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**CORROSION EVALUATION OF BINARY URANIUM
ALLOYS IN WATER AT 100 C**

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For The Atomic Energy Commission

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CORROSION EVALUATION OF BINARY URANIUM ALLOYS IN WATER AT 100 C

by

H. A. Saller, H. A. Pray, R. F. Dickerson, W. E. Berry,
and E. L. Foster, Jr.

The corrosion behavior in boiling water of a number of uranium binary alloys was determined. Additions ranging from 2 to 12 a/o of some 42 elements and effect of heat treatment on corrosion resistance were investigated. The alloying was done in an arc furnace designed particularly to expedite melting of a large number of alloys. Melting characteristics, fabrication temperatures, and heat-treatment temperatures for each alloy were noted. Vickers hardness numbers of all alloys and data on grain size of the more corrosion resistant alloys were also obtained.

Some alloys containing hafnium, nickel, niobium, titanium, and zirconium were resistant to corrosion in boiling water for periods ranging from 672 to 6720 hr. The heat treatment as well as alloy content determined corrosion resistance. In general, the most resistant alloys were those which were water quenched from 700 or 815 C and contained additions of 5 a/o niobium or titanium or 12 a/o hafnium, nickel, or zirconium.

At least one composition and heat treatment of the following uranium binary alloys was resistant, as indicated by an adherent tarnish film and low weight change, for more than a 24-hr exposure, but failed by cracking or the appearance of loose oxide within 672 hr. These were alloys of aluminum, cobalt, germanium, iron, manganese, molybdenum, palladium, platinum, silicon, tantalum, thallium, and vanadium.

All compositions and heat treatments of antimony, barium, beryllium, bismuth, boron, cadmium, carbon, cerium, chromium, copper, gadolinium, gold, lanthanum, lead, lithium, nitrogen, oxygen, selenium, silver, strontium, thorium, tin, tungsten, yttrium, and zinc alloys behaved similarly to unalloyed uranium, i.e., developed heavy, loose oxide coatings and exhibited large weight losses after a 24-hr exposure.

INTRODUCTION

Unalloyed uranium corrodes rapidly in aqueous media, with a weight loss between 3 and 4 mg/(cm²)(hr) at 100 C. Therefore, it is conventionally jacketed or clad with a corrosion-resistant material for utilization in aqueous environments. For such applications it appeared desirable to evaluate small binary alloying additions for their ability to impart corrosion resistance to uranium.

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Initial research effort has been directed toward finding corrosion-resistant alloys, without regard to the effects of alloying on other properties of uranium. The corrosion behavior of some 42 binary alloy systems has been studied and evaluated. Other laboratories have reported corrosion results for some of these alloys*, but, because of differences in composition, heat treatment, and length of exposure, no systematic comparison of effect of alloy additions can be made. Where possible in this study, all alloys were tested at the same composition levels and in the same heat-treated conditions.

With the idea of presenting as much information as possible concerning the binary alloys of uranium, Vickers hardness numbers of all alloys, as well as grain-size data for the resistant and temporarily-resistant alloys, were compiled. Information concerning the melting characteristics, fabrication temperatures, and heat-treatment temperatures of the alloys also was noted, along with any other pertinent data that applied to a particular alloy.

APPARATUS

Melting Equipment

The arc furnace in which the alloys were melted differed from the conventional laboratory arc furnace. The multitude of alloys as well as the number of melts per alloy dictated the need for a furnace in which the alloying could be accomplished in the shortest possible time. The size of the charge, approximately 11 cm³, and the high melting temperature of some of the alloying materials prohibited the use of a simple copper-slab crucible. The use of a heavy-bottom, single-piece, copper crucible eliminated contamination of the alloys which frequently occurs when solder joints are present in the crucible.

The time-consuming and contaminating operations of opening the arc furnace, turning the button, evacuating and flushing, and reestablishing the pressure under which melting is accomplished were minimized in the charge-flipping furnace used for this study.

The charge-flipping arc furnace is pictured functionally in Figure 1. The arc furnace is attached to a rigid platform and, after a melt is made, the electrode is raised and the striking plate is struck a sharp blow with a

*See Bibliography at end.

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Legend

1. Electrode cooling water IN	10. Striking plate
2. DC-arc power lead $\ominus$	11. Tungsten electrode tip
3. Vacuum monitor line for electrode seal	12. One-piece copper crucible
4. Vacuum spacer flange	13. Square-section ring seals
5. Vacuum line	14. Sight glass
6. Inert-gas line	15. Electrode-supporting springs
7. Crucible cooling water OUT	16. Water-cooled copper electrode
8. Crucible cooling water IN	17. Electrode cooling water OUT
9. DC-arc power lead $\oplus$	

FIGURE 1. CHARGE-FLIPPING ARC FURNACE

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heavy hammer. The impact throws the button up into the chamber, flipping it over ready for the next melt. The atmosphere in the furnace remains undisturbed. In addition to eliminating the time-consuming pump down and flushing operations, this procedure restricts any contamination of the alloy to the contaminants present previous to the initial melt.

A conventional laboratory arc furnace was employed in casting the alloyed material into a rectangular slab. This furnace is shown in Figure 2.

Corrosion Test Cell

Corrosion tests were conducted in 1-liter Pyrex, Berzelius beakers with samples supported on Pyrex holders. Cold water, flowing through distilling flasks placed on the top of each beaker, prevented evaporation of the boiling test water. This apparatus is shown in Figure 3.

EXPERIMENTAL PROCEDURES

Alloy Preparation

The alloys were prepared from selected biscuit uranium that had been rolled and sheared to appropriate size for charges. High-purity commercial materials were selected for the alloy additions.

Charges of approximately 11 cm³ were weighed, pickled, and placed in the charge-flipping arc furnace. All of the charges were melted ten times, the button being flipped after each melt. After alloying, the buttons were cast into the rectangular mold shown in Figure 4. The casting operation consisted of placing the alloyed button in the spherical depression as far as possible from the rectangular cavity. An arc was struck and played over the button in an attempt to melt the entire button charge before any portion ran into the rectangular cavity. If necessary, the cast slab was turned and the bottom smoothed with the arc. This rectangular shape could be fabricated directly or cut into convenient-sized specimens.

The cast, rectangular slabs were heated to appropriate temperatures in an inert atmosphere, or salt bath, and rolled to approximately 1/8-in. sheet. After rolling, the sheets were sandblasted to remove the heavy oxide scale and were marked for cutting.

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Legend

1. DC-arc power lead (-)	10. Rectangular slab mold
2. Brass bellows	11. Hearth cooling water OUT
3. Copper water-cooling tubing	12. Tungsten electrode tip
4. Vacuum line	13. Gettering charge
5. Inert-gas line	14. Sight glass
6. Arc-melted button charge	15. Water-cooled copper electrode
7. Copper-slab crucible	16. Bellows and electrode-supporting spring
8. DC-arc power lead (+)	17. Electrode cooling water IN
9. Hearth cooling water IN	18. Electrode cooling water OUT

FIGURE 2. LABORATORY ARC FURNACE

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GROUP 1
Excluded from automatic
downgrading and
declassification

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FIGURE 3. CORROSION TEST CELL

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FIGURE 4. RECTANGULAR SLAB MOLD

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The specimens cut from the rolled sheet or cast slabs were sealed in Vycor tubes and were heat treated. When a quenched specimen was desired, the Vycor tube was taken from the furnace and broken, and the specimen dropped into water.

After heat treatment, a small piece cut from the specimen was mounted in Bakelite and polished, and the Vickers hardness numbers were obtained. If the alloy were corrosion resistant in the heat-treated condition, grain sizes were also determined. The remainder of the specimen was finished with a shaper on all surfaces and readied for corrosion test.

Corrosion Testing

Before testing, the samples were degreased in acetone and pickled 1.5 min in 1:1 solution by volume of nitric acid and water to remove film formed during machining. Gold and platinum alloys were not pickled because of their rapid rate of dissolution in the pickle solution. Samples were then washed 1/2 hr in cold tap water, dipped in acetone, dried, weighed, and immediately placed on test. No attempt was made to control the dissolved-gas content of test water, which was once-distilled and had a specific resistivity of approximately 500,000 ohm-cm. Beakers were re-filled with fresh water after each exposure period. Loose oxide was removed from the corroded test samples with a stiff brush before weighing. No attempt was made to strip off adherent tarnish films on corrosion-resistant samples.

RESULTS

The selection of alloying material, alloy composition, melting technique, heat-treatment temperatures, and test conditions was governed by the desire to provide data on the relative corrosion resistance of binary uranium alloys.

Not all data are strictly comparable. The purity of alloying materials varied the level of contamination. Some alloys were limited in their composition by low liquid solubility, or volatility, of the added element, or the pyrophoric nature of the resulting alloy. The fabricability of the alloy determined whether it was rolled and heat treated or heat treated as-cast.

In general, from 2 to 12 a/o of the alloying element was added to uranium. Most of the alloys were tested in four heat-treated conditions.

All test specimens were identified and are listed in the tables by designations which include the nominal composition of the alloy, the alloying elements, and the heat-treated condition of the alloy. The heat-treatment designations for the alloys are letter abbreviations of the treatments: A, alpha annealed; G, gamma quenched; etc. For example, the test specimen 2 Sb GA is a uranium-2 a/o antimony alloy that had been gamma quenched by being heated 1 hr at 815 C and water quenched; and then alpha annealed by being reheated to 600 C, held for 4 hr at this temperature, and furnace cooled. The designations which identify the particular heat treatment of an alloy are given in Table 1.

TABLE 1. HEAT-TREATING DESIGNATIONS

Designation	Heat Treatment
ac	Tested in as-cast condition
A	4 hr at 600 C, furnace cooled
A'	4 hr at 565 C, furnace cooled
B	1 hr at 700 C, water quenched
B'	1 hr at 665 C, water quenched
G	1 hr at 815 C, water quenched
G'	1 hr at 790 C, water quenched
BA'	B followed by A'
B'A	B' followed by A
GA	G followed by A
GA'	G followed by A'
G'A	G' followed by A

Where any of the conditions of the test samples were varied, notations to that effect are included in the tables. The analyzed composition, the carbon and nitrogen contents, and the Vickers hardness numbers of the alloys are included in the tables. In addition, grain sizes of the alloys that were either resistant or temporarily resistant are given.

The explanations of the various melting comments found in the tables are given in Table 2.

TABLE 2. EXPLANATION OF MELTING COMMENTS

Comment	Physical Meaning
Sat	Satisfactory melting, homogeneous alloy
Seg	Some evidence of alloy inhomogeneity found either after melting or during corrosion test
Vol	Added element was volatile under arc, and difficult to include
Sl Sol	Added element was either immiscible or exhibited slight liquid solubility in uranium
Crk	The thermal conditions present as button was cast into rectangular cavity caused the alloy to crack
Oxd	Alloy oxidized rapidly in air
Cpd	Hard, brittle compounds were formed

All alloy samples were tested to failure. The resulting data were then grouped into three broad classifications of corrosion behavior: resistant, temporarily resistant, and nonresistant. For simplicity of discussion, all compositions and heat treatments for any given element are discussed under the classification in which the most resistant sample fell. For example, if one sample in an alloy series was corrosion resistant, all other compositions and heat treatments of this alloy are discussed in the section on resistant alloys.

The categories under which the corrosion behavior of the alloys are discussed are:

Resistant Alloys. Certain compositions and heat treatments exhibited very little weight change and adherent tarnish films or thin oxide films after exposure of more than 672 hr.

Temporarily Resistant Alloys. Certain compositions and heat treatments were resistant for periods up to 672 hr, then failure occurred by cracking or forming of loose oxide.

Nonresistant Alloys. All alloy compositions in all heat-treated conditions were covered with loose dark oxide and exhibited large weight losses within a 24 hr period of exposure to boiling water.

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In general, alloy samples corroded uniformly, indicating they were homogeneous. Several samples oxidized where they touched glass supporting members, but this can be attributed to contact- or crevice-type corrosion rather than to segregation. Just before failure, several samples of the temporarily resistant group also oxidized in localized areas, but were uniformly covered with oxide after the next exposure period.

Resistant Uranium Alloys

The uranium alloys noted below were resistant to boiling water for exposure periods ranging from 672 to 6720 hr.

Hafnium: 12 a/o, G

Nickel: 12 a/o, ac

Niobium: 5 a/o, B, G, and GA

Titanium: 5 a/o, B, G, and GA

Zirconium: 12 a/o, B and G

Corrosion data for these alloys are presented in Table 3. Resistant samples exhibited low total weight change (less than 1.0 mg/cm^2 for most samples) and were covered with adherent tarnish films or very thin oxide films.

Nickel alloys were removed from test after being exposed 672 hr. Their behavior for longer exposures was not studied.

Titanium alloys pitted along one edge after an 840-hr exposure, but this pitting appeared to result from smearing over of oxide scale during machining, and, therefore, did not necessarily represent the true characteristics of the alloy.

The alloys tabulated below in the corrosion-resistant series were resistant for more than 24 hr but failed within a 672-hr exposure.

Nickel: 2 a/o, A', B, and BA'

Zirconium: 7 a/o, B; 12 a/o, GA

The remaining alloy samples were covered with loose oxide after a 24-hr exposure.

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TABLE 3. CORROSION-RESISTANT URANIUM ALLOYS
Corrosion Data Obtained in Distilled Water at 100 C

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr										Remarks
	Alloy	Carbon	Nitrogen					24	96	216	408	576	1080	1248	1416	2068	2740	
2 Hf A	1.8	0.005	0.047	Sat	600	299	-	-45.9	-	-	-	-	-	-	-	-	-	Loose oxide
B						262	-	-28.5	-	-	-	-	-	-	-	-	-	Loose oxide
G						249	-	-24.0	-	-	-	-	-	-	-	-	-	Loose oxide
GA						282	-	-55.1	-	-	-	-	-	-	-	-	-	Loose oxide
5 Hf A	4.1	0.004	0.010	Sat	600	366	-	-38.8	-	-	-	-	-	-	-	-	-	Loose oxide
B						272	-	-13.2	-	-	-	-	-	-	-	-	-	Loose oxide
G						396	-	-11.1	-	-	-	-	-	-	-	-	-	Loose oxide
GA						362	-	-46.5	-	-	-	-	-	-	-	-	-	Loose oxide
12 Hf A	9.6	0.004	0.009	Sat	790	376	-	-17.5	-	-	-	-	-	-	-	-	-	Loose oxide
B						307	0.094	-23.1	-	-	-	-	-	-	-	-	-	Loose oxide
G						455	<0.009	0.07	-0.02	-0.02	-0.06	-0.37	-0.57	-0.65	-0.72	-0.74	-2.14	Yellow oxide spot, plus several oxide stringers at 576 hr
GA						388	-	-18.4	-	-	-	-	-	-	-	-	-	Loose oxide
								24	48	96	168	336	504	672				
2 Ni A	1.26	0.034	0.007	Seg	600	331	-	0.05	-1.93	-4.51	-13.0	-	-	-	-	-	-	Thin dark oxide, 48 hr; beakers boiled dry, 288 hr; samples heavily oxidized
G						368	-	0	-2.53	-5.38	-8.85	-	-	-	-	-	-	Thin dark oxide, 48 hr; beakers boiled dry, 288 hr; samples heavily oxidized
GA						371	-	0.06	0.08	-1.66	-4.98	-	-	-	-	-	-	Thin dark oxide, 96 hr; beakers boiled dry, 288 hr; samples heavily oxidized
5 Ni ac	1.01	0.036	0.008	Seg	As cast	206	-	-6.59	-	-	-	-	-	-	-	-	-	Loose oxide
A						297	Dendritic	-9.48	-	-	-	-	-	-	-	-	-	Loose oxide
B						328	Dendritic	-10.3	-	-	-	-	-	-	-	-	-	Loose oxide
BA						284	-	-10.8	-	-	-	-	-	-	-	-	-	Loose oxide
12 Ni ac	4.62	0.045	0.008	Seg	As cast	212	Dendritic	-0.03	0.10	-	-0.50	-1.07	-0.84	-0.95	-	-	-	Oxide where touched glass supports, 168 hr
A						427	Dendritic	-0.08	-	-	-	-	-	-	-	-	-	Cracked into small pieces, 48 hr
B						432	Dendritic	-0.11	-	-	-	-	-	-	-	-	-	Cracked into small pieces, 48 hr
BA						404	-	0.22	-	-	-	-	-	-	-	-	-	Cracked into small pieces, 48 hr
								24	96	168	312	480	648	816	1488	2160	2832	3336
2 Nb A	0.71	0.004	0.009	Sat	600	292	-	-48.7	-	-	-	-	-	-	-	-	-	Loose oxide
B						365	-	-16.3	-	-	-	-	-	-	-	-	-	Loose oxide
G						309	-	-26.2	-	-	-	-	-	-	-	-	-	Loose oxide
GA						392	-	-27.4	-	-	-	-	-	-	-	-	-	Loose oxide
5 Nb A	1.59	0.004	0.011	Sat	790 ^(c)	345	-	-57.3	-	-	-	-	-	-	-	-	-	Loose oxide
B						443	0.07-0.08	0.03	0.05	0.05	0.08	0.05	0.02	0.03	0.39	0.01	-0.01	Tamish film
G						408	0.105-0.118	0.01	0.07	0.04	0.07	0.02	0.0	0.02	-0.03	-0.03	-0.08	Tamish film
GA						408	0.105	0.01	0.03	0.04	0.06	0.03	0.02	0.04	-0.02	0.0	-0.05	Tamish film
12 Nb A	4.31	0.006	0.011	Sat	790	377	-	-	-	-	-	-	-	-	-	-	-	Not tested
B						201	-	-	-	-	-	-	-	-	-	-	-	Not tested
G						218	-	-	-	-	-	-	-	-	-	-	-	Not tested
GA						208	-	-	-	-	-	-	-	-	-	-	-	Not tested

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TABLE 3. (Continued)

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr												Remarks				
	Alloy	Carbon	Nitrogen					24	48	96	168	336	672	840	1344	2016	2688	3360						
2 Ti A G GA	0.39	0.002	0.001	Sat	600	299 253 282	— — —	−12.1 −36.6 −27.4	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —	Loose oxide Loose oxide Loose oxide						
5 Ti A B G GA	1.05	0.004	0.004	Sat	790	378 257 438 367	— 0.1 and up 0.118 0.1 and up	−3.63 −0.03 0.0 0.1	— 0.0 0.01 0.02	— 0.06 0.02 0.02	— 0.0 −0.01 −0.01	— 0.08 0.02 0.02	— 0.08 0.07 0.09	— −0.83 −0.96 −0.74	— −1.27 −1.52 −1.30	— −3.14 −3.04 −3.06	— −4.08 −4.22 −3.75	— −4.85 −4.46 −4.10	Loose oxide Tarnish film Tarnish film, pitted along one edge, 860 hr Tarnish film					
12 Ti A B G GA	2.77	0.003	0.004	Sat	790	474 599 363 342	— ≤0.009 — —	−3.16 0.05 −0.01 0.01	— 0.05 −0.02 0.01	— 0.09 −0.01 0.02	— 0.0 −0.04 −0.04	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	Loose oxide Tarnish film; removed from test, 168 hr Tarnish film; removed from test, 168 hr Tarnish film; removed from test, 168 hr						
								24	48	120	168	336	504	672	1344	2016	2688	3360	4032	4704	5376	6048	6720	
5 Zr A B G GA	2.34	0.007	0.010	Sat	600	310 310 452 269	— — — —	−31.1 −2.72 −25.2 −15.6	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	Loose oxide Oxide where touched glass supports, 24 hr Loose oxide Loose oxide					
7 Zr A B G GA	3.66	0.006	0.009	Sat	600	314 349 505 253	— Heavy precipitate — —	−43.4 −0.35 −9.72 −27.8	— −0.39 — —	— — — —	— −2.93 — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	Oxide where touched glass supports, 24 hr Oxide where touched glass supports, 168 hr Oxide where touched glass supports, 24 hr Oxide where touched glass supports, 24 hr					
12 Zr A B G GA	4.95	0.010	0.010	Sat	600	344 521 526 287	Heavy precipitate 0.020 0.013 Heavy precipitate	−35.2 0.03 −0.01 0.02	— 0.03 −0.01 0.03	— — −0.01 —	— 0.05 0.0 −26.0	— 0.03 −0.04 —	— 0.06 0.0 —	— 0.05 0.02 —	— 0.09 0.0 —	— 0.07 0.02 —	— 0.04 0.03 —	— 0.01 −0.01 —	— 0.05 −0.04 —	— 0.0 −0.13 —	— −0.11 −0.10 —	— −0.07 −0.21 —	— −0.18 −0.21 —	Loose oxide Tarnish film Tarnish film Loose oxide, 168 hr

(a) See Table 1 for explanation of alloy designation.

(b) See Table 2 for explanation of melting comments.

(c) Cracked on fabrication.

Hafnium: 2 and 5 a/o, A, B, G, and GA; 12 a/o, A, B, and GA.

Nickel: 5 a/o, ac, A', B, and BA'

Niobium: 2 a/o, A, B, G, and GA; 5 a/o, A

Titanium: 2 a/o, A, G, and GA; 5 and 12 a/o, A.

Zirconium: 5 a/o, A, B, G, and GA; 7 a/o, A, G, and GA;
12 a/o, A

Temporarily Resistant Uranium Alloys

Several binary uranium alloys of certain compositions and heat treatments were resistant to boiling water for periods ranging up to 672 hr before failing. Corrosion results are presented in Table 4. Alloy additions exhibiting this behavior, and the manner in which they eventually failed, are listed below.

Complete Oxidation.

Iron: 12 a/o, A, G', and G'A

Cracking.

Cobalt: 12 a/o, A, B, G', and G'A

Iron: 12 a/o, B

Manganese: 12 a/o, ac

Molybdenum: 12 a/o, A, B, G, and GA

Platinum: 5 a/o, B

Silicon: 5 a/o, G; 12 a/o, B

Vanadium: 5 a/o, G and GA

Loose Oxide. All alloy additions and heat treatments not already noted above fell in this classification.

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TABLE 4. TEMPORARILY CORROSION-RESISTANT URANIUM ALLOYS

Corrosion Data Obtained in Distilled Water at 100 C

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr					Remarks
	Alloy	Carbon	Nitrogen					24	48	96	168	456	
Pure uranium A B G GA	—	0.006	0.013	Sat	600	233	0.033-0.049	-116.3	—	—	—	—	Loose oxide
						205	0.049-0.062	-62.7	—	—	—	—	Loose oxide
						225	0.062-0.073	-83.9	—	—	—	—	Loose oxide
						225	0.062-0.073	-61.4	—	—	—	—	Loose oxide
2 Al A B G GA	0.19	0.037	0.007	Seg	600	316	—	-13.9	—	—	—	—	Loose oxide
						324	—	0.06	-22.7	—	—	—	Loose oxide, 48 hr
						284	—	-6.17	—	—	—	—	Loose oxide
						310	—	-29.9	—	—	—	—	Loose oxide
5 Al A B G GA	0.43	0.047	0.010	Seg	600	354	0.020	-0.37	-19.0	—	—	—	Loose oxide, 48 hr
						363	0.073-0.083	-16.0	—	—	—	—	Loose oxide
						308	0.020-0.033	-0.57	—	-3.04	-4.92	-16.0	Loose oxide, 96 hr
						330	—	-13.7	—	—	—	—	Loose oxide
12 Al A B G GA	1.35	0.039	0.009	Seg	815	354	0.083	-13.3	—	—	—	—	Loose oxide
						295	0.105	-17.0	—	—	—	—	Loose oxide
						335	0.020-0.033	-0.97	—	-5.48	-18.5	—	Loose oxide, 96 hr
						361	—	-1.43	—	-52.3	—	—	Loose oxide, 96 hr
								24	48	120			
2 Co A G GA	0.47	0.033	0.010	Sat	600	275	—	-19.9	—	—			
						308	—	-24.9	—	—			
						309	—	-25.4	—	—			
5 Co A B G GA	1.24	0.041	0.009	Sat	As cast	350	Dendritic	-5.16	—	—			
						380	Dendritic	-6.24	—	—			
						371	—	-8.15	—	—			
						336	—	-8.29	—	—			
12 Co A B G GA	2.99	0.040	0.013	Crk	As cast	453	—	0.18	0.35	—			
						347	Dendritic	0.22	-0.29	—			
						454	—	0.02	0.15	—			
						434	—	-0.06	0.12	—			

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TABLE 4. (Continued)

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr						Remarks
	Alloy	Carbon	Nitrogen					24	120	168	264	336	672	
2 Ge A	0.68	0.009	0.011	Sat	600	275	—	-11.8	—	—	—	—	—	Loose oxide
B						294	—	-84.0	—	—	—	—	—	Loose oxide
G						259	—	-44.0	—	—	—	—	—	Loose oxide
GA						305	—	-34.9	—	—	—	—	—	Loose oxide
5 Ge A	1.82	0.003	0.009	Sat	600	414	—	-1.45	-1.50	—	-30.2	—	—	Loose oxide, 264 hr
B						306	0.049	-0.47	-30.4	—	—	—	—	Loose oxide, 120 hr
G						298	—	-0.02	-10.6	—	—	—	—	Loose oxide, 120 hr
GA						316	—	-3.65	-3.90	—	-56.4	—	—	Loose oxide, 264 hr
12 Ge ac	3.12	0.004	—	Sat	As cast ^(c)	350	—	0.04	—	-0.16	—	-20.8	-49.5	Loose oxide, 336 hr
A						328	0.05-0.06	0.01	—	-0.06	—	-8.90	-25.7	Loose oxide, 336 hr
B						316	0.02	-0.04	—	-0.47	—	-7.10	-15.8	Loose oxide, 336 hr
G						278	Dendritic	0.0	—	0.06	—	-2.30	-11.6	Loose oxide, 336 hr
GA						269	—	0.02	—	0.11	—	-11.0	-21.5	Loose oxide, 336 hr
								24	98	168	288			
2 Fe A	0.49	0.034	0.007	Sat	600	288	—	-41.8	—	—	—	—	—	Loose oxide
B						306	—	-44.4	—	—	—	—	—	Loose oxide
BA						309	—	-46.8	—	—	—	—	—	Loose oxide
5 Fe A	1.13	0.043	0.017	Sat	As cast	354	0.057	-10.3	—	—	—	—	—	Loose oxide
B						448	>0.118	-9.13	—	—	—	—	—	Loose oxide
G						375	—	-13.5	—	—	—	—	—	Loose oxide
GA ^(d)						308	—	-12.9	—	—	—	—	—	Loose oxide
12 Fe A	2.81	0.053	0.027	Crk	As cast	456	—	0.41	1.13	—	—	—	—	Completely oxidized, 168 hr
B						460	—	0.60	0.97	2.14	—	—	—	Cracked into small pieces, 288 hr
G ^(e)						427	Dendritic	0.26	-13.5	—	—	—	—	Cracked into small pieces, 168 hr
GA						434	—	0.46	—	—	—	—	—	Portion completely oxidized, 96 hr
								24	48	96	168	336	624	
2 Mn A	0.38	0.040	0.010	Sat	600	286	—	-10.1	—	—	—	—	—	Loose oxide
B						348	—	—	—	—	—	—	—	Not tested
G ^(f)						285	—	—	—	—	—	—	—	Not tested
GA ^(f)						388	—	—	—	—	—	—	—	Not tested

TABLE 4. (Continued)

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr						Remarks
	Alloy	Carbon	Nitrogen					24	48	96	168	336	624	
5 Mn ac	1.12	0.048	0.012	Sat	As cast	392	—	-8.57	—	—	—	—	—	Loose oxide
A'						334	0.033-0.049	-52.6	—	—	—	—	—	Loose oxide
B						400	0.015	—	—	—	—	—	—	Completely oxidized, 24 hr
BA'						324	—	0.84	-39.0	—	—	—	—	Loose oxide, 48 hr
12 Mn ac	2.48	0.042	0.011	Sat	As cast	442	—	0.08	-0.08	-1.32	-33.9	—	—	Cracked, large area corroded away, 168 hr
A'						416	—	0.04	-0.09	-0.11	-0.22	-1.56	-5.39	Completely oxidized, 792 hr
B ^(f)						465	—	—	—	—	—	—	—	Completely oxidized, 24 hr
BA ^(f)						402	—	—	—	—	—	—	—	Completely oxidized, 24 hr
G'						437	—	—	—	—	—	—	—	Not tested
								24	96	168	336			
2 Mo A	0.73	0.034	0.010	Sat	600	277	—	-10.7	—	—	—	—	—	Loose oxide
G						412	—	-69.0	—	—	—	—	—	Loose oxide
GA						417	—	-64.0	—	—	—	—	—	Loose oxide
5 Mo A	1.89	0.036	0.013	Sat	790	340	<0.009	0.02	-22.8	—	—	—	—	Loose oxide, 96 hr
G						390	—	-0.63	-19.0	—	—	—	—	Loose oxide, 96 hr
GA						401	—	-1.87	-113.0	—	—	—	—	Loose oxide, 96 hr
12 Mo A	4.72	0.040	0.008	Sat	790	343	<0.009-0.015	-0.09	-0.04	-0.48	-110.0	—	—	Sample cracked; 90 per cent covered with loose oxide, 336 hr
B						265	0.062-0.083	0.0	-0.01	-3.80	-57.0	—	—	Sample bowed, oxidized in cracks, 336 hr
G						395	0.020	0.02	0.31	-0.85	-13.1	—	—	Corner cracked off; pitted, 336 hr
GA						410	—	0.0	0.29	-0.86	-19.2	—	—	Cracked one edge; pitted, 336 hr
								24	96	144	240			
2 Pd A'	0.93	0.003	0.007	Sat	600	284	—	-0.18	-5.10	-8.10	—	—	—	Loose oxide, 96 hr
B						268	—	0.11	-5.60	-7.00	—	—	—	Loose oxide, 96 hr
G						326	—	0.04	-0.88	-2.80	-10.6	—	—	Loose oxide, 240 hr
GA'						347	—	0.03	-1.80	-1.82	-8.57	—	—	Loose oxide, 240 hr
5 Pd A'	2.70	0.002	0.010	Sat	600	280	—	-0.14	-27.1	—	—	—	—	Loose oxide, 96 hr
B						286	—	-0.02	-4.30	-9.10	—	—	—	Loose oxide, 168 hr
G						338	—	-0.03	-4.70	-6.20	—	—	—	Loose oxide, 168 hr
GA'						329	—	0.0	-4.70	-7.80	—	—	—	Loose oxide, 168 hr

TABLE 4 (Continued)

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness, Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr					Remarks		
	Alloy	Carbon	Nitrogen					24	96	144	240				
12 Pd A' B G GA'	5.70	0.003	0.008	Sat	790	315 238 344 347	0.073 — 0.020-0.033 0.033	-0.74 -46.1 -0.02 -0.07	-84.5 — -4.10 -0.17	— — -5.60 -13.6	— — -13.9 —	Loose oxide, 96 hr Loose oxide, 24 hr Loose oxide, 240 hr Loose oxide, 144 hr			
								24	48	96	168	240			
2 Pt A' B G GA'	1.80	0.003	0.014	Sat	600	281 302 340 262	— — — —	2.61 — — —	-23.7 — — —	— — — —	— — — —	Loose oxide, 48 hr Completely oxidized, 24 hr Completely oxidized, 24 hr Severe cracking, 24 hr			
5 Pt A' B G GA'	4.20	0.003	0.013	Sat	790	334 362 416 350	0.020 — — 0.009	-0.35 -1.57 -19.2 -0.18	-0.57 — — -0.19	-0.58 — — -0.50	-4.77 — — -6.42	-8.27 — — -10.1	Loose oxide, 240 hr Broke in two, 48 hr Loose oxide, 24 hr Loose oxide, 240 hr		
2 Pt A' B G GA'	10.0	0.004	0.008	Sat	790	314 377 408 320	0.009 — — —	-30.0 0.20 -0.03 -1.26	— -9.52 -1.19 -16.1	— — -1.15 —	— — -2.03 —	— — -11.2 —	Loose oxide, 24 hr Loose oxide, 48 hr Loose oxide, 240 hr Loose oxide, 48 hr		
								24	48	72	144	312			
2 Ta A B G GA	1.99	0.041	0.022	Sat	600	302 280 276 279	— — — —	-7.90 -6.70 -1.89 -0.93	— — -2.00 -1.00	— — -7.57 -7.01	— — — —	— — — —	Loose oxide, 24 hr Loose oxide, 24 hr Loose oxide, 72 hr Loose oxide, 72 hr		
5 Ta A B G GA	3.46	0.045	0.008	Seg	790	332 315 330 344	0.015-0.020 0.033 0.015 0.015	-5.70 -4.27 0.01 0.0	— — 0.0 -0.05	— — — —	— — 0.12 0.20	— — -10.3 -9.63	Loose oxide, 24 hr Loose oxide, 24 hr Loose oxide, 312 hr Loose oxide, 312 hr		
								24	48	120	168	336	504	672	
2 Si A B G GA	0.27	0.040	0.009	Sat	815	309 293 332 291	— — — —	-19.4 -7.69 -30.3 -10.3	— — — —	— — — —	— — — —	— — — —	— — — —	Loose oxide Loose oxide Loose oxide Loose oxide	

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TABLE 4. (Continued)

Alloy Designation ^(a)	Chemical Analysis, w/o			Melting Comment ^(b)	Fabrication Temperature, C	Vickers Hardness Number	Grain Size, mm	Total Weight Change, mg/cm ² , at Time Indicated, hr							Remarks
	Alloy	Carbon	Nitrogen					24	48	120	168	336	504	672	
5 Si A B G GA	0.59	0.042	0.025	Sat	815	324	0.033	-15.7	-	-	-	-	-	-	Loose oxide
						306	0.057	-8.78	-	-	-	-	-	-	Loose oxide
						289	-	-0.36	-4.01	-	-	-	-	-	Loose oxide; sample cracked, 48 hr
						279	-	-18.5	-	-	-	-	-	-	Loose oxide
12 Si A B G GA	1.33	0.047	0.034	Sat	815	316	0.033	0.06	0.14	0.48	0.62	-15.1	-	-	Loose oxide, 336 hr
						335	0.057	0.06	-0.97	-1.01	-1.17	-3.80	-7.86	-12.5	Sample cracked, 168 hr, loose oxide, 336 hr
						297	0.049-0.057	-0.34	-1.49	-1.37	-1.30	-6.03	-	-	Loose oxide, 336 hr
						300	-	-1.82	-	-	-0.66	-1.11	-4.58	-14.7	Loose oxide, 504 hr
2 Ti A B G GA	0.10	0.002	0.009	SI Sol, Seg	600	233	0.015-0.049	24	96						
						208	0.050-0.083	-0.06	-174.0						Loose oxide, 96 hr
						222	0.057-0.083	-0.18	-94.5						Loose oxide, 96 hr
						221	0.073-0.083	-1.71	-109.0						Loose oxide, 96 hr
2 V A B G GA	0.39	0.036	0.012	Seg	600	293	-	24	48	120	168	336	504		
						303	-	-1.74	-15.1	-	-	-	-		Loose oxide, 24 hr
						292	-	-	-	-	-	-	-		Not tested
						292	-	-4.80	-18.2	-	-	-	-		Loose oxide, 24 hr
5 V A B G GA	1.02	0.004	0.018	Seg	600	312	-	-2.04	-16.3	-	-	-	-		Loose oxide, 24 hr
						333	-	-3.88	-6.06	-18.3	-	-	-		Not tested
						446	0.049	-0.03	-0.01	-5.35	-	-	-		Cracked into 3 pieces, 120 hr
						455	0.049-0.057	-0.03	-0.04	0.19	-0.09	-1.46	-17.6		Cracked, plus segregated oxide, 504 hr
12 V A B G GA	2.49	0.006	0.022	Seg	790	321	-	-5.68	-12.8	-	-	-	-		Loose oxide, 24 hr
						420	-	-1.85	-5.55	-11.5	-	-	-		Loose oxide, 24 hr
						469	-	-0.05	-0.19	-0.01	-2.28	-15.9	-		Loose oxide, 336 hr
						475	-	-0.54	-1.81	-4.50	-12.9	-	-		Loose oxide, 48 hr

(a) See Table 1 for explanation of alloy designation.

(b) See Table 2 for explanation of melting comments.

(c) Cracked on previous fabrication at 815 C.

(d) Cracked on anneal.

(e) Sagged or warped during heat treatment.

(f) Cracked on quenching.

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Aluminum: 2 a/o, B; 5 a/o, A and G; 12 a/o, G and GA

Germanium: 5 a/o, A, B, G, and GA; 12 a/o, ac, A, B, C,
and GA

Manganese: 5 a/o, BA'

Molybdenum: 5 a/o, A, G, and GA

Palladium: 2 and 5 a/o, A', B, G, and GA'; 12 a/o, A', G,
and GA'

Platinum: 2 a/o, A'; 5 a/o, A' and GA'; 12 a/o, B, G, and GA'

Silicon: 12 a/o, A, G, and GA

Tantalum: 2 and 5 a/o, G, and GA

Thallium: 2 a/o, A, B, G, and GA

Vanadium: 12 a/o, G, and GA

As a rule, the failures noted above were of the "breakaway" type. That is, resistant samples failed suddenly, after one additional exposure period, rather than slowly over several periods.

The cobalt, iron, and platinum alloy samples which failed by cracking still retained adherent tarnish films, but oxidized in the crevices formed by the cracks.

Not all compositions and heat treatments of the aforementioned alloys were temporarily resistant to boiling water. The remaining samples of each series failed within 24 hr. Except for several samples, all were covered with loose oxide. These samples included those tabulated below.

Aluminum: 2 a/o, A, G, and GA; 5 a/o, B and GA; 12 a/o,
A and B

Cobalt: 5 a/o, A, B, G', and G'A

Germanium: 2 a/o, A, B, G, and GA

Iron: 5 a/o, A, B, G', G'A

Manganese: 5 a/o, ac, A', and B*; 12 a/o, A'*, B*, and BA'*

*Sample completely oxidized.

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Molybdenum: 2 a/o, A, G, and GA

Palladium: 12 a/o, B

Platinum: 2 a/o, B*, G*, and GA'**; 5 a/o, G; 12 a/o, A'

Silicon: 2 a/o, A, B, G, and GA; 5 a/o, A, B, and GA

Tantalum: 2 and 5 a/o, A and B

Vanadium: 2 a/o, A, G, and GA; 5 a/o, A; 12 a/o, A and B

Nonresistant Uranium Alloys

Irrespective of alloy content or heat treatment, alloys containing up to 12 a/o additions of the following elements failed during 24-hr exposure to boiling water: antimony, barium, beryllium, bismuth, boron, cadmium, carbon, cerium, chromium, copper, gadolinium, gold, lanthanum, lead, lithium, nitrogen, oxygen, selenium, silver, strontium, thorium, tin, tungsten, yttrium, and zinc. Corrosion data for these alloys are presented in Table 5.

Test samples described in Table 5 failed by corroding in the manner described below.

Complete Oxidation. Samples were completely oxidized, and the resulting oxide was dispersed in the test beakers.

Antimony: 12 a/o, A, G, and GA

Cerium: 1 a/o, A', B, G, GA'

Chromium: 5 and 12 a/o, B and G'

Formation of Loose Oxide, Plus Pitting. This phenomenon was observed in the carbon series only, on the 5.6, 7.5, and 9.5 a/o additions in all heat-treated conditions. Pitting probably occurred at carbide inclusions.

*Sample completely oxidized.

**Sample cracked.

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TABLE 5. NON-CORROSION-RESISTANT URANIUM ALLOYS

Corrosion Data Obtained in Distilled Water at 100 C

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr	Remarks
	Alloy	Carbon	Nitrogen					
2 Sb A	1.28	0.003	0.016	Sat	790	303	-99.2	Loose oxide
G						264	-56.2	Loose oxide
GA						275	-38.8	Loose oxide
5 Sb A	2.68	0.003	0.017	Sat	790	270	-105.0	Loose oxide
G						270	-98.3	Loose oxide
GA						246	-108.0	Loose oxide
12 Sb A	5.48	0.006	0.016	Sat	790	284	--	Completely oxidized
G						305	--	Completely oxidized
GA						285	--	Completely oxidized
2.2 Ba A	< 0.01	0.009	0.009	Vol	600	245	-12.5	Loose oxide
B						258	-34.2	Loose oxide
G						241	-11.7	Loose oxide
GA						233	-27.3	Loose oxide
2 Be A	0.10	0.001	0.007	Sat	600	234	-15.4	Loose oxide
B						248	-15.8	Loose oxide
G						249	-10.5	Loose oxide
GA						236	-9.80	Loose oxide
5 Be A	0.26	0.001	0.007	Sat	600	246	-18.7	Loose oxide
B						268	-29.4	Loose oxide
G						234	-25.0	Loose oxide
GA						265	-16.0	Loose oxide
12 Be A	0.55	0.002	0.010	Sat	600	258	-21.5	Loose oxide
B						259	-17.2	Loose oxide
G						247	-14.5	Loose oxide
GA						257	-11.9	Loose oxide
1 Bi A	0.01	0.050	0.010	Vol, Oxd	600	244	-38.1	Loose oxide
B						227	-36.8	Loose oxide
G						230	-42.5	Loose oxide
GA						220	-16.7	Loose oxide
0.1 B A	0.007	0.003	0.017	Sat	600	230	-74.2	Loose oxide
B						230	-94.1	Loose oxide
G						225	-86.3	Loose oxide
GA						219	-78.9	Loose oxide
0.5 B A	0.010	0.002	0.010	Sat	600	240	-71.8	Loose oxide
B						210	-83.8	Loose oxide
G						230	-81.9	Loose oxide
GA						226	-77.6	Loose oxide

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TABLE 5. (Continued)

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr	Remarks
	Alloy	Carbon	Nitrogen					
1 B A	0.018	0.003	0.014	Sat	600	268	-81.2	Loose oxide
B						226	-94.5	Loose oxide
G						233	-93.9	Loose oxide
GA						235	-80.7	Loose oxide
5 B A	0.152	0.006	0.015	Sat	790	272	-48.4	Loose oxide
B						253	-54.2	Loose oxide
G						248	-62.4	Loose oxide
GA						271	-49.3	Loose oxide
2 Cd A	0.21	0.003	0.013	Vol	600	272	-70.0	Loose oxide
B						256	-57.5	Loose oxide
G						224	-65.3	Loose oxide
GA						301	-70.0	Loose oxide
5 Cd A	0.36	0.008	0.025	Vol	600	308	-46.3	Loose oxide
B						270	-41.2	Loose oxide
G						262	-34.2	Loose oxide
GA						301	-38.7	Loose oxide
12 Cd A	0.41	0.015	0.015	Vol	600	291	-68.0	Loose oxide
B						248	-62.6	Loose oxide
G						225	-38.8	Loose oxide
GA						274	-78.5	Loose oxide
2 C A	--	0.10	0.011	Sat	600	254	-23.2	Loose oxide
B						268	-10.7	Loose oxide
G						263	-10.9	Loose oxide
GA						260	-20.7	Loose oxide
4 C A	--	0.20	0.014	Sat	600	278	-54.9	Loose oxide
B						288	-31.5	Loose oxide
G						292	-57.2	Loose oxide
GA						260	-58.8	Loose oxide
5.6 C A	--	0.26	0.024	Sat	600	262	-88.5	Loose oxide plus slight pitting
B						300	-40.8	Loose oxide plus slight pitting
G						280	-38.2	Loose oxide plus slight pitting
GA						259	-88.2	Loose oxide plus slight pitting
7.5 C A	--	0.32	0.033	Sat	600	279	-94.2	Loose oxide plus slight pitting
B						333	-98.8	Loose oxide plus slight pitting
G						302	-76.8	Loose oxide plus slight pitting
GA						296	-100.8	Loose oxide plus slight pitting

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TABLE 5. (Continued)

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr	Remarks
	Alloy	Carbon	Nitrogen					
9.5 C A	--	0.38	0.038	Seg	600	273	-101.0	Loose oxide plus large pits
B						330	-109.0	Loose oxide plus large pits
G						330	-89.7	Loose oxide plus large pits
GA						325	-71.2	Loose oxide plus large pits
1 Ce A'	0.50	0.017	0.028	Seg	600	182	--	Completely oxidized
B						214	--	Completely oxidized
G						203	--	Completely oxidized
GA'						208	--	Completely oxidized
2 Ce ac	0.55	0.004	--	Oxd, Seg	As cast(c)	225	4.09	Numerous cracks; sample warped
A'						190	-3.40	Numerous cracks; sample warped
B						211	6.35	Numerous cracks; sample warped
G						228	-3.72	Numerous cracks; sample warped
GA'						206	4.40	Numerous cracks; sample warped
2 Cr A'	0.45	0.038	0.012	Sat	600(d)	430	Not tested	Samples badly cracked from fabrication
B						408	Not tested	Samples badly cracked from fabrication
G						356	Not tested	Samples badly cracked from fabrication
GA'						336	Not tested	Samples badly cracked from fabrication
5 Cr A	1.48	0.038	0.011	Sat	As cast	313	-2.75	Loose oxide
B						389	--	Completely oxidized
G'						243	--	Completely oxidized
G'A						288	-11.1	Loose oxide
12 Cr A	2.60	0.040	0.008	Sat	As cast	339	-8.10	Loose oxide
B						380	--	Completely oxidized
G'						439	--	Completely oxidized
G'A						226	-2.68	Loose oxide
2 Cu A	0.49	0.053	0.013	Sat	600	281	-16.1	Loose oxide
B						266	-13.7	Loose oxide
G						278	-14.6	Loose oxide
GA						279	-10.6	Loose oxide
5 Cu A	1.31	0.043	0.019	Sat	790	272	-11.8	Loose oxide
B						272	-10.2	Loose oxide
G						303	-10.2	Loose oxide
GA						275	-10.1	Loose oxide
12 Cu A	3.72	0.044	0.012	Seg	790	279	-12.1	Loose oxide
B						282	-18.5	Loose oxide
G						281	-15.1	Loose oxide
GA						309	-5.82	Loose oxide

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TABLE 5. (Continued)

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr	Remarks
	Alloy	Carbon	Nitrogen					
2 Gd A	0.79	0.09	0.006	Seg, Sl Sol	600	308	-14.2	Loose oxide
B						261	-20.9	Loose oxide
G						254	-12.4	Loose oxide
GA						288	-31.1	Loose oxide
2 Au A	1.80	0.002	0.006	Sat	600	283	-28.8	Loose oxide
B						281	-25.5	Loose oxide
G'						264	Not tested	Sample reacted violently to clean-up pickle solution
G'A						288	-24.9	Loose oxide
5 Au A	4.40	0.002	0.006	Sat	790	290	-31.7	Loose oxide
B						261	-32.5	Loose oxide
G'						281	-20.4	Loose oxide
G'A						309	-31.4	Loose oxide
12 Au A	10.1	0.003	0.006	Sat	790	316	-14.7	Loose oxide
B						277	-12.6	Loose oxide
G'						218	-12.3	Loose oxide
G'A						317	-16.2	Loose oxide
2 La A	0.10	0.008	0.011	Sl Sol, Seg, Oxd	600	218	-102.0	Loose oxide
B						224	-48.2	Loose oxide
G						181	-57.1	Loose oxide
GA						215	-46.9	Loose oxide
1 Pb A	0.074	0.036	0.007	Vol, Seg	600	249	-60.0	Loose oxide
G						246	-55.0	Loose oxide
GA						250	-55.0	Loose oxide
2 Pb A	0.10	0.036	0.006	Vol, Seg	600	258	-87.2	Loose oxide
G						249	-42.4	Loose oxide
GA						255	-40.0	Loose oxide
1 Li A	0.001	0.002	0.008	Vol, Seg	600	185	-41.5	Loose oxide
B						225	-52.4	Loose oxide
G						247	-55.8	Loose oxide
GA						239	-77.0	Loose oxide
2 Li A	0.001	0.005	0.007	Vol, Seg	600	192	-43.0	Loose oxide
B						219	-63.2	Loose oxide
G						239	-61.7	Loose oxide
GA						232	-74.0	Loose oxide
5 Li A	0.001	0.001	0.007	Vol, Seg	600	188	-45.2	Loose oxide
B						220	-67.4	Loose oxide
G						210	-57.3	Loose oxide
GA						229	-82.3	Loose oxide

2) TABLE 5. (Continued)

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr	Remarks
	Alloy	Carbon	Nitrogen					
3.3 N ac	0.060	0.040	--	Seg	As cast	248	-22.1	Loose oxide
3.0 O ac	0.25 ^(e)	0.005	0.009	Sat	As cast	217	-40.6	Loose oxide
2 Se A	0.59	0.004	0.008	Cpd, Seg	600	258	-56.8	Loose oxide
B						222	-38.4	Loose oxide
G						220	-31.0	Loose oxide
GA						300	-45.6	Loose oxide
2 Ag A	0.41	0.008	0.007	Sl Sol, Seg	600	225	-30.4	Loose oxide
B						241	-33.0	Loose oxide
G						214	-20.4	Loose oxide
GA						223	-30.4	Loose oxide
2 Sr A	<0.01	0.006	0.011	Vol, Seg	600	220	-39.6	Loose oxide
B						241	-35.4	Loose oxide
G						245	-33.4	Loose oxide
GA						214	-44.3	Loose oxide
2 Th A	1.91	0.038	0.008	Sat	600	258	-46.9	Loose oxide
B						245	-70.7	Loose oxide
G						249	-73.2	Loose oxide
GA						246	-72.3	Loose oxide
5 Th A	4.74	0.038	0.012	Sat	790	253	-56.7	Loose oxide
G						225	-67.1	Loose oxide
GA						230	-65.7	Loose oxide
12 Th A	11.4	0.032	0.012	Sat	790	216	-33.6	Loose oxide
G						245	-41.9	Loose oxide
GA						226	-40.7	Loose oxide
0.5 Sn A	0.33	0.008	0.014	Seg	600	252	-102.	Loose oxide
B						225	-52.7	Loose oxide
G						265	-24.5	Loose oxide
GA						228	-28.5	Loose oxide
1 Sn A	0.20	0.006	0.013	Seg	600	279	-106.	Loose oxide
B						286	-69.3	Loose oxide
G						266	-28.7	Loose oxide
GA						263	-62.9	Loose oxide
1.5 Sn A	0.71	0.040	0.007	Seg	815 ^(c)	297	-26.0	Loose oxide
B						289	-91.2	Loose oxide
G						267	-73.8	Loose oxide
GA						300	-42.7	Loose oxide

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TABLE 5. (Continued)

Alloy Designation(a)	Chemical Analysis, w/o			Melting Comment(b)	Fabrication Temperature, C	Vickers Hardness Number	Total Weight Change, mg/cm ² , at 24 Hr		Remarks
	Alloy	Carbon	Nitrogen						
3 Sn A	0.80	0.005	0.009	Seg	815	344	-127.0	Loose oxide	
B						298	-103.0	Loose oxide	
G						282	-59.6	Loose oxide	
GA						254	-123.7	Loose oxide	
2 W A	1.3	0.004	0.019	Sat	600	371	-77.0	Loose oxide	
B						292	-75.9	Loose oxide	
G						252	-63.0	Loose oxide	
GA						279	-70.5	Loose oxide	
5 W A	3.7	0.003	0.017	Sat	600	284	-102.0	Loose oxide	
B						266	-90.8	Loose oxide	
G						245	-87.3	Loose oxide	
GA						283	-92.8	Loose oxide	
2 Y A	0.68	0.005	0.008	Sl Sol, Seg	600	221	-35.5	Loose oxide	
B						226	-35.8	Loose oxide	
G						225	-33.5	Loose oxide	
GA						235	-46.9	Loose oxide	
2 Zn A	0.15	0.005	0.010	Vol, Seg	600	308	-67.2	Loose oxide	
B						292	-72.8	Loose oxide	
G						352	-126.0	Loose oxide	
GA						324	-67.3	Loose oxide	
5 Zn A	0.44	0.004	0.009	Vol, Seg	600	220	-67.8	Loose oxide	
B						216	-61.9	Loose oxide	
G						226	-35.8	Loose oxide	
GA						219	-60.5	Loose oxide	
12 Zn A	0.60	0.005	0.014	Vol, Seg	600	238	-78.0	Loose oxide	
B						244	-71.2	Loose oxide	
G						205	-51.3	Loose oxide	
GA						260	-79.8	Loose oxide	

(a) See page 15 for explanation of alloy designation.

(b) See Table 2, page 16, for explanation of melting comments.

(c) Cracked on previous fabrication at 600 C.

(d) Cracked on fabrication.

(e) Nominal w/o oxygen.

Cracking. Only the 2 a/o cerium alloy in all heat-treated conditions cracked. Samples also warped and appeared to oxidize in crevices formed by cracks.

Loose Oxide. All alloy additions and heat treatments not already noted above fell in this classification.

Antimony: 2 and 5 a/o, A, G, and GA

Barium: 2.2 a/o, A, B, G, and GA

Beryllium: 2, 5, and 12 a/o, A, B, G, and GA

Bismuth: 1 a/o, A, B, G, and GA

Boron: 0.1, 0.5, 1, and 5 a/o, A, B, G, and GA

Cadmium: 2, 5, and 12 a/o, A, B, G, and GA

Carbon: 2 and 4 a/o, A, B, G, and GA

Chromium: 5 and 12 a/o, A' and GA'

Copper: 2, 5, and 12 a/o, A, B, G, and GA

Gadolinium: 2 a/o, A, B, G, and GA

Gold: 2 a/o, A, B, and GA; 5 and 12 a/o, A, B, G, and GA

Lanthanum: 2 a/o, A, B, G, and GA

Lead: 1 and 2 a/o, A, G, and GA

Lithium: 1, 2, and 5 a/o, A, B, G, and GA

Nitrogen: 3.3 a/o, ac

Oxygen: 3.0 a/o, ac

Selenium: 2 a/o, A, B, G, and GA

Silver: 2 a/o, A, B, G, and GA

Strontium: 2 a/o, A, B, G, and GA

Thorium: 2 a/o, A, B, G, and GA; 5 and 12 a/o, A, G, and GA

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Tin: 0.5, 1, 1.5, and 3 a/o, A, B, G, and GA

Tungsten: 2 and 5 a/o, A, B, G, and GA

Yttrium: 2 a/o, A, B, G, and GA

Zinc: 2, 5, and 12 a/o, A, B, G, and GA

Certain heat treatments and compositions of several of the above alloys, notably barium, beryllium, carbon, cerium, chromium, copper, gadolinium, and gold, exhibited lower weight changes than unalloyed uranium, but their corrosion resistance was still poor.

CONCLUSIONS

The following conclusions can be drawn from the study of corrosion behavior of binary uranium alloys containing up to 12 a/o additions of some 42 elements.

- (1) The boiling-water corrosion resistance of uranium, based on corrosion rate after 24-hr exposure, can be improved as much as 1000-fold by the addition of hafnium, nickel, niobium, titanium, and zirconium. The resulting alloys exhibited very little weight change and resisted attack upon continued exposure for periods ranging from 672 to 6720 hr.

Both alloy content and heat treatment determined the corrosion resistance of these alloys. Alloys having minimum additions ranging from 5 a/o in the case of niobium and titanium to 12 a/o in the case of hafnium, nickel, and zirconium were generally resistant when water quenched from 700 to 815 C.

- (2) Certain alloy compositions and heat treatments exhibited temporary corrosion resistance in boiling water. Such alloys were resistant for an exposure period ranging up to 672 hr before failure. After this period, they failed by cracking, the appearance of loose oxide, or both. Uranium containing the following elements exhibited this behavior: aluminum, cobalt, germanium, iron, manganese, palladium, platinum, silicon, tantalum, thallium, and vanadium.

- (3) Irrespective of alloy content or heat treatment, alloys containing additions of the following elements failed by either complete oxidation or by heavy surface oxidation within a 24-hr exposure period: antimony, barium, beryllium, bismuth, boron, cadmium, carbon, cerium, chromium, copper, gadolinium, gold, lanthanum, lead, lithium, nitrogen, oxygen, selenium, silver, strontium, thorium, tin, tungsten, yttrium, and zinc.

While the study of corrosion resistance of binary alloys was made with the objective of providing comparable corrosion data, additional information concerning the actual preparation of the alloys was gathered. From this information, several promising fields have been defined. A more thorough study of heat-treatment conditions and melting techniques would undoubtedly elevate several of the alloys that were temporarily resistant to a position among the resistant alloys. The most promising of the temporarily resistant group would be the alloys that failed by cracking. A more detailed study of composition levels and heat treatments would increase the number of as-cast alloys that were corrosion resistant. The physical properties of corrosion-resistant alloys could be improved by more involved heat treatments without impairing the corrosion resistance of the alloys.

In addition, it is felt that a field of ternary alloys, including the elements that induced in the binary alloys either resistance or temporary resistance to boiling water, has been circumscribed.

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