

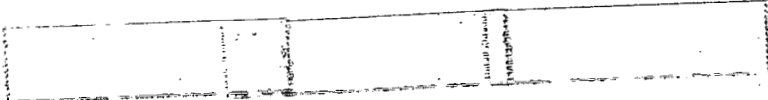
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ARGONNE NATIONAL LABORATORY  
P. O. Box 5207  
Chicago 80, Illinois



AQUEOUS CORROSION OF URANIUM AND ALLOYS:  
SURVEY OF PROJECT LITERATURE

by

J. W. McWhirter and J. E. Draley

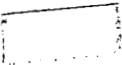
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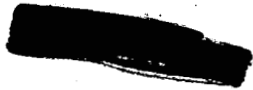


TABLE OF CONTENTS

	<u>Page</u>
I. SUMMARY . . . . .	4
II. INTRODUCTION. . . . .	5
Background . . . . .	5
Purpose and Scope . . . . .	5
Sources . . . . .	5
III. EXPERIMENTAL PROCEDURES. . . . .	6
Test Methods. . . . .	6
Sample Treatment . . . . .	6
IV. AQUEOUS CORROSION OF URANIUM . . . . .	8
Corrosion in Hydrogen-Saturated Water . . . . .	8
Corrosion in Air-Saturated Water . . . . .	11
Effect of Dissolved Gas . . . . .	13
Effect of Hydrogen Peroxide. . . . .	13
Effect of Dissolved Salts . . . . .	14
Corrosion in Steam. . . . .	16
Effect of Velocity . . . . .	17
Galvanic Effects. . . . .	18
Effect of Surface Preparation. . . . .	18
Effect of Heat-Treatment. . . . .	19
V. AQUEOUS CORROSION OF URANIUM ALLOYS . . . . .	21
Preliminary Survey . . . . .	21
Uranium-Columbium Alloys . . . . .	37
Uranium-Molybdenum Alloys . . . . .	40
Uranium-Silicon Alloys . . . . .	42
Aluminum-Uranium Alloys. . . . .	44
Effectiveness of Alloying Constituents . . . . .	46
VI. REFERENCES . . . . .	48

4

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## AQUEOUS CORROSION OF URANIUM AND ALLOYS: SURVEY OF PROJECT LITERATURE

by

J. W. McWhirter and J. E. Draley

### I. SUMMARY

The corrosion rate of uranium in hydrogen-saturated water appears to be constant with respect to time after a brief induction period and to involve only one type of over-all reaction, in which pitting effects are slight or nonexistent. In boiling distilled water the corrosion rate of uranium is between 0.7 and 3.0 mg/cm<sup>2</sup>/hr, depending on the purity and the heat-treatment of the uranium. The logarithm of the corrosion rate of uranium in hydrogen-saturated water versus the reciprocal of the absolute temperature is a straight line in the range tested, from 50 to 226°C.

In aerated distilled water the corrosion rate of uranium is initially less than in hydrogen-saturated water, probably involving the formation of protective oxide films. But after relatively long times on test, the reaction rate increases, apparently approaching that in hydrogen-saturated water.

Most of the uranium alloys, which were tested in an attempt to find a corrosion-resistant alloy, cracked or disintegrated when tested in boiling distilled water. Only five or six alloys of the twenty-three investigated showed sufficient resistance to warrant further study; however, with proper heat-treatment, some of the bad alloys might not have been so reactive. The outstanding characteristic of the favorable alloys was that they were resistant to corrosion in water only when properly heat-treated. Since some of these favorable heat-treated alloys are metastable, they might transform in use to a modification which would be very reactive with water; therefore, an alloy would be preferable from the corrosion standpoint if it were corrosion resistant when fully annealed.

From the information herein reported it appeared that in the temperature range tested, from 100 to 178°C, the most promising corrosion-resistant uranium alloys were:

- (1) The 2 weight per cent zirconium plus 2 weight per cent columbium alloy, homogenized at 1000°C, water quenched.
- (2) The 6.4 weight per cent columbium alloy, heated two hours at 850°C, water quenched, and the same heat-treated alloy tempered 24 hours at 350°C, water quenched.

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- 5
- (3) The 3.4 weight per cent silicon alloy, epsilonized.
  - (4) The 4.3 weight per cent zirconium alloy, heated fifty-three hours at 1000°C, water quenched.

The rate of metal loss was approximately the same for the above alloys, apparently less than 0.01 mg/cm<sup>2</sup>/hr at 100 and at 178°C.

## II. INTRODUCTION

### Background

Uranium metal is jacketed for reactor use to prevent corrosive attack of the reactive uranium and to avoid fission recoils into the coolant. In a water-cooled reactor, penetration of a slug jacket causes operational difficulties owing to the release of active corrosion products and sometimes because of localized swelling, resulting in jamming of the slug.

If the reactor uranium were present in the form of a corrosion-resistant alloy, these operational difficulties would be greatly alleviated. Small holes in the jackets used should not then result in much reaction between the metal and cooling water.

For many possible alloying metals, the amount added to improve corrosion resistance should be as low as possible in order to avoid excessive neutron capture. In this report the results have been given with no consideration of this factor.

### Purpose and Scope

In order to facilitate future work on the development of corrosion-resistant alloys, the present summary has been prepared. As far as possible, all project data on the aqueous corrosion of uranium and its alloys have been examined. Wherever available, details of test conditions and conclusions derived have been given; however, in many cases the average weight loss rates were given with little further information.

### Sources

The information summarized was originally reported by the Metallurgical Laboratory, the Massachusetts Institute of Technology, the Iowa State College, the Battelle Memorial Institute, the Montreal Laboratory, and the Imperial Chemical Industries Limited, Research Department.

### III. EXPERIMENTAL PROCEDURES

#### Test Methods

In the aqueous corrosion tests of uranium and its alloys the testing apparatus can be divided into two groups: the beaker test and the steam autoclave test. The apparatus in the beaker test used by the Corrosion Section, Metallurgical Laboratory, consisted of a constant flow of replenishing liquid through a beaker (400 to 2000 cc), which was heated by a variable voltage hot plate. There was no mechanical agitation of the solution except for the stream of replenishing solution, and in tests using gas-saturated solution the stream of gas bubbles was directed away from the test samples. In the gas-saturated solution test a closed vessel was used. The samples were suspended in glass holders which were totally immersed in the water. Other laboratories used apparatus similar to the above, with variations. Usually only enough water was added to compensate for evaporation.

In the other type of test a prepared sample was immersed in boiled distilled water in a 400-cc Pyrex beaker which was covered with a Petri dish and then placed in an autoclave. Normally these tests were made at temperatures of about 178°C, and at these temperatures silica was leached from the Pyrex beakers at a rate of 100-300 ppm in four to six days. In an effort to reduce the silica content of the water, Vycor beakers were tried and were found to give 50-100 ppm silica in four to six days, which was not a significant improvement. Since there was no replenishing solution in the steam autoclave tests, the leached silica might very well have acted as an inhibitor. However, the autoclaves had a valve which was cracked open to allow the hydrogen gas to escape, for uranium reacts vigorously with hydrogen at these temperatures. Another difficulty was the possibility that a heat-treated alloy would undergo transformation during the autoclave test at temperatures of 178°C and higher. Interpretation of test results was thus somewhat uncertain.

#### Sample Treatment

The technique used by many of the laboratories for sample preparation consisted of polishing the surface of the metal sample with various grades of abrasives, finishing with a fine grit paper. At the Corrosion Section, Metallurgical Laboratory, the surface areas were measured; the samples were dipped in acetone and sometimes in 25% HNO<sub>3</sub> at 28°C for five minutes followed with a dip in water; the samples were then rinsed in acetone, dried, and weighed.

Normally the samples were corroded for the duration of the test without removing from the water. This avoided irreversible changes in the film of corrosion products due to dehydration.

To find the amount of metal that has been corroded, the corrosion products must be removed. A simple technique was frequently used: the corrosion products were either polished or brushed off. However, when the metal or alloys showed resistance to corrosion, the removal of the corrosion products was a more difficult problem. The only laboratory which reported having spent a large amount of time on the removal of these films was the Corrosion Section, Metallurgical Laboratory. They usually removed the films with about a five-minute dip of the sample in 25%  $\text{HNO}_3$  at 28°C, but there were a few exceptions. The aluminum-uranium alloys were cleaned in 10% chromic and 30% phosphoric acid. Samples of uranium-molybdenum and uranium-columbium alloys were cleaned with various weight per cents of nitric acid, and one sample of uranium-molybdenum was cleaned with 95%  $\text{H}_2\text{SO}_4$  saturated with  $\text{Na}_2\text{Cr}_2\text{O}_7$  at 26°C. For samples having resistive films, "cleaning curves" were determined in which cumulative weight losses were plotted against time of exposure in the cleaning solution. When the slope of the curve became constant, the metal sample was cleaned of corrosion products. The first point at which the curve had a constant slope was the upper limit of metal loss, and by extrapolation of the constant slope back to zero time the lower limit of metal loss was calculated. If the "cleaning curve" showed only a slight change in slope, then the point at which a sample became clean was obtained mainly by noting the disappearance of interference colors of the oxide film.

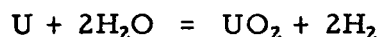
Since most of the work at the other laboratories was to be used as a rough survey of the uranium alloys and since the above method was rather difficult and time consuming, the metal samples were not cleaned of their corrosion products by stripping solutions. A few uranium alloys which had been tested by the Metallurgy Section, Metallurgical Laboratory, were cleaned of their corrosion products by the Corrosion Section. This was a boiling water test in which the water was maintained at a roughly constant level by addition as required by evaporation. In some cases, the heat was turned off overnight, leaving the samples in the water; in others, the systems were kept going.

The term "metal loss" has been used in this report as an indication that the metal sample had been cleaned of corrosion products, and the term "weight loss" to indicate no attempt at stripping the corrosion products from the sample. The term "corrosion rate" has been used to indicate that a curve of metal loss versus time has been plotted and that the slope of the curve has become approximately constant with time. This constant slope has been called the corrosion rate.



#### IV. AQUEOUS CORROSION OF URANIUM

The main mechanism by which uranium corrodes in liquid water can be represented by the displacement reaction



with the hydrogen bubbling out through the water. Therefore, in tests made in closed vessels with static distilled water or in distilled water at 100°C or above, the water will become hydrogen saturated. The Corrosion Section, Metallurgical Laboratory, reported that in water plus hydrogen peroxide higher uranium oxides were formed, with  $UO_4$  and  $UO_3$  being indicated by chemical analysis.

##### Corrosion in Hydrogen-Saturated Water

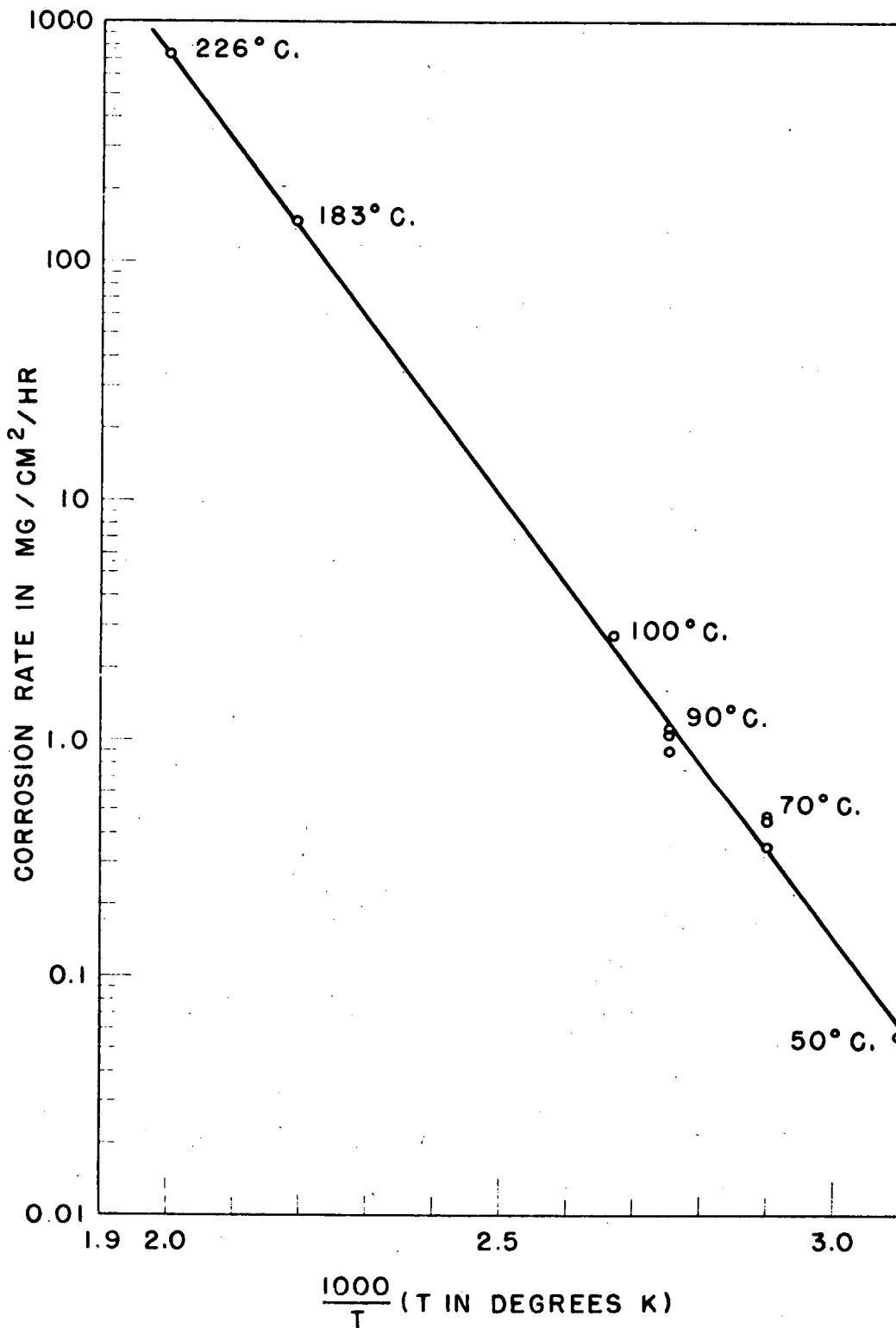
The corrosion of uranium in water containing an excess of hydrogen was indicated to be the same in reaction mechanism over-all the temperature range tested, from 50 to 226°C. The results of the hydrogen-saturated water tests of the Corrosion Section, Metallurgical Laboratory, showed that the logarithm of the corrosion rate versus the reciprocal of the absolute temperature was a straight line, as shown in Figure 1. The corrosion rates were essentially constant with time after a short induction period.

In Table I are reported all data for the corrosion of uranium in hydrogen-saturated distilled water. The different corrosion rates at 100°C can be explained by the varying quality of the samples and the varying purity of the water. In BR-549 it was reported that in general the corrosion rate increased with increasing purity of the uranium. One group of uranium samples "A" had a corrosion rate at 100°C in distilled water of 0.85 to 0.95 mg/cm<sup>2</sup>/hr, and a group of samples "B" gave 2.6 to 2.9 mg/cm<sup>2</sup>/hr (the value reported by the Corrosion Section, Metallurgical Laboratory, was 2.7 mg/cm<sup>2</sup>/hr and that by the Montreal Laboratory was 1.95 mg/cm<sup>2</sup>/hr). The main differences in the composition of samples "A" and "B", both of hot extruded metal, were

	Si	Fe	Cu
"A"	0.054 wt. %	0.037 wt. %	0.12 wt. %
"B"	0.024 wt. %	0.063 wt. %	0.066 wt. %

There are indications in the report PR - C.E. - 8 that low corrosion rates of uranium exist in raw filtered Ottawa River water, but further information on test conditions and a longer test period are needed before they can be compared with the other tests.

FIGURE 1  
CORROSION RATE OF STANDARD URANIUM  
IN HYDROGEN-SATURATED WATER VERSUS  $\frac{1}{T}$   
(Reference CT-3055)



10

Table I

## CORROSION OF AS-CAST URANIUM IN HYDROGEN-SATURATED DISTILLED WATER

Temperature, °C	Time in Test, hours	Metal Loss, mg/cm <sup>2</sup>	Corrosion Rate, mg/cm <sup>2</sup> /hr	Reference
50	24.5	1.6		CT-3055
50			0.062(1)	CT-3055
70	24	8.4		
70	66	31		
70			0.35 (1)	CT-3055
90	22	22		
90			1.2 (1)	CT-3055
100	3.08	6.27		CT-3055
100	6.62	17.8		CT-3055
100	22.7	62.0		CT-3055
100	28.7	52.7		CT-3055
100	98.0	274		CT-3055
100	126.5	358		CT-3055
100	287	871		CT-3055
100	384	944		CT-3055
100	769	2200	2.7 (2)	CT-3055
100			1.95 (3)	BR-403
100	25	62.7		CT-2715
100	230		0.85-0.95	BR-549
100	240		2.6 -2.9	BR-549
100			2.0 -2.2 (4)	BR-549
100			2.6 -3.0 (5)	BR-549
100			2.5 (1)	
183	2	234		CT-3043
183	5	570		CT-3043
183	9	1330		CT-3043
183	10	1540		CT-3043
183	16	2590		CT-3043
183	23	2630		CT-3043
183	32	4350		CT-3043
183	37.5	5900		CT-3043
183			139 (1)	
226	1.5	1035		CT-3043
226	1.5	1100		CT-3043
226	1.5	1170		CT-3043
226			710 (1)	

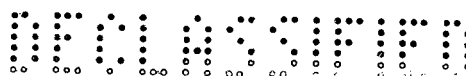
(1) This information was taken from Figure 1.

(2) This value was obtained by the Corrosion Section, Metallurgical Laboratory.

(3) Greenwood, Montreal Laboratory, obtained this corrosion rate in boiling distilled water at atmospheric pressure. The rate was constant over a period of seven days.

(4) Experiment performed in a silver vessel with the uranium sample of metal "B" suspended by a cotton thread, pH 7.5-7.6.

(5) Experiment performed in a glass beaker with the uranium sample of metal "B" suspended on a glass hook, pH 9.0-9.2.



## Corrosion in Air-Saturated Water

The corrosion of uranium in air-saturated distilled water was found to be different from that in hydrogen-saturated water. In hydrogen-saturated water the corrosion of uranium was constant with time and seemed to involve only one type of over-all reaction, in which pitting of the surface was slight or non-existent. In aerated distilled water the corrosion was initially less than in hydrogen-saturated water, probably involving the formation of protective oxide films. For example, the amount of corrosion in hydrogen-saturated water at 70°C after forty-two hours was approximately forty times that in aerated water. After a relatively long time on test in aerated water, the reaction rates increased, apparently approaching the rates in hydrogen-saturated water, indicated by short straight lines in Figure 2. Samples tested at 50 and 70°C seemed not to have run long enough to attain the rate observed in hydrogen-saturated water. Above 70°C, an increase in temperature caused the rate in aerated water to increase very rapidly until it approached the rate in hydrogen-saturated water.

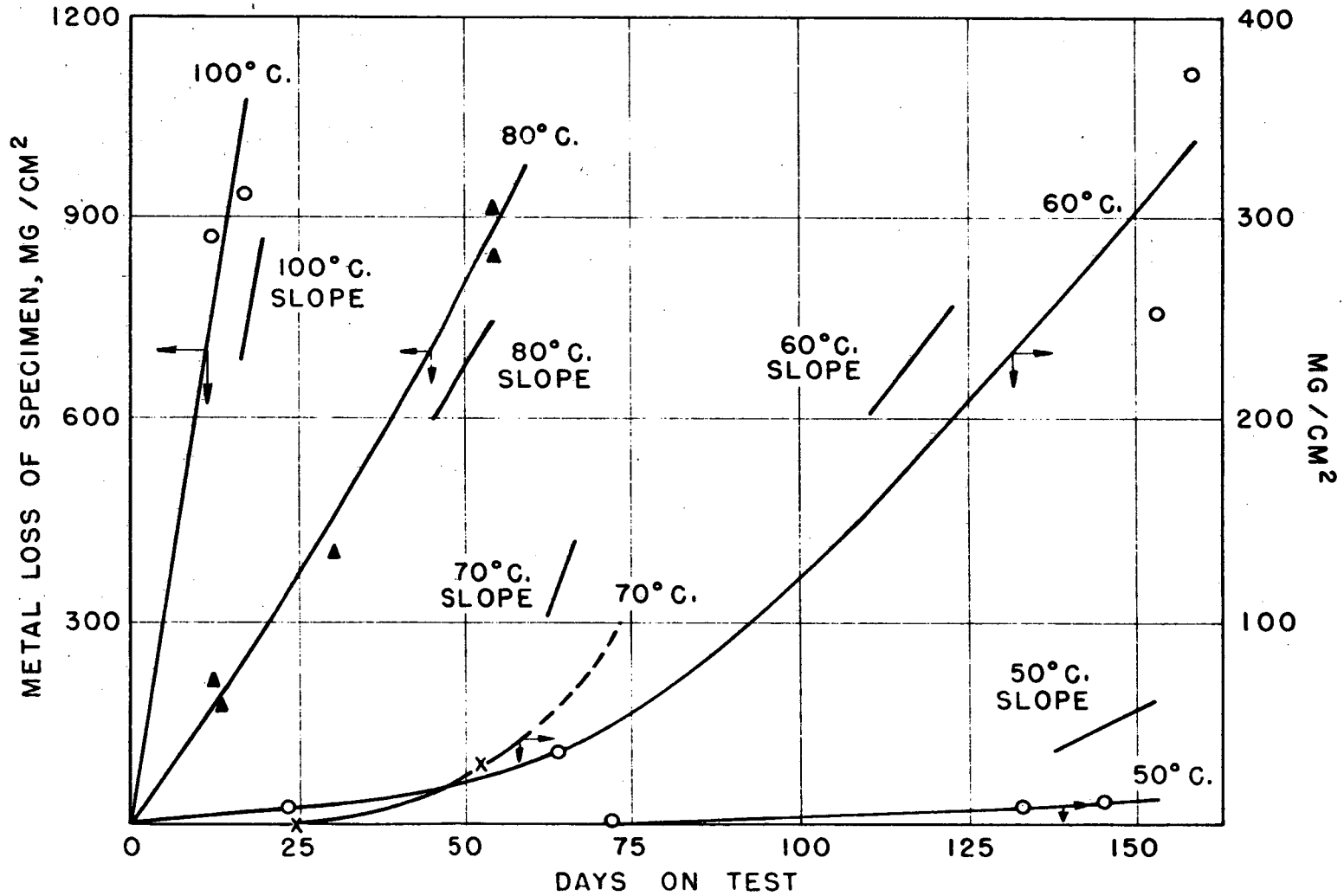
Table II

### CORROSION OF URANIUM IN AERATED DISTILLED WATER (Reference CT-3055)

Temperature, °C	Time in Test, days	Metal Loss, mg/cm <sup>2</sup> (1)	Remarks
50	1.0	0	1 test
50	34.3	0.41	1 test
50	72.0	2.15	1 test
50	137.3	8.12	2 tests averaged
60	23.9	9.75	3 tests averaged
60	64.0	33.7	1 test
60	89.3	64.3	2 tests averaged
60	155.7	313	2 tests averaged
70	1.8	0.42	2 tests averaged
70	17.2	3.98	2 tests averaged
70	53.1	27.1	2 tests averaged
80	2.0	0.45	2 tests averaged
80	2.9	2.5	2 tests averaged
80	5.0	19.5	2 tests averaged
80	12.1	192	2 tests averaged
80	30.2	395	10 tests averaged
80	53.4	878	2 tests averaged

(1) Data plotted in Figure 2.

FIGURE 2  
CORROSION OF STANDARD URANIUM  
IN AERATED DISTILLED WATER  
(Reference CT-3055)



13

Effect of Dissolved Gas

Although it was clear that oxygen had a marked decelerating effect on the aqueous corrosion of uranium, it was not known whether hydrogen played any important role. In an effort to lower the amount of hydrogen available to the surface of a metal, tests were made in which tank helium was bubbled through the solution and over the surfaces of the sample, and also tests were made with nitrogen. There was a slight reduction in the corrosion rate as compared with hydrogen-saturated water, as shown in Table III, but whether the reductions were due to the small oxygen content of the gases or to the removal of the hydrogen from the sample surfaces more quickly than in the absence of the inert gases was not clear. Perhaps the former was more likely.

Table III

CORROSION OF URANIUM IN WATER SATURATED WITH  
VARIOUS GASES  
(Reference CT-3055)

Gas Used	Temperature °C	Time in Test, hours	Metal Loss, mg/cm <sup>2</sup>	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr
Hydrogen	50	24.5	1.6	0.066
Oxygen	50	766	27.6	0.036
Air	50	823	0.41	0.0005
Hydrogen	70	24	8.4	0.35
Oxygen	70	45	0.14	0.003
Air	70	42	0.42	0.010
Helium	70	18	4.7	0.21
Nitrogen	70	48	11.9	0.25
Hydrogen	90	22	22	1.0
Oxygen	90	47	49	1.0

Effect of Hydrogen Peroxide

Except for retention of a protective oxide film to a slightly higher temperature (perhaps ten degrees), adding dilute hydrogen peroxide to distilled water in contact with air caused little change in the corrosion behavior of uranium. The data are presented in Table IV.

14

Table IV

CORROSION OF URANIUM IN DISTILLED WATER AND  
IN DILUTE HYDROGEN PEROXIDE (pH 6.0-6.5)  
 (Reference CT-1943)

Temperature, °C	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	
	In Distilled Water	In $1 \times 10^{-5}N$ H <sub>2</sub> O <sub>2</sub>
37	0.0011	0.0020
50	0.005	0.005
60	0.011	0.007
70	0.012	0.015
80	0.2	0.03
90	0.7	0.6

Effect of Dissolved Salts

The tests reported in Table V were made to see the effects of certain dissolved salts on the corrosion rate of uranium. The addition of sodium chloride caused a definite reduction in the corrosion rate at 100°C which checked with previously determined effects of sulfate and phosphate in hydrogen-saturated water at 70°C, as reported in CT-1943.

The experiment with 2 ppm cupric ion in distilled water indicated that the electrochemical reaction of uranium with water was not cathodically controlled. This was based on the failure of the corrosion rate to increase even though copper was observed to deposit on the corroding surface.

In the autoclave tests at 183°C with 1% sodium dichromate solution the uranium samples corroded with uniformly wide pit-like holes. At this temperature uranium was reported in Table I as having a corrosion rate in water of  $139 \pm 17$  mg/cm<sup>2</sup>/hr; therefore, there was an increase in the corrosion rate of uranium due to the addition of sodium dichromate.

Table V

EFFECTS OF DISSOLVED SALTS ON THE CORROSION OF URANIUM

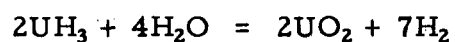
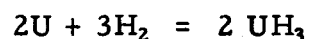
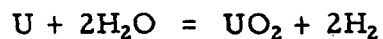
Temperature °C	Time in Test, hours	Metal Loss, mg/cm <sup>2</sup>	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	Remarks	Reference
100	24	41.5	1.73	1 wt. % conc. NaCl	CT-3055
100	24	33.8	1.41	10 wt. % conc. NaCl	CT-3055
100	24	34.3	1.43	20 wt. % conc. NaCl	CT-3055
100	96	230	2.40	Distilled water plus 2 ppm cupric ion	
183	5	672	134	1% Dichromate Solution	CT-3043
183	25	12000	3100	1% Dichromate Solution	CT-3043
183	37.5	668	267	1% Dichromate Solution	CT-3043



16

Corrosion in Steam

It is believed that the mechanism by which uranium corrodes in steam can be represented by the equations:



For the first two hours of steam corrosion of uranium the reaction was roughly the same as in liquid water at the same temperature, as shown in Tables I and VI. From this, it can be assumed that at the beginning only the first reaction was taking place. After this, however, parts of the surface were protected from the steam well enough so that the uranium was able to react with the hydrogen, and the second reaction became important. As the steam penetrated the outer corrosion products, it came in contact with  $UH_3$ , and the third reaction took place. The rate of the second reaction has been reported as 4.0 gm/cm<sup>2</sup>/hr at 180°C in CT-3044.

Table VI

CORROSION OF URANIUM IN STEAM

Temperature, °C	Time in Test, hours	Metal Loss, mg/cm <sup>2</sup>	Oxide Formed		Reference
			UO <sub>2</sub> %	U <sub>3</sub> O <sub>8</sub> %	
150	1	19.1	100		BR-403
150	1	16.8			BR-223A
183	1	106			CT-3043
183	2	280			CT-3043
183	3	4890			CT-3043
183	3	429			CT-3043
183	4	6080			CT-3043
183	5	5570			CT-3043
183	25	5540			CT-3043
183	37.5	7090			CT-3043
200	1	117			93.8
250	1	970	24.2	75.8	BR-223A
300	1	1120	17.3	82.7	BR-223A
400	1	1470	8.3	91.7	BR-223A

17

These inferences were drawn from the fact that after two hours in steam the reaction rate became much higher and more erratic as shown in the results reported in Table VI by the Corrosion Section, Metallurgical Laboratory. Measured average values were as high as 1.63 gm/cm<sup>2</sup>/hr. The cut ends of uranium rolled bar samples were found to be attacked more vigorously than the peripheral surfaces, probably involving hydride formations at penetrated reactive areas such as at grain boundaries and inclusions. Sometimes when the autoclave was opened, the corrosion product glowed and burned, and on occasion sharp explosions were heard; this was due to air coming in contact with the uranium hydride.

In the steam tests made at the Imperial Chemical Industries Limited, Research Department, the uranium was exposed to the steam only for one hour. From the above theory, the uranium was not protected enough to allow the hydrogen to react with the uranium. From the information reported in Table VI the transition temperature from UO<sub>2</sub> to U<sub>3</sub>O<sub>8</sub> formation for the steam oxidation was found to be between 200 and 300°C. The incomplete conversion to U<sub>3</sub>O<sub>8</sub> in the case of steam oxidation may be due to the presence of hydrogen formed from the reaction of uranium and steam.

#### Effect of Velocity

Some tests were made with a flow rate of 20-25 ft/sec, using distilled water and "simulated River water," reported in Table VII, to investigate the effect of such flow rates upon uranium corrosion. Beaker tests were also made using "simulated River water." Rates of attack in the "simulated River water" were found to be higher than in distilled water with hydrogen peroxide in both solutions. The high flow rate did not seem to have increased the corrosion rate over that in the beaker tests.

Table VII  
HIGH FLOW RATE TESTS OF URANIUM IN  
SIMULATED RIVER WATER  
 (Reference CT-3055)

Time in Test, hours	Flow Rate over Sample, ft/sec	Gas Bubbled through Solution	pH	H <sub>2</sub> O <sub>2</sub> Conc., $\bar{N} \times 10^3$	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr
<u>Tested in Distilled Water at 70°C</u>					
450	20-25	Air	6.5	5	0.043
450	20-25	Hydrogen	6.5	5	0.016
<u>Tested in "Simulated River Water" at 70°C</u>					
357	20-25	Air	6.5	5	0.20
381	20-25	Hydrogen	6.5	5	0.32
373	0	Air	7.8	1.2	0.20

DEPARTMENT

18

The original object of the experiments of spinning uranium samples in "simulated River water" was to determine the effect of couple action on the rate of corrosion of uranium.

The results in Table VIII seemed to indicate that the corrosion of spinning uranium was not accelerated by coupling with aluminum. However, the corrosion apparently caused by a rubbing electrical contact arm above the solution surface was so great as to overshadow possible coupling effects.

Table VIII

CORROSION OF SPINNING U SAMPLES IN SIMULATED  
RIVER WATER (pH 6.2-6.3)  
(N-1703)

Temperature °C	Couple	Peripheral Speed, ft/sec	Time in Test, days	Original Diameter of Samples, inches	Diameter of Sample After Corrosion, inches
72.1	None	20.6	88.3	1.190	1.186
72.9	2S Al wire	20.6	80.7	1.186	1.184
71.0	2S Al wire	22.6	80.5	1.300	1.299

### Galvanic Effects

It was stated in report CT-1943 that uranium was generally anodic to stainless steel when coupled and that uranium corroded worse when coupled to aluminum than to stainless steel.

In the uranium-aluminum couple the aluminum generally stayed anodic for the first fifty to seventy-five hours, and the uranium lost weight at up to one and one-third times the usual rate. The effect possibly was associated with the liberation of hydrogen at the cathodic uranium and consequent increase in its corrosion rate. The weight loss of the couple was intensified several fold if the aluminum was brazed to the uranium with aluminum-silicon or zinc-tin, perhaps because of better electrical contact or the existence of triple couples.

### Effect of Surface Preparation

The results reported in Table IX showed that the surface preparation of the samples played an important part in determining the rate of

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19

corrosion. The main conclusion that can be drawn from these tests was that a standard technique should be used in sample preparation so that comparison of corrosion rates will not be affected by various types of surface.

Table IX

EFFECT OF SURFACE PREPARATION ON URANIUM CORROSION

Surface Preparation	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	Remarks	Reference
<u>Tested in Distilled Water at 70°C</u>			
Polished, fine finish	0.32	0.351 V. neg. to 0.1N calomel electrode (initially)	CT-1943
Polished, medium finish	0.46	0.498 V. neg. to 0.1N calomel electrode (initially)	CT-1943
Polished, coarse finish	0.40	0.402 V. neg. to 0.1N calomel electrode (initially)	CT-1943
<u>Tested in Steam for Two Hours at 178°C</u>			
Polished on No. 1 emery paper, nitric acid dipped	109	Corrosion uniform	CT-3043
Polished on No. 1 emery paper, not acid dipped	105	Corrosion uniform	CT-3043
As received, oxide layer	205	Corrosion uniform	CT-3043

Effect of Heat-Treatment

The heat-treatment of uranium had a decided effect on the corrosion rate in boiling distilled water, reducing it as much as seventy per cent if the metal had been quenched after heating in the gamma range; however, the results reported in Table X were not too consistent. The amount of time that the sample was heat-treated seemed to have an important effect on the corrosion rate.

REF ID: A61071

Table X

CORROSION OF HEAT-TREATED URANIUM IN DISTILLED WATER AT 100°C

Heat-Treatment	Time in Test, hours	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	Remarks	Reference
None	7-769	2.7		CT-3055
64 hrs. at 100°C, W. Q.	308	1.1	Decreasing rate	CT-2925
2 hrs. at 900°C, W. Q.	413	0.78	3 tests averaged	CT-3055
96 hrs. at 900°C, W. Q.	26	1.55	3 tests averaged	CT-3055
96 hrs. at 900°C, W. Q.	96	2.04	3 tests averaged	CT-3055
64 hrs. at 850°C, W. Q.	308	1.8	Decreasing rate	CT-2925
2 hrs. at 725°C, W. Q.	413	1.16	3 tests averaged	CT-3055
2 hrs. at 600°C, W. Q.	98	2.17	3 tests averaged	CT-3055
2 hrs. at 900°C, F. C.	98	1.17	3 tests averaged	CT-3055
96 hrs. at 900°C, F. C.	24	0.94	3 tests averaged	CT-3055
96 hrs. at 900°C, F. C.	97	1.10	3 tests averaged	CT-3055
2 hrs. at 725°C, F. C.	484	1.68	3 tests averaged	CT-3055
2 hrs. at 600°C, F. C.	96	2.13	3 tests averaged	CT-3055
96 hrs. at 900°C, W. Q. and 2 hrs. at 600°C, F. C.	24	0.66	2 tests averaged	CT-3055
96 hrs. at 900°C, W. Q. and 2 hrs. at 600°C, F. C.	98	2.44	2 tests averaged	CT-3055
Slow cooled and worked	310	0.77	Worked sample corroded faster at first	CT-2794
Slow cooled and unworked	310	0.77	Worked sample corroded faster at first	CT-2794

21

## V. AQUEOUS CORROSION OF URANIUM ALLOYS

### Preliminary Survey

At the beginning of the investigation of uranium alloys for resistance to aqueous corrosion, very little information was available about the alloying properties of uranium; therefore, with little basis for choosing, groups of binary alloys were made and corrosion tested. The results of a large number of these tests are reported in Table XI. These tests were inconclusive as there still exists the possibility that a few of these alloys with proper heat-treatment could have good resistance to aqueous corrosion. For example, in the preliminary corrosion testing of uranium-silicon as-cast alloys there was nothing to suggest that they would have any better resistance if heat-treated than some of the other alloys. But it was found at the Massachusetts Institute of Technology that the heat-treatment "epsilon-ization" would produce a corrosion-resistant alloy.

From the information given in Table XI, uranium alloys with either columbium, molybdenum, nickel, silicon, tantalum, titanium, vanadium, or zirconium showed improved resistance to aqueous corrosion.

In uranium alloys containing either columbium, silicon, or zirconium, heating into the gamma region and water quenching brought a better resistance to aqueous corrosion than that of the as-cast alloys. At 100°C the aqueous corrosion rate of uranium was reduced as much as 1,000 times for several of these alloys. The results in Tables XI and XII on the 2 weight per cent zirconium alloy were not too favorable, but the addition of either 2 or 1 weight per cent columbium gave the alloy a good resistance to corrosion. Results of corrosion testing in boiling distilled water for alloys containing 3.6 and 8.7 nominal weight per cent zirconium showed in Figure 3 that the as-cast alloys corroded almost as rapidly as pure uranium. For both alloys, the long-time weight loss rate decreased nearly to zero when quenched from either 850 or 1150°C. When quenched from 1000°C, both alloys corroded almost as rapidly as in the as-cast condition. This behavior was inconsistent with the other results and was not understood.

Alloys which had shown promise of corrosion resistance were prepared, and their corrosion rates carefully determined by the Corrosion Section of the Metallurgical Laboratory. At the time the work was done, only three alloying constituents were known to be particularly promising. The results of this work, on alloys containing columbium, molybdenum, and silicon, are given in the following sections. In no other instances were samples stripped of corrosion product to the extent that "corrosion rates" of reasonable reliability can be reported. Other promising alloys, including those with zirconium and zirconium-columbium, were prepared later, and no "corrosion rates" comparable to those given for the three systems treated separately are available.

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Table XI

CORROSION OF URANIUM BINARY ALLOYS IN DISTILLED WATER

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Aluminum	0.01	---	---	0.42	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.02	---	---	0.2	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.1	---	---	0.48	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.6	---	---	Disintegrated	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.01	---	---	0.4	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.6	---	---	Disintegrated	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Aluminum	0.65	As-cast	---	1.4	100		BR-549 (6)
Antimony	5.4	---	---	1.5	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Antimony	5.4	---	---	2.0	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Antimony	0.5	---	39	2.8	100		CT-2659 <sup>(2)</sup>
Antimony	0.5	---	---	5.5	100		CT-2668 <sup>(2)</sup>
Antimony	5	---	<24	Disintegrated	100		CT-2668 <sup>(2)</sup>
Beryllium	0.01	---	---	0.91	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.02	---	---	0.3	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.2	---	---	0.5	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.4	---	---	0.8	90	In $4 \times 10^{-5} \text{N H}_2\text{O}_2$ , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.01	---	---	0.5	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.02	---	---	0.8	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.2	---	---	0.5	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.4	---	---	0.56	90	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Beryllium	0.2	As-cast	308	3.3	100	In $3 \times 10^{-5} \text{N H}_2\text{O}_2$ , 2 ppm Cl <sup>-</sup> , pH 6.0 Increasing rate	CT-1943 <sup>(1)</sup> CT-2925 <sup>(2)</sup>

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Beryllium	0.75	As-cast	47.3	1.20	100		CT-2715
Beryllium	1.0	As-cast	308	2.6	100	Increasing rate	CT-2925 <sup>(2)</sup>
Beryllium	1.6	As-cast	308	1.6	100	Increasing rate	CT-2925 <sup>(2)</sup>
Beryllium	2.5	As-cast	308	1.8	100	Increasing rate	CT-2925 <sup>(2)</sup>
Beryllium	7.0	As-cast	19.8	0.82	100		CT-2715
Beryllium	0.75	As-cast	64	7.7	140		CT-2715
Cerium	0.17 (act.)	72 hrs. at 850°C, W. Q.	---	0.35	100		CT-2668 <sup>(2)</sup>
Cerium	0.17 (act.)	72 hrs. at 850°C, W. Q.	288	0.70	100		CT-2925 <sup>(2)</sup>
Cerium	0.17 (act.)	72 hrs. at 850°C, W. Q.	660	1.18	100		CT-2703 <sup>(2)</sup>
Cerium	0.17 (act.)	72 hrs. at 850°C, W. Q.	802	1.3	100		CT-2703 <sup>(2)</sup>
Cerium	0.57 (act.)	72 hrs. at 850°C, W. Q.	94	14.7	100		CT-2925 <sup>(2)</sup>
Cerium	0.57 (act.)	72 hrs. at 850°C, W. Q.	207	1.6	100		CT-2659 <sup>(2)</sup>



24

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Chromium	0.06	---	---	0.6	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	0.1	---	---	0.3	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	0.2	---	---	0.7	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	1.2	---	---	0.31	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	2.4	---	---	0.08	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	3.7	---	---	0.06	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	5.1	---	---	0.02	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	18	---	---	0.03	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Chromium	0.06	---	---	0.8	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	0.1	---	---	0.4	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	0.2	---	---	0.6	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	1.2	---	---	0.36	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	2.4	---	---	0.5	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	3.7	---	---	0.22	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	5.1	---	---	0.22	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	18	---	---	0.04	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Chromium	0.87 act.	---	168	0.21	100	Specimens cracked	BR-549 (6)
Chromium	2.40 act.	---	288	0.17	100	Specimens cracked	BR-549 (6)
Columbium	1	1 wk. at 1000°C, B. Q.	426	0.71	100	Increasing rate, pH 5.6-5.8	CT-2925(2)
Columbium	2.1 act.	As-cast	540	0.29**	100	Inconsistent rate, pH 5.6-5.8	CT-2794(2)
Columbium	2.0	1 wk. at 1000°C, 15 days at 500°C.	308	1.7	100	Increasing rate, pH 5.6-5.8	CT-2925(2)

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Columbium	2.4	1 wk. at 1000°C, B. Q.	426	gain 0.0007	100	pH 5.6-5.8	CT-2925 <sup>(2)</sup>
Columbium	4.6 act.	As-cast	562	0.17**	100	pH 5.6-5.8 insignificant weight change first 230 hours	CT-2794 <sup>(2)</sup>
Columbium	4.6 act.	5.5 days at 1000°C, W. Q.	1708	0.002	100	Cleaned with 25% HNO <sub>3</sub> , pH 5.6-5.8	CT-2925 <sup>(3)</sup>
Columbium	10.2 act.	As-cast	1081	0.002	100	Cleaned with 20% HNO <sub>3</sub> , pH 5.6-5.8	CT-2925 <sup>(3)</sup>
Columbium	10.2 act.	11 days at 100°C, W. Q.	1708	0.0006	100	Cleaned with 25% HNO <sub>3</sub> , pH 5.6-5.8	CT-2925 <sup>(3)</sup>
Columbium	23.2 act.	11 days at 1000°C, W. Q.	1708	0.0006	100	Cleaned with 25% HNO <sub>3</sub> , pH 5.6-5.8	CT-2925 <sup>(3)</sup>
Columbium	24.8 act.	As-cast	560	none**	100	pH 5.6-5.8	CT-2794 <sup>(2)</sup>
Columbium	2.01	---	10	42	185	In liquid water	CT-3043 <sup>(1)</sup>
Columbium	4.16	---	10	Disintegrated	185	In liquid water	CT-3043 <sup>(1)</sup>
Columbium	14.33	---	2	0.00	185	In liquid water	CT-3043 <sup>(1)</sup>
Columbium	14.33	---	16	0.00	185	In liquid water	CT-3043 <sup>(1)</sup>
Columbium	100 (Sheet)	---	16	0.00	185	In liquid water	CT-3043 <sup>(1)</sup>
Columbium	8.89	---	2	0.03	226	In liquid water	CT-3043 <sup>(1)</sup>

Table XI

1  
(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Copper	0.07	---	---	0.3	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	0.1	---	---	0.23	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	0.3	---	---	0.4	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	1.4	---	---	0.2	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	2.9	---	---	0.2	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	84	---	---	Disintegrated	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	96	---	---	0.007	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Copper	0.07	---	---	0.6	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	0.1	---	---	0.3	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	0.3	---	---	0.9	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	1.4	---	---	0.4	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	2.9	---	---	0.4	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	84	---	---	Disintegrated	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Copper	96	---	---	0.007	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943(1)
Gold	0.5 act.	As-melted	288	2	100	Surface rough with shallow pits	HR-549 (6)
Lead	0.9	---	---	Disintegrated	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Lead	4.4	---	---	Disintegrated	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Molybdenum	0.15	As-cast	9.3	4.35	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)
Molybdenum	0.30	As-cast	11.7	2.95	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)
Molybdenum	0.61	As-cast	17.7	1.77	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)
Molybdenum	1.53	As-cast	15.2	1.01	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)
Molybdenum	3.09	As-cast	17.2	0.97	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)
Molybdenum	6.31	As-cast	6.0	0.145	100	Cleaned with 25% HNO <sub>3</sub>	CT-3031(1)

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Molybdenum	6.31	As-cast	2	15	185	Sample pitted badly and started to crack	CT-3043 <sup>(1)</sup>
Nickel	0.25	As-cast	---	0.05	90		CT-1272 <sup>(1)</sup>
Nickel	0.5	As-cast	---	0.02	90		CT-1272 <sup>(1)</sup>
Nickel	1.3	As-cast	---	0.02	90		CT-1272 <sup>(1)</sup>
Nickel	0.25	As-cast	---	0.23	90	In distilled water plus 2 ppm Cl <sup>-</sup>	CT-1272 <sup>(1)</sup>
Nickel	0.5	As-cast	---	0.08	90	In distilled water plus 2 ppm Cl <sup>-</sup>	CT-1272 <sup>(1)</sup>
Nickel	1.3	As-cast	---	0.04	90	In distilled water plus 2 ppm Cl <sup>-</sup>	CT-1272 <sup>(1)</sup>
Nickel	0.25	As-cast	---	0.08	90	In 10 <sup>-3</sup> N H <sub>2</sub> O <sub>2</sub>	CT-1272 <sup>(1)</sup>
Nickel	0.5	As-cast	---	0.08	90	In 10 <sup>-3</sup> N H <sub>2</sub> O <sub>2</sub>	CT-1272 <sup>(1)</sup>
Nickel	1.3	As-cast	---	0.05	90	In 10 <sup>-3</sup> N H <sub>2</sub> O <sub>2</sub>	CT-1272 <sup>(1)</sup>
Nickel	1.10 act.	As-cast	192	0.6	100	Specimens cracked	BR-549 <sup>(6)</sup>
Nickel	3.13 act.	As-cast	144	0.2	100	Specimens cracked	BR-549 <sup>(6)</sup>
Rhodium	1.8	As-cast	453	1.06	100		CT-2703 <sup>(2)</sup>
Rhodium	1.8	As-cast	686	0.78	100		CT-2755 <sup>(2)</sup>
Rhodium	4	As-cast	157	11.8	100	Disintegrated completely	CT-2668 <sup>(2)</sup>
Rhodium	4.6	850°C, W. Q.	162	8.1	100		CT-2659 <sup>(2)</sup>
Ruthenium	2.2 act.	As-cast	118	3.9	100		CT-2857 <sup>(2)</sup>
Ruthenium	2.2 act.	As-cast	286	5.4	100		CT-2925 <sup>(2)</sup>

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Silicon	2.0	To form Epsilon	500	0.008	70	In hydrogen-saturated water	CT-2780(4)
Silicon	3.4	To form Epsilon	500	0.006	70	In hydrogen-saturated water	CT-2780(4)
Silicon	0.03	---	---	0.24	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Silicon	0.06	---	---	0.8	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Silicon	0.1	---	---	0.7	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Silicon	0.6	---	---	0.57	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Silicon	1.3	---	---	0.34	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943(1)
Silicon	0.03	---	---	0.51	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0 2 ppm Cl <sup>-</sup>	CT-1943(1)
Silicon	0.06	---	---	0.9	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0 2 ppm Cl <sup>-</sup>	CT-1943(1)
Silicon	0.1	---	---	0.8	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0 2 ppm Cl <sup>-</sup>	CT-1943(1)
Silicon	0.6	---	---	0.3	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0 2 ppm Cl <sup>-</sup>	CT-1943(1)
Silicon	0.94 act.	As-cast	168	0.43	100		ME-64 (7)
Silicon	1.7 act.	As-cast	168	0.16	100		ME-64 (7)
Silicon	2.5 act.	As-cast	168	0.14	100		ME-64 (7)
Silicon	2.9 act.	As-cast	168	0.03	100		ME-64 (7)
Silicon	2.9 act.	As-cast	336	0.04	100		ME-64 (7)
Silicon	2.9 act.	As-cast	504	0.09	100		ME-64 (7)
Silicon	2.9 act.	As-cast	672	0.26	100		ME-64 (7)
Silicon	3.67 act.	As-cast	168	0.06	100		ME-64 (7)
Silicon	3.67 act.	As-cast	336	0.05	100		ME-64 (7)
Silicon	3.67 act.	As-cast	504	0.05	100		ME-64 (7)
Silicon	3.67 act.	As-cast	672	0.18	100		ME-64 (7)
Silicon	4.96 act.	As-cast	168	0.12	100		ME-64 (7)
Silicon	8.2 act.	As-cast	168	0.03	100		ME-64 (7)
Silicon	8.2 act.	As-cast	336	0.01	100		ME-64 (7)

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Silicon	8.2 act.	As-cast	504	0.00	100		ME-64 (7)
Silicon	8.2 act.	As-cast	672	0.00	100		ME-64 (7)
Silicon	2.0	To form Epsilon	500	0.006	100		CT-2780(4)
Silicon	3.4	To form Epsilon	500	0.006	100		CT-2780(4)
Silicon	2.9 act.	As-cast	168	0.26	125	The vessel was enclosed; thus hydrogen was not allowed to escape	ME-64 (7)
Silicon	3.67 act.	As-cast	168	0.26	125	The vessel was enclosed; thus hydrogen was not allowed to escape	ME-64 (7)
Silicon	2.9 act.	As-cast	96	0.83	150	The vessel was enclosed; thus hydrogen was not allowed to escape	ME-64 (7)
Silicon	(90% Epsilon, 10% U)		240		178	Sample cracked	CT-3194(4)
Silicon	(100% Epsilon)		1248	>0.006	178	Only slightly faster than 1000°C	CT-3309(4)
Silicon	3.77	---	2	0.03	185		CT-3043(1)
Silicon	3.77	---	10	0.01	185		CT-3043(1)
Silicon	3.77	---	2	0.18	225		CT-3043(1)
Silver	0.017 act.	As-melted	72	4	100		BR-549 (6)
Strontium	<0.006act.	As-cast	264	2.2 - 3.2	100	No Sr in alloy probably (1.5% Sr nominal)	BR-549 (6)
Tantalum	0.44	As-cast	96	4.5	100		BR-549 (6)
Tantalum	2	As-cast	161	3.6	100		CT-2703(2)
Tantalum	4	As-cast	188	4.5	100		CT-2703(2)
Tantalum	4.5	As-cast	43.5	1.63	100	After test, sample polished to a bright metallic luster & weighed	CT-2715

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Tantalum	8	As-cast	141	2.2	100		CT-2703 <sup>(2)</sup>
Tantalum	12	As-cast	20	80.2	100		CT-2703 <sup>(2)</sup>
Tantalum	16	As-cast	235	4.9	100		CT-2703 <sup>(2)</sup>
Tantalum	0.8	1000°C for week, W. Q.	762	0.92	100		CT-2703 <sup>(2)</sup>
Tantalum	2	1000°C for week, W. Q.	755	1.1	100		CT-2703 <sup>(2)</sup>
Tantalum	3.85	1000°C for week, W. Q.	973	0.006	100		CT-2925 <sup>(3)</sup>
Tantalum	4	1000°C for week, W. Q.	740	0.003	100		CT-2703 <sup>(2)</sup>
Tantalum	7.8	1000°C for week, W. Q.	972	0.005	100		CT-2925 <sup>(3)</sup>
Tantalum	8	1000°C for week, W. Q.	739	0.002	100		CT-2703 <sup>(2)</sup>
Tantalum	12	1000°C for week, W. Q.	188	2.3	100		CT-2703 <sup>(2)</sup>
Tantalum	7.79	As-cast	2	76	185	Cleaned up completely after test	CT-3043 <sup>(1)</sup>
Tin	0.12	---	---	0.2	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943 <sup>(1)</sup>
Tin	0.25	---	---	0.9	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943 <sup>(1)</sup>
Tin	(0.5, 2.6, & 5.3)	---	---	Disintegrated	90	In 4 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , pH 6.0	CT-1943 <sup>(1)</sup>
Tin	0.12	---	---	0.46	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Tin	0.25	---	---	1.4	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Tin	(0.5, 2.6, & 5.3)	---	---	Disintegrated	90	In 3 x 10 <sup>-5</sup> N H <sub>2</sub> O <sub>2</sub> , 2 ppm Cl <sup>-</sup> , pH 6.0	CT-1943 <sup>(1)</sup>
Titanium	Unknown	---	135	1.40	90	Titanium applied by sintering from powder for 10 hrs. at 600, 700, 800, & 900°C, respectively, test in "simulated River water"	CP-1728

Table XI

(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Titanium	Unknown	---	44	0.19	90	Titanium applied by sintering from powder for 10 hrs. at 600, 700, 800, & 900°C respectively, test in "simulated River water"	CP-1728
Titanium	Unknown	---	50	1.21	90	Titanium applied by sintering from powder for 10 hrs. at 600, 700, 800, & 900°C respectively, test in "simulated River water"	CP-1728
Titanium	Unknown	---	46	0.94	90	Titanium applied by sintering from powder for 10 hrs. at 600, 700, 800, & 900°C respectively, test in "simulated River water"	CP-1728
Titanium	3.15	As-cast	500	0.2	100		CT-2903(5)
Titanium	7.2	As-cast	500	<0.001	100		CT-2903(5)
Titanium	9.5	As-cast	500	<0.001	100		CT-2903(5)
Titanium	3.24	---	---	---	178	Badly cracked and corroded	CT-3011(1)
Titanium	7.57	---	96	5.9	178		CT-3011(1)
Tungsten	0.60 act.	As-cast	144	7.0	100	Sample cracked	BR-549 (6)
Tungsten	0.60 act.	Annealed	288	4.0	100	Sample cracked	BR-549 (6)
Tungsten	2.01 act.	As-cast	72	1.8	100	Sample cracked	BR-549 (6)
Tungsten	2.01 act.	Annealed	336	0.65	100	Sample cracked	BR-549 (6)
Vanadium	0.2	---	206	0.59	100		CT-2659(2)
Vanadium	1.0	---	208	0.29	100		CT-2659(2)
Vanadium	1.0	72 hrs. at 850°C, W. Q.	138	1.7	100		CT-2857(2)
Vanadium	1.1 act.	72 hrs. at 850°C, W. Q.	288	1.7	100	Consistent rate	CT-2925(2)
Vanadium	2.5 act.	72 hrs. at 850°C, W. Q.	306	0.014	100	Decreasing rate	CT-2925(2)
Vanadium	2.5	72 hrs. at 850°C, W. Q.	164	0.33	100		CT-2659(2)
Vanadium	2.5	72 hrs. at 850°C, W. Q.	138	0.016	100		CT-2857(2)



Table XI  
(Cont'd.)

Alloying Element	Nominal Weight Per Cent	Heat-Treatment	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Temperature, °C	Remarks	Reference*
Zirconium	1.9 act.	As-cast	264	0.53 **	100	pH 5.7, consistent rate	CT-2794 <sup>(2)</sup>
Zirconium	1.9 act.	18 hrs. at 850°C, W. Q.	849	0.41 **	100	pH 5.7, fairly consistent rate	CT-2794 <sup>(2)</sup>
Zirconium	1.9 act.	53 hrs. at 1000°C, W. Q.	130	0.71 **	100	pH 5.7, sample fell apart	CT-2794 <sup>(2)</sup>
Zirconium	4.3 act.	As-cast	398	0.02 **	100	pH 5.7, corroded slowly first 150 hours	CT-2794 <sup>(2)</sup>
Zirconium	4.3 act.	18 hrs. at 850°C, W. Q.	994	0.017**	100	pH 5.7, consistent rate	CT-2794 <sup>(2)</sup>
Zirconium	4.3 act.	53 hrs. at 1000°C, W. Q.	919	0.008	100	pH 5.7, 25% HNO <sub>3</sub> used in cleaning	CT-2925 <sup>(3)</sup>
Zirconium	8.7 act.	As-cast	400	0.65 **	100	pH 5.7, consistent rate	CT-2794 <sup>(2)</sup>
Zirconium	8.7 act.	18 hrs. at 850°C, W. Q.	991	0.17 **	100	pH 5.7, corroded slowly first 170 hours	CT-2794 <sup>(2)</sup>
Zirconium	8.7 act.	53 hrs. at 1000°C, W. Q.	848	0.006**	100	pH 5.7, consistent rate	CT-2794 <sup>(2)</sup>
Zirconium	2.06	As-cast	2	37**	183	Sample still black after cleaning after test	CT-3043

\*The test was reported by the:

- (1) Corrosion Section at the Metallurgical Laboratory.
- (2) Metallurgy Section at the Metallurgical Laboratory.
- (3) Metallurgy Section did the testing and the Corrosion Section cleaned the samples.
- (4) Massachusetts Institute of Technology.
- (5) Batelle Memorial Institute.
- (6) Imperial Chemical Industries Limited, Research Department.
- (7) Montreal Laboratory.

\*\*This figure is an average rate of metal loss of samples which had been "cleaned" after the corrosion tests. (2 or 3 minutes in 25 wt. % HNO<sub>3</sub>)

Table XII

CORROSION OF URANIUM MIXED ALLOYS IN DISTILLED WATERAlloying Constituents: Zr, Cb, Mo

Nominal Weight Per Cent Zr	Nominal Weight Per Cent Cb	Heat-Treatment*	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr**	Remarks	Reference***
Tested at 100°C						
2	2	1	476	0.58	pH 5.6-5.8, decreasing rate	CT-2925(2)
4	2	1	476	0.70	pH 5.6-5.8, decreasing rate	CT-2925(2)
6	2	1	476	0.46	pH 5.6-5.8, increasing rate	CT-2925(2)
2	4	1	476	0.49	pH 5.6-5.8, increasing rate	CT-2925(2)
4	4	1	476	0.27	pH 5.6-5.8, increasing rate severe flaking	CT-2925(2)
2	6	1	476	0.17	pH 5.6-5.8, increasing rate	CT-2925(2)
2	2	2	566	0.0005	pH 5.6-5.8	CT-2925(2)
4	2	2	566	-0.0001	pH 5.6-5.8	CT-2925(2)
6	2	2	566	0.0007	pH 5.6-5.8	CT-2925(2)
2	4	2	566	-0.0004	pH 5.6-5.8	CT-2925(2)
4	4	2	566	0.0002	pH 5.6-5.8	CT-2925(2)
2	6	2	566	none	pH 5.6-5.8	CT-2925(2)
2	2	3	566	-0.0001	pH 5.6-5.8	CT-2925(2)
4	2	3	566	-0.0002	pH 5.6-5.8	CT-2925(2)
6	2	3	566	0.0001	pH 5.6-5.8	CT-2925(2)
2	4	3	566	-0.0003	pH 5.6-5.8	CT-2925(2)
4	4	3	566	-0.0002	pH 5.6-5.8	CT-2925(2)
2	6	3	566	-0.0002	pH 5.6-5.8	CT-2925(2)

34

Table XII  
(cont'd.)

Nominal Weight Per Cent Zr	Nominal Weight Per Cent Cb	Heat-Treatment*	Time in Test, hours	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr**	Remarks	Reference***
2	2	4	733	0.0013	pH 5.6-5.8, wt. rate before cleaning No loss	CT-2794 & CT-2925 <sup>(3)</sup>
4	2	4	733	0.003	pH 5.6-5.8, wt. rate before cleaning -0.0007	CT-2925 <sup>(3)</sup>
6	2	4	733	---	pH 5.6-5.8, wt. rate before cleaning -0.0006	CT-2925 <sup>(3)</sup>
2	4	4	733	0.0013	pH 5.6-5.8, wt. rate before cleaning -0.00014	CT-2925 <sup>(3)</sup>
4	4	4	733	0.0013	pH 5.6-5.8, wt. rate before cleaning -0.0002	CT-2925 <sup>(3)</sup>
2	6	4	733	0.0007	pH 5.6-5.8, wt. rate before cleaning No loss	CT-2925 <sup>(3)</sup>
1	1	5	531	> 0.01		CT-3071 <sup>(2)</sup>
2	1	5	531	< 0.01		CT-3071 <sup>(2)</sup>
3	1	5	531	< 0.01		CT-3071 <sup>(2)</sup>
4	1	5	531	< 0.01		CT-3071 <sup>(2)</sup>
Tested in Autoclave at 178°C						
2	2	---	192	0.0007		CT-3011 <sup>(1)</sup>

- \*Heat-Treatments: No. 1. 256 hrs. at 600°C, W. Q.  
 No. 2. 256 hrs. at 725°C, W. Q.  
 No. 3. 256 hrs. at 850°C, W. Q.  
 No. 4. 100 hrs. at 1000°C, W. Q.  
 No. 5. Homogenized at 1000°C, W. Q.

\*\*Negative sign indicates a weight gain.

\*\*\*See footnotes (1), (2), and (3) in Table XI.

Table XII

(Cont'd.)

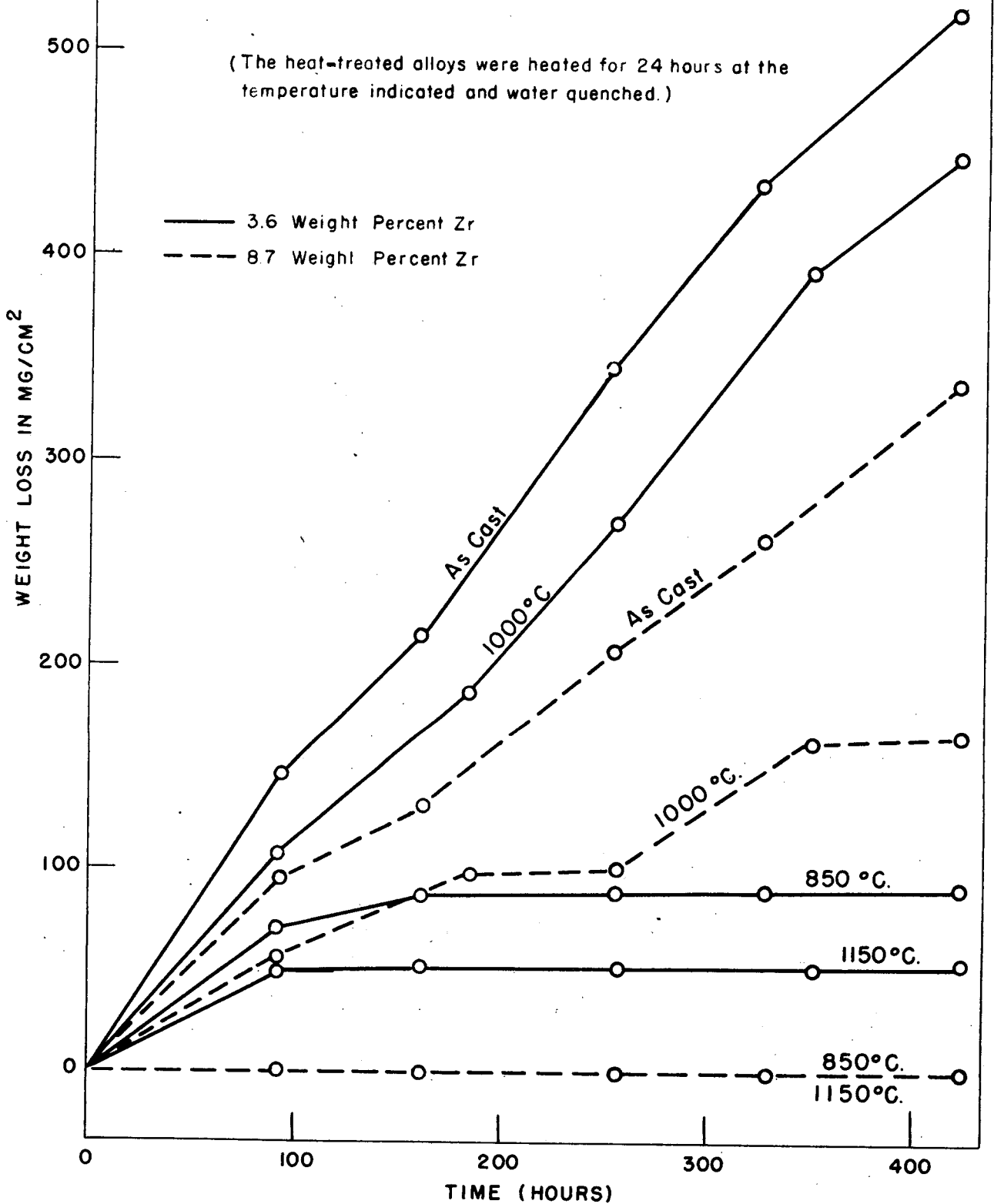
(Reference CT-3194)

Nominal Weight Per Cent of Zr	Nominal Weight Per Cent of Mo	Nominal Weight Per Cent of Cb	Total Loss in Weight in 250 Hours, mg/cm <sup>2</sup> (1)			
			As Melted	850°C(2)	1000°C(2)	1100°C(2)
<u>Tested in Distilled Water at 100°C</u>						
1.8			390 (3)	48 (4)	100 (7)	62 (7)
4			330 (3)	85 (4)	110 (3)	50 (4)
9			200 (3)	-0.12	0.07(7)	0.06
2	0.8		160 (3)	46 (4)	40 (4)	330 (3)
4	2		180 (3)	4.4 (4)	68 (3)(6)	48 (3)
4	4		-0.15	(5)	(5)	(5)
9	2		-1.30	1.10(4)	1.30(7)	0.05
2		0.8	380	15 (7)	66 (4)	37 (7)
2		2	190	0.24	0.39	0.13
2		4	-0.44	0.06	0.12	-0.08
4		2	110 (3)	0.03	0.51	-0.06
		6	-1.20	-0.16	0.02	-0.21
	2	2	(5)	0.19	0.32	0.05
2	2	2	0.66	0.41(7)	0.20	0.05(4)

- (1) The negative sign indicates a weight gain.  
(2) The heat-treated alloys were held 24 hours at the temperature indicated and then quenched.  
(3) Corrosion rate approximately constant.  
(4) Corrosion rate decreasing.  
(5) Disintegrated before 250 hours.  
(6) Disintegrated before 400 hours.  
(7) Irregular curve, indicating flaking.

36

FIGURE 3  
CORROSION OF URANIUM-ZIRCONIUM ALLOYS  
IN DISTILLED WATER AT 100 °C.  
(Reference CT-2606)



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### Uranium-Columbium Alloys

Three uranium alloys were prepared containing, according to analysis, an average of 1.55, 3.57, and 6.44 weight per cent columbium with the following heat-treatments:

- No. 1: 2 hours at 850°C, water quenched;
- No. 2: 2 hours at 850°C, furnace cooled;
- No. 3: 2 hours at 850°C, water quenched, plus  
24 hours at 350°C, water quenched.

These alloys were corrosion tested at 100 and 178°C. The results are reported in Table XIII. At all the concentrations of columbium tested, the water-quenched materials were more corrosion resistant than the furnace-cooled alloys.

In the 100°C tests the less-resistant columbium alloys were the furnace-cooled 4 weight per cent columbium alloy and all heat-treatments of the 2 weight per cent columbium alloys. The other alloys, the two 4 weight per cent columbium alloys with the heat-treatments No. 1 and 3, and the three 6 weight per cent columbium alloys with the heat-treatments No. 1, 2, and 3, acquired thin protective oxide films. Although these alloys corroded at substantially equal rates,  $0.0006 \pm 0.0001$  mg/cm<sup>2</sup>/hr, variations in the time required for the corresponding colors of the oxide films to appear showed that real differences in corrosion rates occurred. This difference in corrosion resistance was very apparent at 178°C, as shown in Table XIII. The water-quenched 6 weight per cent columbium alloy with heat-treatment No. 1 lost 6.5 mg/cm<sup>2</sup> in a 62.6-day exposure, which is to be compared with a loss of 2450 mg/cm<sup>2</sup> in a one-day exposure for uranium. This alloy and the 6 weight per cent columbium alloy with heat-treatment No. 3 were the most resistant at 178°C.

Uranium-columbium alloys containing 4 to 6 weight per cent columbium are unusually resistant to aqueous corrosion when they are properly heat-treated. And provided these metastable alloys do not transform to a readily corrodible modification during use, they are, from a corrosion standpoint, much superior to uranium for slug material.

Table XIII

AQUEOUS CORROSION OF URANIUM-COLUMBIUM ALLOYS

(Reference CT-3052)

In Open Beaker

Nominal Weight Per Cent of Cb	Heat-Treatment (1)	Metal Loss, mg/cm <sup>2</sup>			Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	Corrosion Rate, mg/cm <sup>2</sup> /hr
		4 days	29 days	32 days		
<u>Tested in Distilled Water at 100°C<sup>(2)</sup></u>						
6	1	0.53		0.99		0.0005
4	1	0.63		1.13		0.0005
2	1	0.85		6.14		0.0076
6	3	0.63		1.3		0.0006
4	3	0.91		1.2		0.0006
2	3	0.33		5.19		0.0075
6	2	1.05		1.15		0.0007
4	2	10.89		73.3		0.16
2	2	45.6		357.4		0.49
<u>Tested at 50°C in Aerated Water Containing Hydrogen Peroxide and Electrolytes such as Might Occur in a Ground Water</u>						
6	1		0.80		0.0011	
4	1		1.75		0.0024	
2	1		12.2		0.017	
"Standard" U			93		0.13	

Table XIII  
(Cont'd.)In Autoclave

Nominal Weight Per Cent of Cb	Heat-Treatment (1)	Weight Loss, mg/cm <sup>2</sup> (3)							
		Days in Test							
		1 day	2 days	3 days	4 days	8 days	16 days	32 days	62.6 days
<u>Tested in Distilled Water at 178°C</u>									
6	1		0.03		0.00	-0.05	-0.21	(0.04 1.76 <sup>(5)</sup> )	(1.2 6.5 <sup>(5)</sup> )
6	2	335	810	1168					
6	3	0.00	0.05		0.2	0.23	0.025	0.03	0.3
4	1		1.06		8.15	18.0	37.6	85	203
4	2	451		1385	1776				
4	3	0.83		3.7	5.5	31.9	53.7		
2	1	365	813						
2	2	1060		2500					
2	3	357	920	1529					
"Standard" U		2450 (4)							
<u>Tested in 1% NaCl Water Solution at 178°C</u>									
6	1	0.06	0.17		0.26	0.73	1.61	1.96 (at 24 days)	
4	1	0.55	2.5		7.2	17.9	43.5		
2	1	497	950		1921	3170	Disin- tegrated		

- (1) The heat-treatments for the uranium-columbium alloys were:
- No. 1. 2 hours at 850°C, water quenched.
  - No. 2. 2 hours at 850°C, furnace cooled.
  - No. 3. 2 hours at 850°C, water quenched, and 24 hours at 350°C, water quenched.
- (2) The samples were tested for 1, 2, 4, 8, 16, 32, 48, and 64 days; and after each period of time, the samples were cleaned and weighed.
- (3) The weight of the corroded specimens included adherent corrosion products. A negative number meant a weight gain.
- (4) This value was found by interpolation of 100°C rate and 185°C rate.
- (5) The corrosion products were removed with 40 weight per cent nitric acid at 27°C.



40Uranium-Molybdenum Alloys

Six uranium-molybdenum alloys of 5 nominal weight per cent molybdenum were tested at 100 and 178°C. Half of the test samples were melted in beryllia crucibles, and the other half in graphite crucibles. These alloys were subjected to the same type of heat-treatment as the columbium alloys, and the numbering system for the heat-treatments was the same.

The phase diagram for the uranium-molybdenum binary system is very similar to the uranium-columbium system, indicating a high solubility of molybdenum in the gamma phase with only a limited solubility in the alpha phase. Molybdenum and columbium tend to stabilize the gamma phase.

The results of various heat-treatments reported in Table XIV showed that the heat-treatments of uranium-molybdenum alloys have a definite effect on the corrosion rate in boiling water. The alloys with a No. 1 heat-treatment corroded approximately ten times more rapidly than those with a No. 3 heat-treatment; the alloys with a No. 2 heat-treatment corroded approximately twice as rapidly as those with No. 3 heat-treatment but cracked after about sixteen days in test.

These uranium-molybdenum alloys were not very resistant to corrosion in the autoclave test. The best alloy tested, that melted in beryllia crucible with heat-treatment No. 3, corroded in distilled water heated to 178°C at an average rate of about 7 to 8 mg/cm<sup>2</sup>/hr, while uranium corroded approximately sixteen times more rapidly under these conditions. Samples which had heat-treatment No. 2 disintegrated in three days, and the alloy with heat-treatment No. 3 and melted in a graphite crucible cracked in three days.

Uranium corroded in boiling distilled water approximately 135 times as fast as the best uranium-molybdenum alloy, melted in a beryllia crucible with heat-treatment No. 3; and uranium corroded about 10 times as fast as the least resistant alloy, melted in graphite crucible with heat-treatment No. 1. Thus, the gamma phase was less corrosion resistant than the alpha phase.

4/

Table XIV

**CORROSION OF URANIUM-MOLYBDENUM ALLOYS**  
**IN BOILING DISTILLED WATER**  
 (Reference CT-3031)

Actual Weight Per Cent of Mo	Heat-Treatment (1)	Metal Loss, mg/cm <sup>2</sup> (2)		Corrosion Rate, mg/cm <sup>2</sup> /hr
		4 days	32 days	
<u>Alloys were Melted in Beryllia Crucibles.</u>				
4.6	1	20.7	135.4	0.18
	2	4.8	20.0	0.07 (initial slope)
	3	2.1	18.4	0.02
<u>Alloys were Melted in Graphite Crucibles</u>				
4.4	1	20.0	198.1	0.26
	2	7.0	41	0.07 (initial slope)
	3	4.0	20.9	0.03

(1) The heat-treatments for the uranium-molybdenum alloys were:

- No. 1. 2 hours at 850°C, water quenched.
- No. 2. 2 hours at 850°C, furnace cooled.
- No. 3. 2 hours at 850°C, water quenched; then  
24 hours at 350°C, water quenched.

(2) Samples were tested for 1, 2, 4, 8, 16, 24, and 32 days; and after each period of time, the samples were cleaned and weighed.

REF ID: A63576

42

## Uranium-Silicon Alloys

To form the epsilon phase of the uranium-silicon alloys, Massachusetts Institute of Technology melted uranium and silicon in graphite crucibles with beryllia slip linings and then cast the alloys into cooled copper molds. The cast alloys were heat-treated in a vacuum for about 150 hours at 750°C to make sure that the epsilon transformation was complete. Actually an alloy heat-treated for only sixteen hours gave about the same corrosion behavior. As reported in CT-3309, the epsilon formation temperature was found to be greatly dependent on the carbon content of the metal.

Cast uranium-silicon alloys which had been heat-treated to produce the epsilon phase were corrosion tested in relatively pure, air-free water at 100 and 178°C. The alloy containing 3.63 weight per cent silicon was the most resistant material tested. In Table XV the corrosion rate of this alloy at 100°C was reported as 0.003 mg/cm<sup>2</sup>/hr. This composition contained more silicon than the pure epsilon phase (3.40 weight per cent silicon), with the excess silicon present as U<sub>5</sub>Si<sub>3</sub> compound. Silicon alloys of 3.82, 3.07, and 2.58 actual weight per cent silicon were also tested. The 3.82 weight per cent silicon alloy contained more U<sub>5</sub>Si<sub>3</sub> than the 3.63 weight per cent silicon alloy; the 3.07 and 2.58 weight per cent silicon alloys contained free uranium.

The alloy containing 3.07 weight per cent silicon cracked up completely between the second and third day in the autoclave at 178°C, and the 2.58 weight per cent silicon alloy cracked in one day. The 3.63 weight per cent silicon alloy had an average metal loss rate of 0.0086 mg/cm<sup>2</sup>/hr at 178°C, which is very favorable as compared to the rate of 115 mg/cm<sup>2</sup>/hr for pure uranium at 178°C, which was taken from Figure 1.

These silicon alloys were exceedingly brittle and quite unworkable; however, the epsilon alloys containing a slight excess of U<sub>5</sub>Si<sub>3</sub>, but no free uranium, are very promising alloys from a corrosion standpoint. An advantage of the epsilon phase alloys, containing 3.40 weight per cent silicon, is that they are stable below 930°C.

An investigation was made at Massachusetts Institute of Technology on uranium-silicon ternary systems in order to evaluate possible alloying effects on the epsilon reaction and on the corrosion resistance. Ternary mixtures of 15 atomic per cent silicon and from 1 to 10 atomic per cent of the alloying component were made. Samples were epsilonized, examined microscopically, and then subjected to corrosion testing in boiling distilled water. The elements studied included columbium, nickel, iron, beryllium, aluminum, zirconium, and copper with molybdenum, tin, titanium, and germanium.

REF ID: A57120

43

Table XV

CORROSION OF EPSILONIZED URANIUM-SILICON ALLOYS IN DISTILLED WATER  
(Reference CT-3035)

Actual Weight Per Cent of Si	Metal Loss, mg/cm <sup>2</sup>					Corrosion Rate, mg/cm <sup>2</sup> /hr	Remarks
	4 days	9 days	16 days	32 days	52.3 days		
<u>Tested at 100°C<sup>(2)</sup></u>							
2.58	5.0			16.4 ± 1.9		0.014	
3.07	1.8			9.7 ± 0.9		0.008	
3.63	1.4			4.3 ± 0.4		0.003	
3.82	(0.5 at 2 days)			11.1 ± 0.3		(Not given because of insufficient data)	
<u>Tested in Autoclave at 178°C</u>							
2.58							
3.07							Cracked in one day
3.63	2.98	18.4 <sup>(1)</sup>	10		10.9		Cracked in 2-3 days

(1) Evidently in error.

(2) Samples were tested for 1, 2, 4, 8, 14, 16, and 32 days; and after each period of time, the samples were cleaned and weighed. The corrosion rates were based on the portions of the curve between 8 and 32 days.

44

As reported in CT-2997, the system which showed good possibilities in the corrosion field was an alloy containing 75 U - 15 Si - 10 Al, atomic per cent (96.29 U - 2.26 Si - 1.45 Al, weight per cent). The cast alloy especially was interesting as it exhibited a corrosion resistance almost comparable to a straight 15 atomic per cent silicon (2.07 weight per cent silicon) epsilon alloy. Annealing increased the resistance so that the alloy behaved much like the straight 23 atomic per cent silicon (3.40 weight per cent), pure epsilon silicon alloy.

It was reported in CT-3122 that coupling with silver, aluminum, beryllium, copper, lead, zinc, tin, nickel, Monel, and stainless steel caused no significant increase in the corrosion of epsilon silicon alloy in boiling distilled water.

### Aluminum-Uranium Alloys

Specimens of the aluminum-uranium alloys were tested in "simulated River water," flowing at 9 ft/sec past the specimens, at 70°C for 470 hours; the results reported in Table XVI indicated that:

- (1) The alloys were resistant to corrosion up to 9 weight per cent uranium, approximately the same as 2S aluminum.
- (2) They were not satisfactory above 16.8 weight per cent uranium because of their low resistance to corrosion and their tendency to pit.
- (3) The addition of  $5 \times 10^{-3}N$   $H_2O_2$  caused the rate of metal loss to increase to five times that in its absence.

Aluminum-uranium alloys appeared to be very resistant to the steam autoclave test at 178°C, with specimens immersed in boiling distilled water in Pyrex beakers; however, the weight changes were too low to give any correlation between uranium content and resistance to corrosion (0-1.0 mg/cm<sup>2</sup> in 64 days). It may be that silica, which was dissolved from the beakers, acted as an inhibitor. The weight changes for the aluminum-uranium alloys were approximately the same as those for 2S aluminum under the same condition. The maximum weight per cent of uranium in these alloys was 29.1, which corresponded to less than 5 atomic per cent uranium.

A large number of solution potential tests were made with these alloys, and the effects of various amounts of sodium dichromate, silica, and hydrogen peroxide are reported in CT-3029.

REF ID: A57111

45

Table XVI

AQUEOUS CORROSION OF ALUMINUM-URANIUM ALLOYS  
(Reference CT-3029)

Actual Weight Per Cent of U (1)	Time in Test, days	Metal Loss, mg/cm <sup>2</sup>	Average Rate of Metal Loss, mg/cm <sup>2</sup> /hr	Remarks
<u>Tested in "Simulated River Water" at 70°C (2)</u>				
1.88	16.8		1.72	Smooth surface
1.88	19.6		2.25	Smooth surface
4.95	16.8		1.96	Smooth surface
4.95	19.6		1.85	Smooth surface
9.0	16.8		2.12	Smooth surface
9.0	19.6		4.43	Smooth surface
16.8	19.6		6.00	Smooth surface
21.2	15.7		5.20 (3)	Few pits on edges
26.2	15.7		21.70	Pits up to 0.3 mm in diameter on the surface; up to 1 mm in diameter on edge
29.1	19.6		26.10	Numerous pits up to 1 mm in diameter on edges
<u>Tested at 70°C Solution Base, Distilled Water (4)</u>				
16.8	18.5		6.13	Few pits up to 0.2 mm deep
<u>Tested at 70°C Solution Base, Distilled Water (5)</u>				
16.8	18.5		1.32	Smooth surface
<u>Tested in Relatively Pure Water at 178°C, pH ~ 8</u>				
0.0	64	0.4		
1.88	64	0.9		
4.95	64	0.8		
9.0	64	0.5		
16.8	64	0.9		
29.1	64	0.0		

- (1) The remaining percentage was aluminum.
- (2) The water contained  $5 \times 10^{-3} \text{N}$   $\text{H}_2\text{O}_2$  and 1 ppm  $\text{Cl}^-$ , with a pH 6.5, a flow rate of 9 ft/sec.
- (3) This alloy was clad with 2S aluminum; however, the alloy was exposed at the edges.
- (4) The water contained  $2 \times 10^{-5} \text{N}$   $\text{H}_2\text{O}_2$  and 10 ppm  $\text{Cl}^-$ , with a pH 6.5, and a flow rate of 9 ft/sec.
- (5) The water contained 1 ppm  $\text{Cl}^-$ , with a pH 6.5, and a flow rate of 9 ft/sec.

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46

### Effectiveness of Alloying Constituents

A brief summary of some of the more favorable corrosion results on uranium alloys is reported in Table XVII. From results of corrosion testing of alloys containing varying percentages of a particular alloying element, the lowest rate of weight loss is included without regard to the percentage of alloying element; if the rates are relatively the same for more than one alloy, the rate for that containing the lowest amount of the alloying element is given. The average rate of weight loss reported in Table XVII should be used only as a relative indication of corrosion resistance except in the case of the columbium, molybdenum, and the silicon alloys, for these alloys were investigated rather thoroughly by the Corrosion Section, Metallurgical Laboratory. The alloy which appeared second best of the columbium alloys is reported since no cleaned sample weights were available for the best. The uranium ternary alloy containing 2 weight per cent each of columbium and zirconium has the lowest rate of weight loss reported at 178°C. It may be possible to have this good resistance with a smaller amount of columbium in the alloy. The work reported in Table XVII on the 2 weight per cent zirconium plus 1 weight per cent columbium would allow one to draw this inference.

REF ID: A57110

47  
Table XVII

CORROSION OF THE BEST URANIUM ALLOYS IN DISTILLED WATER

Nominal Weight Per Cent of Alloying Element	Heat-Treatment	Average Rate of Weight Loss, mg/cm <sup>2</sup> /hr	Reference
<u>Tested at 90°C</u>			
Standard Uranium	As-cast	1.0	CT-3055
0.5 Nickel	As-cast	0.02	CT-1272
<u>Tested at 100°C</u>			
Standard Uranium	As-cast	2.7	CT-3055
Standard Uranium	2 hrs. at 900°C, W.Q.	0.78	CT-3055
2 Zr - 2 Cb	256 hrs. at 850°C, W.Q.	-0.0001 (gain)	CT-2925
2 Zr - 1 Cb	Homogenized at 1000°C, W.Q.	<0.01	CT-3071
6 Columbium	2 hrs. at 850°C, W.Q.	0.0005 (1)	CT-3052
7.2 Titanium	As-cast	<0.001	CT-2903
3.63 Silicon act.	Epsilonized	0.003 (1)	CT-3035
3.85 Tantalum	1000°C for week, W.Q.	0.006	CT-2925
4.3 Zirconium act.	53 hrs. at 1000°C, W.Q.	0.008 (2)	CT-2925
2.46 Vanadium act.	72 hrs. at 850°C, W.Q.	0.014	CT-2925
5 Molybdenum	2 hrs. at 850°C, W.Q. plus 24 hrs. at 350°C, W.Q.	0.02 (1)	CT-3031
<u>Tested in Autoclave at 178°C</u>			
Standard Uranium	As-cast	115	Figure 1
2 Zr - 2 Cb	Not given	0.0007	CT-3011
6 Columbium	2 hrs. at 850°C, W.Q.	0.004 (2)	CT-3052
3.63 Silicon act.	Epsilonized	0.009 (2)	
7.57 Titanium	Not given	5.9	CT-3011
Molybdenum	2 hrs. at 850°C, W.Q. plus 24 hrs. at 350°C, W.Q.	8	CT-3031

(1) "Corrosion rate," as previously defined.

(2) "Average rate of metal loss," as previously defined.



48

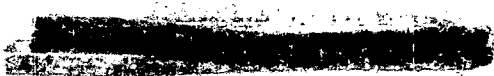
VI. REFERENCES

- BR-223 A T. Wathen, Corrosion of Uranium Metal in Air and Steam at Various Temperatures, Imperial Chemical Industries, May 13, 1943
- BR-403 U Metal Sub-Committee Review of Existing State of Knowledge as of March 1, 1944.
- BR-549 E. W. Colbeck, H. J. Spencer-Palmer, et al., Some Preliminary Experiments on Possible Methods of Protecting U Metal Against Corrosion, Imperial Chemical Industries, January 9, 1945.
- CP-1728 W. W. Watson et al., General Physics Research Monthly Report, May 25, 1944.
- CT-1272 J. E. Draley et al., Metallurgical Laboratory, Corrosion Section Technical Division Progress Report, February 11, 1944.
- CT-1943 J. E. Draley and G. C. English, Corrosion Research - Uranium and Alloys, July 1, 1945.
- CT-2606 M. Cohen et al., Massachusetts Institute of Technology Monthly Report, March, 1945.
- CT-2659 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Weekly Report, January 20-27, 1945.
- CT-2668 F. Foote et al., Metallurgy Division, Metallurgical Laboratory Monthly Report, January, 1945.
- CT-2703 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Weekly Report, February 10-17, 1945.
- CT-2715 J. G. Feibig, Water Corrosion of Alloys of Thorium and of Uranium, Ames Project, April 25, 1945.
- CT-2755 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Weekly Report, February 24 - March 3, 1945.
- CT-2780 M. Cohen et al., Massachusetts Institute of Technology Monthly Report, February, 1945.
- CT-2794 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Monthly Report, March, 1945.
- CT-2857 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Weekly Report, March 24-31, 1945.

REF ID: A60711

49

- CT-2903 H. W. Russel, H. R. Nelson, and L. H. Grenell, Battelle Memorial Institute Progress Report, April 1, 1945.
- CT-2925 A. B. Greninger et al., Metallurgy Division, Metallurgical Laboratory Monthly Report, April, 1945.
- CT-2997 M. Cohen et al., Massachusetts Institute of Technology Monthly Report, April, 1945.
- CT-3011 F. Foote et al., Metallurgy Division, Metallurgical Laboratory Monthly Report, May, 1945.
- CT-3029 J. W. Arendt and W. W. Binger, Corrosion of Aluminum-Uranium Alloys, June 5, 1945.
- CT-3031 J. M. Hopkins, Frederick Nelson, and W. W. Binger, Corrosion of Uranium-Molybdenum Alloys by Water, May 31, 1945.
- CT-3035 J. M. Hopkins, W. W. Binger, and F. Nelson, Aqueous Corrosion of Uranium-Silicon Alloys, June 14, 1945.
- CT-3043 N. Bensen, R. P. Straetz, and J. E. Draley, Autoclave Tests of Uranium slugs and Alloys, June 4, 1945.
- CT-3052 F. Nelson, W. W. Binger, and J. M. Hopkins, Corrosion Testing of Uranium Columbium Alloys, June 19, 1945.
- CT-3055 W. A. Mollison, G. C. English, and F. Nelson, Corrosion of Uranium in Distilled Water, June 23, 1945.
- CT-3071 F. Foote et al., Metallurgy Division, Metallurgical Laboratory Monthly Report, June, 1945.
- CT-3194 M. Cohen et al., Massachusetts Institute of Technology Monthly Report, June, 1945.
- CT-3309 G. Bitsianes, A. R. Kaufman, B. D. Cullity, and M. Neher, Alloys of Uranium and Silicon, II. The Epsilon Phase, June, 1945.
- ME-64 H. Greenwood, Corrosion Tests on a Series of Uranium-Silicon Alloys, Montreal Laboratory, May 16, 1944.
- N-1703 N. Goldowski and E. Sherman, Corrosion of Heavy Metal Spinners, November 4, 1944.
- PR - C.E.-8 W. B. Lewis et al., Chalk River Progress Report, September to November, 1950.



REF ID: A65715