible that alloys with smaller additions of zirconium also are resistant to these conditions, although this has not been investigated.

The effect of heat treatment on corrosion resistance is not well defined, particularly for alloys which corrode rather rapidly. However, high-zirconium-content alloys are sensitive to heat treatment and are most resistant in the quenched condition.

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