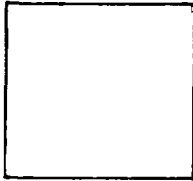


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CORROSION STUDIES ON TITANIUM AND ZIRCONIUM METALS

L. B. Golden, I. R. Lane, Jr., J. T. Pons, W. R. Acherman, and W. Mace

Semiannual Report for June 1951:

A comprehensive corrosion resistance investigation of titanium, zirconium, and their alloys was initiated in June 1947. These corrosion studies involve a wide variety and concentration of media including acids, bases, salts, and organic compounds. Temperature and pressure variables have also been incorporated in the broad program.

From the earliest laboratory tests, these two relatively new metals have exhibited unique corrosion resistant properties. More recently, numerous evaluation studies have shown that titanium is a potential replacement for stainless steels in many applications. Zirconium, on the other hand, is similar in its corrosion properties to tantalum and may ultimately be used as a replacement or substitute for the less abundant and expensive metal, tantalum. Due to the general similarity of titanium to stainless steels and zirconium to tantalum, these metals and alloys have been used in companion or parallel corrosion tests for comparison data of their relative corrosion resistance.

In the present reporting period, tests have been made on the corrosion resistance of zirconium and zirconium alloys in hydrochloric acid (embrittlement tests), sulfuric acid, and phosphoric acid. A comparison was made of the relative corrosion resistance of low hafnium arc melted zirconium and zirconium containing less than 3 percent hafnium induction melted in graphite. A series of zirconium alloys was subjected to tests in various rocket fuels and substitute ocean water spray. Corrosion rates were determined for zirconium and stainless steel in aqua regia. Titanium, zirconium,

and stainless steel were also tested in ammonium chloride solutions and boiling substitute ocean water. Titanium and lead were exposed to sulfuric and nitric acid mixtures.

Galvanic corrosion tests were conducted on titanium coupled with magnesium, zinc, aluminum, lead, tin, nickel, and copper. Galvanic potentials and corrosion rates were determined in substitute ocean water, one percent hydrochloric acid, and one percent sodium hydroxide solutions. Solution potentials were determined in substitute ocean water under different conditions of aeration. Open circuit potentials were determined and the potential of each metal relative to the saturated calomel half-cell was recorded for magnesium, tin, and nickel coupled with titanium.

Arc melted zirconium alloys - hydrochloric acid under pressure (embrittlement tests):

Tests were conducted on a series of one hundred and three zirconium alloys furnished by the Northwest Electrodevelopment Laboratory of the Bureau of Mines at Albany, Oregon. The samples were exposed for six days in concentrated (37 percent) hydrochloric acid at 60°C. Individual specimens were sealed in glass tubes half-filled with acid (70-85 ml.) and tested under the pressure developed at this temperature, calculated to be approximately three atmospheres.

The zirconium binary alloys investigated included: silver, nickel, aluminum, silicon, tungsten, molybdenum, antimony, iron, copper, manganese, cobalt, tantalum, cerium, chromium, and beryllium. Twenty gram compacts of all the alloys were prepared from accurately weighed metal powders of the best quality available and minus 10-mesh X-grade zirconium chips of the following composition:

Chemical analysis, parts per million

N=20, C=100, Fe=1500, Al=20

Spectrographic analysis, parts per million

Al=50, Sb<50, Bi<1, Sn=2, Cu=5, Pb=100
Mg>500, Zn<50, Cr=50, Fe=1000, Mn=20, Ni=5
Si=300, Ti=50, V<50, Mo<10, B<0.05

The pressed compacts were arc melted with a tantalum tipped electrode in a helium atmosphere, sheath rolled at 850°C, the sheath removed, and the alloys pickled and sand blasted. Previous experience in arc melting indicated that the alloy content was normally 0.1 to 0.2 percent less than the nominal values, consequently, the individual arc melted ingots were not chemically analyzed.

The results of the tests in hydrochloric acid are recorded in Tables I and II. Alloys of zirconium with tantalum, molybdenum, silver, manganese, aluminum, and chromium possess the greatest corrosion resistance. The corrosion rates for these binary alloys ranged from 0.00 to 25.2 mils per year. Alloys with nickel, tungsten, copper, cobalt, and beryllium were the least resistant. At room temperature and atmospheric pressure, the corrosion rate for an 8 percent nickel alloy was 116 mils per year and for a 10 percent copper alloy, 80.6 mils per year.

In general, increasing amounts of the alloying constituent caused a decrease in the corrosion resistance of the alloys.

Forty-six of the alloys which had an average corrosion rate of less than 4 mils per year in the tests at 60°C were selected for further tests at 100°C. Under these conditions the pressures developed were much higher, (about 11 atmospheres). Results of these tests are recorded in Table II. The molybdenum, aluminum, manganese, and tantalum alloys have the greatest corrosion

resistance. Those having the least resistance are the silver and antimony alloys. Here again, increasing amounts of the alloying constituent generally caused a decrease in the corrosion resistance of the alloys.

Arc melted zirconium versus zirconium induction melted in graphite:

Samples of six different lots of arc melted, low hafnium, cold rolled zirconium metal and samples of ordinary purity, cold rolled zirconium induction melted in graphite were tested for six days, (1) at 100°C in aerated concentrated (85 percent) phosphoric acid, (2) at 35°C in 80 percent sulfuric acid, and (3) at 35°C in 20 percent ferric chloride solution.

Corrosion rates of the arc melted metal in phosphoric acid ranged from 61.0 to 80.2 mils per year as compared to 28.4 to 31.2 mils per year for the induction melted metal. In 80 percent sulfuric acid, arc melted zirconium rates ranging from 0.46 to 1.35 mils per year compared to 4.44 to 9.51 mils per year for the induction melted metal were observed. In 20 percent ferric chloride solution corrosion rates for the arc melted zirconium ranged from 22.7 to 68.8 mils per year compared to 113 to 237 mils per year for induction melted zirconium.

Zirconium-titanium alloys -- hydrochloric, sulfuric, and phosphoric acids:

A series of zirconium-titanium alloys were tested at 35°C and 60°C for six days in aerated 5, 10, 12.5, 15, 17.5, and 20 percent hydrochloric acid solutions and in non-aerated 37.5 percent (concentrated) acid. Additional tests were also performed at 35°C and 60°C in aerated sulfuric acid solutions ranging in concentration from 10 to 96.5 percent (concentrated) and in aerated phosphoric acid solutions ranging in concentration from 10 to 40 percent. The results of these tests are shown in Table III together with results obtained previously for titanium and zirconium metals. An examination of the

data in this table shows that, in general, (1) increasing amounts of titanium in the alloy causes a corresponding increase in the corrosion rate for all concentrations of acid studied, (2) increasing acid concentrations cause a corresponding increase in the corrosion rate, and (3) a zirconium-titanium alloy containing as little as 14 percent zirconium shows remarkable corrosion resistance as compared to ordinary titanium. One specific example is the rate obtained in 15 percent hydrochloric acid solution at 60°C. The 14 percent zirconium alloy is satisfactorily resistant with a rate of only 16.9 mils per year whereas ordinary titanium gives an excessive rate of 789 mils per year.

Zirconium alloys--substitute ocean water spray test:

A group of 103 Bureau of Mines arc melted zirconium alloys was exposed to substitute ocean water spray (A.S.T.M. Designation D 1141-50T) in a salt spray cabinet at room temperature for thirty days. Except for negligible gains or losses in weight almost all of the samples tested showed no signs of corrosion. The exceptions were two alloys containing 7 and 10 percent copper. Green colored corrosion products were present on the evenly corroded surfaces of these samples. Corrosion rates were 0.47 and 0.48 mils per year, respectively.

(Table IV)

Zirconium alloys--rocket fuels:

Ninety-one of the Bureau of Mines arc melted zirconium alloys were tested at room temperature for thirty days in red fuming nitric acid. A majority of the samples showed gains in weight caused by the formation of blue-to-black colored films on the surfaces. The samples showing the greatest corrosion resistance were the tantalum alloys (5, 10, and 15 percent Ta), molybdenum alloys (5 and 10 percent Mo), a 3 percent iron alloy, a 2 percent silicon alloy, and two copper alloys (7 and 10 percent Cu). These samples

showed little discoloration and negligible gains in weight. The results of these tests are summarized in Table V together with the composition of the alloys. Because of the irregular shapes of most of the samples, the results are expressed in weight gain or loss in grams together with a description of the appearance of the samples and changes in physical properties.

Samples of seven different lots of Bureau of Mines arc melted, low hafnium, cold rolled zirconium metal were tested at room temperature for thirty days in red fuming nitric acid. These samples showed small gains in weight (0.5 to 3.6 milligrams) caused by the formation of very thin, tightly adhering, blue-gray colored films on their surfaces. There were no signs of embrittlement.

One hundred and three of the Bureau of Mines arc melted zirconium alloys were tested in mixed acid (84% white fuming nitric acid plus 14 percent fuming sulfuric acid) at room temperature for thirty days. These samples showed appreciable weight losses. Twenty-three of the samples were completely dissolved or disintegrated. Alloys showing excellent corrosion resistance were the silver (1, 3, 5, and 10 percent Ag), iron (1, 3, and 5 percent Fe), silicon (1, 2, and 3 percent Si), tungsten (1, 5, and 10 percent W), copper (1, 3, 5, 7, and 10 percent Cu), and chromium (1, 2, and 5 percent) alloys. In each instance, the corrosion rates were less than 5 mils per year. The results of these tests are summarized in Table VI together with the composition of the alloys. Corrosion rates are expressed in mils per year and a description of the appearance of the samples and changes in physical properties are noted.

The some 103 zirconium alloys were also tested at room temperature for thirty days in ethyl alcohol (95 percent ethanol). Except for very slight

gains or losses in weight amounting to a few tenths of a milligram the alloys, in general, showed no signs of corrosion. The exceptions were three copper alloys containing 5, 7, and 10 percent copper. These samples showed areas of dulled, evenly corroded metal; however, maximum weight losses were less than 0.6 milligram.

Sixty-one of the Bureau of Mines zirconium alloys were tested at room temperature for thirty days in methyl alcohol (absolute methanol). Except for negligible gains or losses in weight, none of the samples showed signs of corrosion. Similar tests were made on 64 alloys in xylidine, and 69 alloys in aniline. Except for very slight gains or losses in weight none of the samples showed any signs of corrosion.

Forty-two of the zirconium alloys furnished by the Foote Mineral Company were tested in white fuming nitric acid at room temperature for thirty days. Most of these samples were relatively unaffected and only slight gains or losses in weight were noted. However, samples of the following alloys showed appreciable losses in weight: 1 and 5 percent beryllium, 5 percent platinum, 5 percent vanadium, and 5 percent silicon. The results of these tests are summarized in Table VII.

Eighty of the zirconium alloys furnished by the Foote Mineral Company were tested in 95 percent ethyl alcohol at room temperature for thirty days. The samples were unaffected by this media. Similar results were obtained with the Foote alloys in leaded gasoline.

Zirconium--aqua regia:

Samples of two different lots of arc melted, low hafnium, hot rolled zirconium metal and samples of six different lots of arc melted, low hafnium, cold rolled zirconium metal were tested at room temperature for

fourteen days in concentrated aqua regia (3 parts of concentrated HCl plus 1 part of concentrated HNO₃) solution. Neither the hot rolled nor the cold rolled metal showed substantial corrosion resistance although the hot rolled metal gave much lower rates (156 mils per year average) than the cold rolled metal (357 mils per year average). Corrosion rates for these samples are recorded in Table VIII.

Titanium, zirconium, and stainless steel--ammonium chloride solutions:

Titanium, zirconium, and Carpenter No. 20 stainless steel were tested for six days at 60°C and 100°C in aerated 1 and 10 percent ammonium chloride solutions. Corrosion rates were negligible for all three materials as shown in Table IX. Tests were also made for six days in boiling 10 percent and saturated solutions of ammonium chloride. In both solutions, rates for titanium and zirconium were negligible. However, the titanium samples showed typical "chloride pitting" consisting of rather large but shallow pits filled with corrosion products. The stainless steel samples were badly pitted, especially in the saturated solution. Rates in the 10 percent and saturated solutions were 3.02 and 20.1 mils per year, respectively.

Titanium--inorganic compounds:

Corrosion rates for titanium in aerated 5 and 20 percent trisodium phosphate solutions and in aerated 2 percent calcium hypochlorite solution at 60°C for six days were negligible. (Table IX) In aerated 5 percent sulfuric acid at 60°C for six days the corrosion rate was found to be 190 mils per year.

Titanium and lead--sulfuric and nitric acid mixtures:

Titanium and lead were tested in concentrations (60-70 percent) of

sulfuric acid. This strength acid is approximately that of "chamber acid" formed in the lead chamber process for the production of sulfuric acid. Enough nitric acid was added to give a concentration of 1 percent. Corrosion rates were determined in these aerated acid mixtures at 100°C for six days. Corrosion rates for lead were low but those for titanium were excessively high. (Table IX)

Titanium, zirconium, stainless steel, and monel metal--boiling substitute ocean water:

Samples of titanium, zirconium, Carpenter No. 20 stainless steel and monel metal were tested for seven days in boiling substitute ocean water. All of the samples gained very slightly in weight caused by the formation of very thin, varicolored, iridescent films on their surfaces. However, there was no pitting or any other form of corrosion on any of the samples.

Titanium--galvanic corrosion studies:

Galvanic corrosion studies of titanium coupled with common metals were initiated. Preliminary tests were made to find the difference in corrosion rate between coupled and uncoupled samples. Non-aerated, air-aerated and helium-aerated substitute ocean water (A.S.T.M. designation D-1141-50T), one percent hydrochloric acid and one percent sodium hydroxide were used in the room temperature tests. Titanium was completely immune to corrosion under these conditions.

Titanium--metal couples in substitute ocean water:

With few exceptions the coupled samples showed the greatest average corrosion rates. (Table X) All tests with magnesium were of short duration because of disintegration of the coupled magnesium samples. The uncoupled magnesium samples showed a slight gain in weight due to the formation of an

adherent film on their surfaces. The corrosion rate of the uncoupled zinc samples in non-aerated solutions was greater than that of the coupled samples. There was no difference in the corrosion rates of coupled and uncoupled aluminum in either non-aerated or air-aerated solutions. In helium aerated solution, however, the rate for coupled aluminum was greater than that for the uncoupled metal. The corrosion rate of uncoupled lead was slightly higher than the coupled in air-aerated solutions. The corrosion of nickel under all conditions of aeration was negligible. The corrosion rates of copper coupled and uncoupled, in air-aerated solutions were identical. The rate for uncoupled copper in the helium-aerated solution was slightly higher than the coupled metal.

Titanium--metal couples in 1 percent hydrochloric acid:

With the exception of tin in non-aerated one percent hydrochloric acid and nickel in air-aerated solution, the coupled metals showed the greatest corrosion rates. (Table XI)

Titanium--metal couples in 1 percent sodium hydroxide solution:

The corrosion rate of magnesium, both coupled and uncoupled, in one percent sodium hydroxide was zero or negligible under all three conditions of aeration. (Table XII) The corrosion rate of both coupled and uncoupled zinc in non-aerated solution ^{was} /quite low, although a slight gain in weight of each of the samples caused by the formation of an adherent film on the surfaces was noted. There was a very slight difference between the average corrosion rates of coupled and uncoupled zinc in both air-aerated and helium-aerated solutions. Tests of aluminum in one percent sodium hydroxide were of short duration due to rapid attack on the metal. The corrosion rate for uncoupled

aluminum was greater than the coupled in both non-aerated and air-aerated solutions. The rates for uncoupled lead and tin in air-aerated solutions were greater than the coupled metals. The corrosion of nickel under all conditions tested was negligible. The rates for copper in air-aerated and helium-aerated solutions were essentially zero. There again, a slight gain in weight of each of the samples was recorded.

From the data obtained, titanium should be placed at the bottom of the galvanic series (i.e. titanium is more noble or cathodic than any of the metals tested).

Solution potentials of metals:

Studies were made to determine the solution potentials of titanium and seven other metals on which galvanic corrosion studies are being made. Tests were made in non-aerated, air-aerated and helium-aerated substitute ocean water at 35°C. Potentials were measured relative to the saturated calomel half-cell with an L and N Type K-2 potentiometer.

The metals tested are arranged in a galvanic series in Table XIII according to the average potential of the metal. Potentials are recorded relative to the normal hydrogen electrode (i.e. metals with a minus (-) voltage value are less noble than the hydrogen electrode and those with a plus (+) value are more noble). This sequence was valid for all types of aeration with the exception of helium-aerated solutions in which nickel was slightly more noble than titanium. Initial EMF was recorded immediately after placing the metals in the solution. Average EMF is the average of the voltages recorded after the first twenty-four hours of the test. The solution potential of aluminum was considerably less initially than at the end of twenty-four hours and that of nickel and titanium was greater.

With a slight rearrangement of the metals in the middle of the series, this galvanic series would be similar to a series arranged according to increasing nobility relative to corrosion rate. (Table XIII) The results further confirm the data obtained in the preliminary tests regarding the relative nobility of titanium.

Electrical measurements of metal couples:

Tests have been completed in non-aerated and air-aerated substitute ocean water at 35°C in which the open circuit potential measurements between coupled and uncoupled metals, the potential of each metal relative to the saturated calomel half-cell and the average current between coupled samples have been determined using magnesium, zinc, tin and nickel coupled with titanium. It was found that titanium coupled to another metal and exposed to substitute ocean water undergoes polarization effects which causes it to assume a potential nearly equal the potential of the coupled metal. The recorded average final potentials in the tables were recorded approximately five minutes after the circuit between coupled samples was broken. This was necessary due to a rapid change in potential because of breakdown of polarization effects immediately after breaking the circuit.

When tin (Table XV) and nickel (Table XVI) were coupled with titanium the polarization effects of both members of the couple were so great that no measureable amount of current flow could be detected at any time. The current flow between magnesium-titanium couples (24.5 milliamperes in non-aerated and 21.5 milliamperes in air-aerated solutions) (Table XIV) and zinc-titanium couples (0.3 milliamperes and 0.4 milliamperes respectively) (Table XVII) was less than might be expected from their solution potentials.

The average corrosion rates of coupled magnesium (895 mils per year in non-aerated and 1190 mils per year in air-aerated solutions) were higher than uncoupled magnesium (22.4 mils per year and 58.7 mils per year respectively), while the difference between coupled zinc (9.11 mils per year and 8.7 mils per year respectively) and uncoupled zinc (1.27 mils per year and 8.2 mils per year respectively) was not so pronounced. Coupled tin showed a slightly higher corrosion rate than the uncoupled metal in both non-aerated and air-aerated solutions. There may have been a very small flow of current that could not be measured. The corrosion rate of nickel (less than 0.2 mils per year) and the difference between coupled and uncoupled specimens were negligible. It may be tentatively concluded that corrosion due to galvanic action does not occur when equal areas of nickel and titanium are coupled and exposed to non-aerated or air-aerated substitute ocean water.

Future program:

The program for the immediate future will include a continuation of tests on titanium and zirconium metals and their alloys with inorganic and organic compounds at different concentrations and temperatures. A comparison of the relative corrosion resistance of arc melted metals (both titanium and zirconium) and metals melted in graphite will be continued. Further tests will be made on zirconium alloys in materials used for rocket fuels and in simulated marine atmosphere (salt spray) tests.

Galvanic corrosion research will be continued on titanium and zirconium and their alloys. Galvanic corrosion tests to date have been limited to tests with equal areas for each electrode. Future work will include variation in ratio of areas of electrodes as well as tests with additional metals and electrolytes.

Table I. Zirconium Alloys - Hyd Chloric Acid Under Pressure

Alloy Number	Composition (percent by wt.)	Corrosion Rate		Observations
		(mils per year)		
MA 1721	1 Ag	0.53		No visible signs of corrosion.
22	1 Ag	0.26		" " " " " "
25	3 Ag	1.32		" " " " " "
26	3 Ag	0.48		" " " " " "
29	5 Ag	1.22		" " " " " "
30	5 Ag	6.80		" " " " " "
33	10 Ag	2.98		" " " " " "
34	10 Ag	5.20		" " " " " "
43	1 Ni	0.64		" " " " " "
44	1 Ni	0.53		" " " " " "
47	1 Al	0.21		" " " " " "
48	1 Al	0.16		No visible signs of corrosion.
51	2 Al	0.16		Sample covered with very thin varicolored film.
52	2 Al	0.32		" " " " " "
55	3 Al	21.3		Sample dulled (tarnished). No signs of embrittlement.
56	3 Al	2.17		" " " " " "
60	1 Si	3.62		Sample showed small, irregular-shaped, shallow patches of embrittled metal.
61	1 Si	2.45		" " " " " "
64	2 Si	11.5		" " " " " "
65	2 Si	14.0		" " " " " "
68	3 Si	9.03		" " " " " "
69	3 Si	7.97		" " " " " "
72	3 Ni	12.4		" " " " " "
73	3 Ni	11.1		" " " " " "
81	5 Ni	68.5		" " " " " "
82	5 Ni	70.2		" " " " " "
85	8 Ni	93.0#		" " " " " "
1786	8 Ni	116 #		" " " " " "
1805	1 W	55.2		Sample covered with thin film of embrittled metal with patches of more deeply embrittled metal
06	1 W-	47.6		" " " " " "
09	5 W	41.9		" " " " " "
10	5 W	40.2		" " " " " "
14	10 W	52.3		" " " " " "
15	10 W	70.6		" " " " " "

Table I. Zirconium Alloys - Hyd. Chloric Acid Under Pressure (Cont.)

Alloy Number	Composition (percent by wgt.)	Corrosion		Observations
		Rate (mils per year)		
WA 1818	1 Mo	0.32	No visible signs of corrosion.	
19	1 Mo	0.32	" " " "	
22	3 Mo	1.01	Sample dulled (tarnished). No signs of embrittlement.	
23	3 Mo	0.64	" " " "	" " " "
26	5 Mo	1.06	" " " "	" " " "
27	5 Mo	0.95	" " " "	" " " "
30	10 Mo	2.82	" " " "	" " " "
31	10 Mo	1.38	" " " "	" " " "
37	1 Sb	0.26	No visible signs of corrosion.	
42	3 Sb	1.96	" " " "	
43	3 Sb	1.54	" " " "	
46	5 Sb	13.8	" " " "	
47	5 Sb	11.9	" " " "	
50	1 Fe	1.11	" " " "	
51	1 Fe	1.22	" " " "	
54	3 Fe	5.88	" " " "	
55	3 Fe	9.00	" " " "	
58	5 Fe	35.7	Sample showed areas on one side where shallow embrittlement was present.	
59	5 Fe	40.1	No visible signs of corrosion.	
62	1 Cu	1.06	" " " "	
63	1 Cu	1.33	" " " "	
66	3 Cu	96.3	" " " "	
67	3 Cu	136	Sample showed darkened areas on one side. No embrittlement.	
70	5 Cu	12.2#	No visible signs of corrosion.	
71	5 Cu	21.2#	" " " "	
74	7 Cu	44.7#	Sample showed large areas of dulled metal on one side.	
75	7 Cu	37.5#	" " " "	" " " "
78	10 Cu	68.6#	Surfaces of sample slightly dulled.	
79	10 Cu	80.6#	" " " "	" " " "
82	1 Mn	0.26	No visible signs of corrosion.	
83	1 Mn	0.32	" " " "	
86	3 Mn	0.00	" " " "	
87	3 Mn	0.37	" " " "	
90	5 Mn	1.59	" " " "	
91	5 Mn	1.27	" " " "	
94	10 Mn	2.45	" " " "	
95	10 Mn	4.15	" " " "	

Table I. Zirconium Alloys - Hydrochloric Acid Under Pressure (Cont.)

Alloy Number	Composition (percent by wt.)	Corrosion		Observations
		Rate (mils per year)		
WA 1898	1 Co	4.30		No visible signs of corrosion.
99	1 Co	24.0		" " " " " "
1902	3 Co	38.3		Sample showed small, shallow areas of embrittlement.
05	3 Co	50.2		" " " " " "
06	5 Co	195		Sample showed definite signs of embrittlement over entire surface.
07	5 Co	292		" " " " " "
10	7 Co	274		Sample badly embrittled.
11	7 Co	538		" " " " " "
18	5 Ta	0.00		No visible signs of corrosion.
19	5 Ta	0.11		" " " " " "
22	10 Ta	0.00		" " " " " "
23	10 Ta	0.00		" " " " " "
34	15 Ta	0.21		" " " " " "
35	15 Ta	0.32		" " " " " "
14	1 Ce	0.58		" " " " " "
15	1 Ce	0.26		" " " " " "
26	2 Ce	5.30		" " " " " "
27	2 Ce	3.97		" " " " " "
30	3 Ce	44.1		Sample showed signs of general embrittlement.
WA 1931	3 Ce	—		Sample was completely disintegrated.

Specimen configuration - 1" x 0.5" x 0.040" (approx.)

All tests were run at 60°C unless otherwise stated.

Samples run at room temperature and atmospheric pressure because of excessive gas evolution.

Table 1.
Zirconium Alloys - Hydrochloric Acid Under Pressure

Alloy No.	Composition (percent by weight)	Corrosion Rate (mils per year)	Observations
WA-2064	1 Cr	0.32#	No visible signs of corrosion.
55	1 Cr	0.32#	" " " " " "
58	2 Cr	0.26#	" " " " " "
59	2 Cr	0.42#	" " " " " "
64	5 Cr	3.55#	" " " " " "
65	5 Cr	2.12#	" " " " " "
89	8 Cr	25.2 #	Embrittlement in the form of evenly distributed flakes on the surface.
90	8 Cr	20.2 #	" " " " " "
93	1 Be	15.6 #	Embrittlement cracks in which powdery, embrittled metal was present.
94-	1 Be	9.40#	" " " " " "
97	2 Be	35.7 #	" " " " " "
98	2 Be	18.2 #	" " " " " "
WA-1721	1 Ag	3.40	Badly embrittled and easily broken in the hand.
22	1 Ag	4.19	" " " " " "
25	3 Ag	-	Completely embrittled and disintegrated.
26	3 Ag	-	" " " " " "
29	5 Ag	54.7	Badly embrittled and easily broken in the hand.
30	5 Ag	42.3	" " " " " "
33	10 Ag	105	" " " " " "
34	10 Ag	203	" " " " " "
43	1 Ni	0.42	No visible signs of corrosion.
44	1 Ni	0.37	" " " " " "
47	1 Al	0.53	Surfaces covered with a varicolored film.
48	1 Al	0.37	" " " " " "
51	2 Al	1.05	" " " " " "
52	2 Al	1.48	" " " " " "
55	3 Al	29.6	Evenly corroded to a gray-black, pickled finish. No signs of embrit.
56	3 Al	17.8	" " " " " "
60	1 Si	3.51	No visible signs of corrosion.
61	1 Si	3.06	" " " " " "
WA-1818	1 Mo	0.21	" " " " " "
19	1 Mo	0.53	" " " " " "
26	5 Mo	0.11	Surfaces covered with a gray-black film.
27	5 Mo	3.40	" " " " " "

Table II.
Zirconium Alloys - Hydrochloric Acid Under Pressure (Cont.)

Alloy No.	Composition (percent by weight)	Corrosion Rate (mils per year)	Observations
WA-1850	10 Mo	6.35	Surfaces covered with very thin, iridescent, varicolored film.
31	10 Mo	4.61	" " " " " "
42	3 Sb	285	Badly embrittled and easily broken in the hand.
43	3 Sb	92.0	" " " " " "
50	1 Fe	1.69	No visible signs of corrosion.
51	1 Fe	1.11	" " " " " "
62	1 Cu	4.13	" " " " " "
63	1 Cu	4.30	" " " " " "
82	1 Mn	0.53	" " " " " "
83	1 Mn	0.69	" " " " " "
86	3 Mn	0.53	" " " " " "
87	3 Mn	0.70	Sample snapped in two on bending by hand (?embrittled?)
90	5 Mn	1.59	No visible signs of corrosion.
91	5 Mn	1.70	" " " " " "
94	10 Mn	1.43	" " " " " "
95	10 Mn	3.35	" " " " " "
1918	5 Ta	0.42	" " " " " "
19	5 Ta	3.77	Surfaces covered with a gray film (some evidence of embrittlement).
22	10 Ta	0.52	Surfaces covered with a gray-black film.
23	10 Ta	0.85	No visible signs of corrosion but some evidence of embrittlement.
34	15 Ta	0.26	Surfaces colored a smoky amber.
35	15 Ta	0.42	" " " " " "
1914	1 Ce	0.53	No visible signs of corrosion.
WA-1915	1 Ce	0.48	" " " " " "

Specimen configuration - 1" x 0.5" x 0.040" (approx.)
All tests were run at 100°C unless otherwise stated.
Samples run at 60°C.

Table III. Zirconium-Titanium Alloys - Inorganic Acids

Solution Percent by Weight	Temp. °C	Corrosion Rate - mils per year					
		1346	1372	1373	1375	Ti	Zr
5 HCl	35	0.00	0.02	0.00	0.00	1.46	0.00
10 HCl	35	0.02	0.18	0.19	0.53	40.1	0.26
12.5 HCl	35	0.19	0.14	0.33	0.97	59.5	-
15 HCl	35	0.13	0.09	0.37	1.10	96.7	0.30
17.5 HCl	35	0.13	0.30	0.36	20.1	122	-
20 HCl	35	0.03	0.23	0.48	14.2	175	0.28
37.5 HCl	35	1.41	126	904 ₃ /	2640 ₃ /	1990	0.32
5 HCl	60	0.19	0.39	0.61	1.23	42.5	0.06
10 HCl	60	0.20	0.41	1.32	12.6	351	0.41
15 HCl	60	0.17	0.44	1.66	16.9	789	0.37
17.5 HCl	60	0.26	1.18	8.36	94.3	-	-
20 HCl	60	0.00	0.94	48.8	156	1098	0.52
37.5 HCl	60	4.17	-	-	-	-	-
10 H ₂ SO ₄	35	0.05	0.12	0.30	0.63	66.0	0.05
20 H ₂ SO ₄	35	0.16	0.30	0.67	1.07	135.0	0.08
30 H ₂ SO ₄	35	0.23	0.35	0.70	6.91	268	0.34
40 H ₂ SO ₄	35	0.24	0.54	1.44	34.9	456	0.41
50 H ₂ SO ₄	35	0.34	0.78	5.47	138	133	0.37
60 H ₂ SO ₄	35	0.23	10.1	63.7	61.7	43.4	0.42
70 H ₂ SO ₄	35	18.6	238	199	2365 ₁ /	49.8	0.34
80 H ₂ SO ₄	35	898 ₁ /	2410 ₁ /	682 ₁ /	2590 ₁ /	1760	56.3
90 H ₂ SO ₄	35	6085 ₂ /	3693 ₃ /	2275 ₃ /	1395 ₃ /	574	1620
96.5 H ₂ SO ₄	35	3710 ₂ /	1323 ₃ /	900 ₃ /	535 ₃ /	270	752
10 H ₂ SO ₄	60	0.06	0.54	1.23	18.8	-	-
20 H ₂ SO ₄	60	0.09	0.68	2.29	50.0	-	-
30 H ₂ SO ₄	60	0.16	1.11	11.7	64.4	-	-
40 H ₂ SO ₄	60	0.29	2.03	20.2	336	-	-
50 H ₂ SO ₄	60	0.29	11.0	74.7	-	-	-
60 H ₂ SO ₄	60	0.81	142	-	-	-	-
70 H ₂ SO ₄	60	148	-	-	-	-	0.52
10 H ₃ PO ₄	35	0.19	0.36	0.42	0.69	0.30	0.05
20 H ₃ PO ₄	35	0.38	0.79	0.99	1.50	0.60	0.23
30 H ₃ PO ₄	35	0.54	1.15	1.60	1.95	0.77	0.37
40 H ₃ PO ₄	35	0.60	1.75	2.75	3.33	13.4	0.44

Tests were run for six days unless otherwise indicated and aerated at the rate of 250 ml. of air per minute. All tests in 37.5% HCl were non-aerated and static.

1/ Three day run

2/ One day run

3/ Two day run

Alloy No. *	Percent Ti	Percent C	Specimen Configuration
1346	20.6	0.20	1" x 1" x 0.041"
1372	35.4	0.37	1" x 1" x 0.054"
1373	45.1	0.56	1" x 1" x 0.053"
1375	85.4	0.78	1" x 1" x 0.049"

*Note: These alloys were prepared by induction melting in graphite and sheath rolling at 850°C. They were then sand-blasted and pickled.

Table IV
Zirconium Alloys - Substitute Ocean Water Spray Test

Alloy Number	Composition (percent by weight)	Weight of sample in grams	Loss or gain (+) in weight (grams)
WA-1721	1 Ag	3.5858	0.0000
22	1 Ag	3.5471	+0.0001
25	3 Ag	3.4578	0.0001
26	3 Ag	3.1400	+0.0001
29	5 Ag	3.2735	+0.0001
30	5 Ag	2.8717	0.0000
33	10 Ag	2.2046	+0.0001
34	10 Ag	3.5996	0.0000
43	1 Ni	3.7539	0.0002
44	1 Ni	1.2681	0.0001
47	1 Al	3.3618	0.0001
48	1 Al	3.2912	0.0001
51	2 Al	3.1216	0.0004
52	2 Al	3.1755	0.0005
55	3 Al	3.4237	0.0002
56	3 Al	2.8055	0.0002
60	1 Si	3.4547	0.0006
61	1 Si	3.4299	0.0003
64	2 Si	1.2544	+0.0002
65	2 Si	2.9955	0.0002
68	3 Si	2.7997	0.0001
69	3 Si	3.6061	0.0003
72	3 Ni	3.5343	0.0001
73	3 Ni	1.9816	0.0003
81	5 Ni	2.6320	0.0002
82	5 Ni	1.7787	0.0002
85	8 Ni	3.0107	0.0002
86	8 Ni	1.4110	0.0002
1805	1 W	3.1376	0.0001
08	1 W	3.4427	0.0003
09	5 W	3.1610	0.0001
10	5 W	3.3389	0.0001
14	10 W	3.3030	0.0004
15	10 W	3.6060	0.0002
18	1 Mo	3.7963	0.0000
19	1 Mo	3.1625	0.0001
22	3 Mo	3.2276	0.0001
23	3 Mo	2.2982	0.0002
26	5 Mo	3.0253	0.0000
27	5 Mo	2.5291	0.0002
30	10 Mo	3.3111	0.0000
31	10 Mo	2.9448	0.0000
37	1 Sb	3.0968	0.0001
42	3 Sb	2.8890	0.0000
43	3 Sb	2.9543	0.0000
46	5 Sb	2.9413	0.0000
47	5 Sb	2.4781	0.0001
50	1 Fe	3.2054	+0.0001
51	1 Fe	3.3141	0.0001
54	3 Fe	3.5249	0.0000
55	3 Fe	3.1801	0.0002

Table IV
Zirconium Alloys - Substitute Ocean Water Spray Test (Cont.)

Alloy Number	Composition (percent by weight)	Weight of sample in grams	Loss or gain (+) in weight (grams)
WA-1858	5 Fe	2.8143	0.0000
59	5 Fe	1.4508	0.0000
62	1 Cu	3.2496	0.0002
63	1 Cu	1.2616	0.0001
66	3 Cu	3.0353	0.0003
67	3 Cu	1.4955	0.0001
70	5 Cu	4.2907	0.0003
71	5 Cu	1.3382	0.0002
74	7 Cu	3.4818	0.0044
75	7 Cu	1.3533	0.0002
78	10 Cu	3.3117	0.0039
79	10 Cu	1.1560	0.0026
82	1 Mn	3.5793	0.0002
83	1 Mn	2.9714	0.0002
86	3 Mn	2.8284	0.0002
87	3 Mn	3.8278	0.0002
90	5 Mn	2.6268	0.0000
91	5 Mn	3.2054	0.0000
94	10 Mn	3.0132	0.0003
95	10 Mn	3.3373	0.0000
98	1 Co	2.9247	0.0003
99	1 Co	3.5480	0.0004
1902	3 Co	2.7621	0.0002
03	3 Co	3.2252	0.0003
06	5 Co	2.8843	0.0005
07	5 Co	3.8434	0.0005
10	7 Co	2.7379	0.0004
11	7 Co	3.1878	0.0006
18	5 Ta	2.8465	0.0006
19	5 Ta	2.6489	0.0004
22	10 Ta	3.0195	0.0002
23	10 Ta	3.4392	0.0002
34	15 Ta	2.7163	0.0002
35	15 Ta	2.3616	0.0003
1914	1 Ce	3.4245	0.0003
15	1 Ce	3.1938	0.0005
26	2 Ce	1.7791	0.0006
27	2 Ce	2.0566	0.0006
30	3 Ce	2.0173	0.0003
31	3 Ce	2.3386	0.0005

Table IV
Zirconium Alloys - Substitute Ocean Water Spray Test (Cont.)

Alloy Number	Composition (percent by weight)	Weight of sample in grams	Loss or gain (+) in weight (grams)
WA-2054	1 Cr	3.2532	0.0005
55	1 Cr	2.7227	0.0005
58	2 Cr	2.4276	0.0003
59	2 Cr	1.9428	0.0002
64	5 Cr	2.8507	0.0006
65	5 Cr	3.3000	0.0015
89	8 Cr	3.1458	0.0003
90	8 Cr	3.5179	0.0002
93	1 Be	2.3345	0.0004
94	1 Be	2.2836	0.0003
97	2 Be	3.0682	0.0002
WA-2098	2 Be	2.7644	0.0003

Specimen configuration - 1"x0.5"x0.040" (approx.)
 Samples were run at room temperature for 30 days.

Table V. Zirconium Alloys - Red Fuming Nitric Acid

Alloy Number	Composition (percent by wgt.)	Wgt. of samples in grams	Loss or gain (+) in wgt.	Observations
WA 1721	1 Ag	1.9246	+0.0069	Sample covered with thin, blue-black film.
22	1 Ag	1.7714	+0.0375	" " " " " " " "
25	3 Ag	1.6923	+0.0007	" " " " " " " "
26	3 Ag	1.7616	+0.0103	" " " " " " " "
29	5 Ag	1.9769	+0.0008	" " " " " " " "
30	5 Ag	1.7469	+0.0071	" " " " " " " "
33	10 Ag	1.8411	+0.0052	" " " " " " " "
34	10 Ag	2.0970	+0.0107	" " " " " " " "
43	1 Ni	1.4927	+0.0173	" " " " " " " "
44	1 Ni	1.6833	+0.0102	" " " " " " " "
47	1 Al	2.0340	+0.0052	" " " " " " " "
48	1 Al	1.6956	+0.0111	" " " " " " " "
51	2 Al	2.0342	+0.0055	" " " " " " " "
52	2 Al	1.9196	+0.0037	" " " " " " " "
55	3 Al	1.3223	+0.0007	" " " " " " " "
56	3 Al	2.0136	+0.0026	" " " " " " " "
60	1 Si	1.4063	0.0329	" " " " " " " "
61	1 Si	1.1902	0.0506	Sample covered with a scaly, blue-black film.
64	2 Si	1.7683	+0.0010	" " " " " " " "
65	2 Si	1.2796	+0.0032	" " " " " " " "
68	3 Si	1.3719	+0.0023	" " " " " " " "
69	3 Si	1.2642	0.0537	Similar to 1768, but showed several embrittlement cracks.
72	3 Ni	1.5072	+0.0359	Sample covered with thin, blue-black film.
73	3 Ni	2.6373	+0.1039	Similar to 1772, but was severely embrittled.
81	5 Ni	2.4053	0.0092	Sample covered with a scaly, blue-black film.
82	5 Ni	1.8155	0.0830	Similar to 1781, but was severely embrittled.
85	8 Ni	1.5294	+0.0068	Sample covered with thin, blue-black film.
86	8 Ni	1.3264	+0.0103	" " " " " " " "
1805	1 W	1.4589	+0.0066	Sample covered with a scaly, blue-black film.
06	1 W	1.6382	+0.0073	" " " " " " " "
09	5 W	1.8649	+0.0285	" " " " " " " "
10	5 W	1.2863	+0.0160	" " " " " " " "

Table V. Zirconium Alloys - Red Fuming Nitric Acid (Cont.)

Alloy Number	Composition (percent by wgt.)	Wgt. of samples in grams	Loss or gain (+) in wgt.	Observations
WA-1814	10 W	1.5550	+0.0170	Similar to 1782.
15	10 W	1.3738	+0.0178	Sample covered with a scaly, blue-black film.
18	1 Mo	1.5799	+0.0078	Sample covered with thin, blue-black film.
19	1 Mo	2.1173	+0.0364	" " " "
22	3 Mo	1.6362	0.0032	Surfaces half covered with thin, blue-black film.
23	3 Mo	1.8312	0.0006	" " " "
26	5 Mo	1.5162	+0.0036	" " " "
27	5 Mo	1.8510	+0.0019	" " " "
30	10 Mo	1.1080	0.0003	Sample covered with very pale, amber-colored film.
31	10 Mo	1.6071	0.0008	" " " "
37	1 Sb	1.5796	+0.0039	Sample covered with thin, blue-black film.
42	3 Sb	1.7533	+0.0078	" " " "
43	3 Sb	1.1123	+0.0009	" " " "
46	5 Sb	1.0937	+0.0040	" " " "
47	5 Sb	1.4245	+0.0022	" " " "
50	1 Fe	1.6633	+0.0196	" " " "
51	1 Fe	1.6970	+0.0270	" " " "
54	3 Fe	0.9264	+0.0004	Surfaces half covered with thin, blue-black film.
55	3 Fe	1.7.67	+0.0022	" " " "
58	5 Fe	1.4732	+0.0159	" " " "
59	5 Fe	1.4510	+0.0047	" " " "
62	1 Cu	1.5248	+0.0070	Sample covered with thin, blue-black film.
63	1 Cu	1.5607	+0.0113	" " " "
66	3 Cu	1.0479	+0.0246	" " " "
67	3 Cu	1.2500	+0.0044	" " " "
70	5 Cu	1.2038	+0.0098	" " " "
71	5 Cu	1.5346	+0.0015	" " " "
74	7 Cu	1.5884	+0.0039	" " " "
75	7 Cu	1.3812	+0.0035	" " " "
78	10 Cu	1.2706	+0.0011	" " " "
79	10 Cu	1.1261	+0.0039	" " " "
1882	1 Mn	1.8770	+0.0136	Sample covered with thin, blue black film.

Table V. Zirconium Alloys - Red Fuming Nitric Acid (Cont.)

Alloy Number	Composition (percent by wgt.)	Wgt. of samples in grams	Loss or gain (+) in wgt.	Observations
1883	1 Mn	1.3192	+0.0021	Sample covered with thin, blue-black film.
86	3 Mn	1.4582	+0.0018	" " " " " "
87	3 Mn	1.4334	+0.0053	" " " " " "
90	5 Mn	1.5099	+0.0033	" " " " " "
91	5 Mn	0.9352	+0.0011	" " " " " "
94	10 Mn	1.6289	+0.0060	" " " " " "
95	10 Mn	1.6335	+0.0033	" " " " " "
98	1 Co	2.2670	+0.0067	" " " " " "
99	1 Co	1.6618	+0.0220	" " " " " "
1902	3 Co	1.5728	+0.0036	" " " " " "
03	3 Co	2.0162	+0.0028	" " " " " "
06	5 Co	1.7156	+0.0039	Sample covered with gray-black film.
07	5 Co	2.0372	0.0245	Sample covered with flaky, gray-black film. #
10	7 Co	1.6860	0.3020	Sample covered with gray-black film. #
11	7 Co	1.3175	+0.0066	Sample covered with thin, blue-black film.
18	5 Ta	1.5653	+0.0002	Sample covered with very thin, amber-colored film.
19	5 Ta	1.3870	0.0000	Sample covered with very thin, iridescent-colored film.
22	10 Ta	1.6760	+0.0001	Sample covered with very thin, iridescent-colored film.
23	10 Ta	1.3344	+0.0002	Sample covered with very thin, iridescent-colored film.
34	15 Ta	1.3223	0.0000	Sample covered with very thin, iridescent-colored film.
35	15 Ta	1.1701	0.0001	Sample " " " " " "
14	1 Ce	1.5983	+0.0058	Sample covered with thin, blue-black film.
15	1 Ce	1.8798	+0.0069	" " " " " "
26	2 Ce	1.0048	+0.0038	" " " " " "
27	2 Ce	1.6147	+0.0007	" " " " " "
30	3 Ce	1.6617	+0.0094	" " " " " "
1931	3 Ce	1.8637	+0.0146	" " " " " "

Specimen configuration - 1" x 0.5" x 0.040" (approx.)

Samples were run at room temperature for 30 days, non-aerated and static.

Sample showed embrittlement cracks.

Table VI. Zirconium Alloys - Mixed Acid

Alloy Number	Composition (percent by wgt.)	Rate (mils per yr.)	Observations
WA-1721	1 Ag	1.06	Samples covered with a thin, very hard, dark gray film.
22	1 Ag	1.42	" " " " " " " "
25	3 Ag	0.64	" " " " " " " "
26	3 Ag	0.87	" " " " " " " "
29	5 Ag	1.16	" " " " " " " "
30	5 Ag	1.89	Samples covered with a thin, very hard, light gray film.
33	10 Ag	1.64	" " " " " " " "
34	10 Ag	3.05	" " " " " " " "
43	1 Ni	0.84	Samples covered with thin, hard, gray-black film.
44	1 Ni	0.77	" " " " " " " "
47	1 Al	-	Samples were completely disintegrated.
48	1 Al	-	" " " " " " " "
51	2 Al	-	" " " " " " " "
52	2 Al	-	" " " " " " " "
55	3 Al	-	" " " " " " " "
56	3 Al	-	" " " " " " " "
60	1 Si	3.15	Samples covered with thin, hard, light gray film.
61	1 Si	2.82	" " " " " " " "
64	2 Si	3.24	Samples covered with thick, hard, gray-white film.
65	2 Si	4.25	" " " " " " " "
68	3 Si	4.04	" " " " " " " "
69	3 Si	4.55	" " " " " " " "
72	3 Ni	10.0	Samples covered with thin, relatively soft, dark-gray film.
73	3 Ni	13.9	" " " " " " " "
81	5 Ni	21.8	" " " " " " " "
82	5 Ni	28.3	" " " " " " " "
85	8 Ni	39.5	" " " " " " " "
86	8 Ni	48.0	" " " " " " " "
1805	1 W	0.99	Samples covered with thin, hard, gray-black film.
06	1 W	6.38	" " " " " " " "
09	5 W	2.48	" " " " " " " "

Table VI. Zirconium Alloys - Mixed Acid (Cont.)

Alloy Number	Composition (percent by wgt.)	Rate (mils per yr.)	Observations
WA-1810	5 W	1.45	Samples covered with thin, hard, gray-black film.
14	10 W	0.82	" " " " " " " "
15	10 W	1.07	" " " " " " " "
18	1 Mo	2.25	Sample covered with thin, very hard, dark gray film with greenish cast.
19	1 Mo	2.10	" " " " " " " "
22	3 Mo	3.33	Sample covered with thick, very hard, dark green film.
23	3 Mo	4.70	" " " " " " " "
26	5 Mo	17.5	" " " " " " " "
27	5 Mo	20.3	" " " " " " " "
30	10 Mo	64.9	" " " " " " " "
31	10 Mo	66.9	" " " " " " " "
37	1 Sb	1.67	Sample covered with thin, very hard, dark gray film.
42	3 Sb	2.63	Sample covered with thin, very hard, light gray film.
43	3 Sb	2.65	" " " " " " " "
46	5 Sb	4.40	Sample covered with thin, very hard, cream-colored film.
47	5 Sb	4.40	" " " " " " " "
50	1 Fe	1.54	Sample covered with thin, very hard, light gray film.
51	1 Fe	1.60	" " " " " " " "
54	3 Fe	1.67	" " " " " " " "
55	3 Fe	2.06	" " " " " " " "
58	5 Fe	2.23	" " " " " " " "
59	5 Fe	3.66	" " " " " " " "
62	1 Cu	0.94	Samples covered with thin, hard, dark gray film.
63	1 Cu	1.28	" " " " " " " "
66	3 Cu	1.09	" " " " " " " "
67	3 Cu	1.78	" " " " " " " "
70	5 Cu	0.73	" " " " " " " "
71	5 Cu	1.16	" " " " " " " "
74	7 Cu	0.87	" " " " " " " "
75	7 Cu	1.25	" " " " " " " "
78	10 Cu	2.60	" " " " " " " "
79	10 Cu	1.29	" " " " " " " "

Table VI. Zirconium Alloys - Mixed Acid (Cont.)

Alloy Number	Composition (percent by wgt.)	Rate (mils per yr.)	Observations
WA-1882	1 Mn	-	Samples were completely disintegrated.
83	1 Mn	-	" " " " " "
86	3 Mn	-	" " " " " "
87	3 Mn	-	" " " " " "
90	5 Mn	-	" " " " " "
91	5 Mn	-	" " " " " "
94	10 Mn	61.0	Sample corroded to light gray, pickled finish. No film present.
95	10 Mn	54.1	" " " " " "
98	1 Co	-	Samples were completely disintegrated.
99	1 Co	-	" " " " " "
1902	3 Co	70.9	Sample corroded to light gray, pickled finish. No film present.
03	3 Co	72.4	" " " " " "
06	5 Co	61.0	" " " " " "
07	5 Co	62.4	" " " " " "
10	7 Co	59.6	" " " " " "
11	7 Co	53.1	" " " " " "
18	5 Ta	-	Samples were completely disintegrated.
19	5 Ta	-	" " " " " "
22	10 Ta	-	" " " " " "
23	10 Ta	-	" " " " " "
34	15 Ta	-	" " " " " "
35	15 Ta	-	" " " " " "
14	1 Ce	-	" " " " " "
15	1 Ce	-	" " " " " "
26	2 Ce	91.5	Sample corroded to rough, pickled finish. No film formation.
27	2 Ce	-	Sample was completely disintegrated.
30	3 Ce	86.1	Sample corroded to rough, pickled finish. No film formation.
31	3 Ce	62.1	" " " " " "
2054	1 Cr	1.30	Samples covered with thin, hard, gray-black film.
55	1 Cr	1.13	" " " " " "
58	2 Cr	0.72	" " " " " "
59	2 Cr	0.98	" " " " " "

Table VI. Zirconium Alloys - Mixed Acid (Cont.)

Alloy Number	Composition (percent by wgt.)	Rate (mils per yr.)	Observations
WA-2064	5 Cr	1.11	Samples covered with thin, hard, gray-black film.
65	5 Cr	2.16	" " " " " "
89	8 Cr	12.4	Samples covered with flaky, gray-black film.
90	8 Cr	8.34	" " " " " "
93	1 Be	27.2	Sample corroded to a gray, pickled finish. No film formation.
94	1 Be	17.2	Large areas of sample covered with a hard, gray film.
97	2 Be	45.0	Sample corroded to a gray, pickled finish. No film formation.
98	2 Be	28.7	" " " " " "

Specimen configuration - 1" x 0.5" x 0.040" (approx.)

Samples were run at room temperature for 30 days, non-aerated and static.

Tab VII
Zirconium Alloys - Nitric Acid

Alloy Number	Composition (percent by weight)	Weight of sample in grams	Loss or Gain (+) in wt. (grams)	Observations
27	50 Ti	27.5249	0.0015	Sample partly covered with bright blue, very thin film.
31	5 Ti-15 Cr	34.6285	0.0043	Segregated crystals covered with black film; Zr matrix unaffected.
32	5 Ti-15 Ta	18.0348	0.0002	No visible signs of corrosion.
33	5 Ti	19.1315	0.0005	" " " "
42	5 Al	14.8923	0.0020	Similar to sample 31.
46	5 Al	8.8327	+0.0001	" " " "
47	5 Be	20.6603	3.1387	Sample covered with hard, thick, black coating.
48	5 Pt	20.4014	3.0696	" " " "
49	5 V	17.0848	0.1632	Sample covered with very thin, very adherent, gray coating.
50	5 Si	10.3843	0.0728	" " " "
51	1 Al	9.4476	0.0008	No visible signs of corrosion.
52	100 Zr	9.8024	+0.0008	" " " "
53	2.25 O ₂	12.9503	0.0018	" " " "
54	10 Ta	13.6722	0.0000	" " " "
55	20 Ta	5.8427	+0.0001	" " " "
56	5 Cb	13.1115	0.0008	Sample covered with very thin, tightly adhering, black film.
121	65 Ti	7.2425	0.0022	Sample covered with bright amber and blue-colored film.
168	2 Al	15.8829	0.0006	Sample showed large, stringer-like areas with black surfaces; Zr matrix unaffected.
169	4 Al	13.5314	+0.0005	" " " "
170	6 Al	25.6365	+0.0003	" " " "
180	3 Al	20.6680	0.0052	Similar to sample 56.
181	5 Al	13.9623	0.0028	" " " "
196	27.5 Cb	1.7514	0.0312	Sample covered with thick, sealy, black film.
320	2.5 Ni	1.6166	+0.0002	Sample covered with mottled, thin, tightly-adhering, black film.
321	2.5 Nb	2.4840	+0.0068	" " " "
324	1 W	2.8091	+0.0053	" " " "
325	1 Ni	3.5875	+0.0044	" " " "
328	10 W	4.0938	0.0000	No visible signs of corrosion.
329	10 Ni	3.2020	0.0004	" " " "
408	1 Si	37.0527	0.0008	" " " "
409	0.5 B	47.1956	0.0180	" " " "
414	0.25 Si	24.1018	0.0006	" " " "
420	0.5 Fe	24.9448	0.0000	" " " "
421	1 Fe	20.4862	+0.0010	Sample covered with very thin, dark gray film.

Table VII.
Zirconium Alloys - Fuming Nitric Acid (Cont.)

Alloy No.	Composition (percent by weight)	Weight of sample in grams	Loss or gain (+) in wgt. (grams)	Observations
423	1 Be	21.2284	0.3627	Sample showed a large pitted and blistered area on one side.
424	1 B	16.4370	0.0113	No visible signs of corrosion.
425	0.5 V	23.6854	0.0004	" " " "
426	1 V	20.5616	0.0006	" " " "
427	0.5 Cr	13.0947	0.0005	" " " "
428	1 Cr	18.6539	0.0004	" " " "
429	0.5 Mn	18.1082	0.0005	" " " "
430	1 Mn	20.3332	+0.0003	Similar to sample 421.

Notes:

- (1) Compositions listed are intended compositions. Actual compositions may vary somewhat from those listed.
- (2) Alloys numbered 27-196 were prepared in graphite crucibles (induction melted). Alloys numbered 320-430 were prepared in water cooled copper crucibles (arc melted in inert atmosphere).
- (3) Samples were run at room temperature for thirty days, non-aerated and static.

Table VIII.
Arc Melted Zirconium - Aqua Regia

Sample Number	Rate (M.d.d.) ¹	Rate (M.p.y.) ²
1109	392	86.5
1110	1025	226
1300	1420	313
1306	1640	362
1313	1570	346
1330	1550	342
1401	1810	399
1413	1730	382

¹M.d.d. - Milligrams per square decimeter per day.

²M.p.y. - Mils per year

Specimen configuration - 1/2" x 2" x 0.040".

Note: Samples 1109 and 1110 are hot rolled metal, the remainder are cold rolled.

Table IX.
Titanium, Zirconium, Stainless Steel,
and Lead - Inorganic Compounds

Test solution (percent by weight)	Temp. °C	Average corrosion rate, 6-day run, mils per year			
		Ti	Zr	20 S.S.	Pb
1 NH ₄ Cl	60	0.00	0.05	0.06	
10 NH ₄ Cl	60	0.00	0.03	0.08	
1 NH ₄ Cl	100	0.00	0.13	0.01	
10 NH ₄ Cl	100	0.01	0.19	0.01	
5 H ₂ SO ₄	60	190			
5 Na ₂ PO ₄	60	0.09			
20 Na ₂ PO ₄	60	0.01			
2 Ca(ClO) ₂	60	0.00			
60 H ₂ SO ₄ + 1 HNO ₃	100	129			2.13
65 H ₂ SO ₄ + 1 HNO ₃	100	323			2.25
70 H ₂ SO ₄ + 1 HNO ₃	100	1190			4.81

Titanium - 1"x1"x0.060"
Specimen configuration - Zirconium - 1" x 1" x 0.040"
Stainless Steel - 1" x 1" x 0.082"

Table X.
Titanium - Metal Couples in Synthetic Sea Water

Metal	Duration of test (Hours)	Aeration	Av. corrosion rate (mils per year)			Ratio Coupled Uncoupled
			Coupled	Uncoupled	Difference*	
Magnesium	64	Non-aerated	1990	0.00#	1990	∞
Magnesium	144	Air-aerated	926	0.00#	926	∞
Magnesium	120	Helium-aerated	575	0.00#	575	∞
Zinc	720	Non-aerated	3.48	18.2	-	0.19
Zinc	240	Air-aerated	12.6	2.6	10.0	4.84
Zinc	240	Helium-aerated	5.09	0.00	5.09	∞
Aluminum	744	Non-aerated	0.05	0.05	0.00	1.00
Aluminum	240	Air-aerated	0.00	0.00	0.00	-
Aluminum	240	Helium-aerated	1.56	0.00	1.56	∞
Lead	240	Non-aerated	0.23	0.16	0.07	1.44
Lead	240	Air-aerated	0.65	0.69	-	0.94
Lead	240	Helium-aerated	2.08	0.12	1.96	17.5
Tin	720	Non-aerated	0.19	0.00	0.19	∞
Tin	240	Air-aerated	0.26	0.04	0.22	6.50
Tin	240	Helium-aerated	1.30	0.00	1.30	∞
Nickel	720	Non-aerated	0.03	0.01	0.02	3.00
Nickel	240	Air-aerated	0.01	0.02	-	0.50
Nickel	240	Helium-aerated	0.07	0.05	0.02	1.40
Copper	744	Non-aerated	0.96	0.69	0.27	1.59
Copper	240	Air-aerated	2.95	2.95	0.00	1.00
Copper	240	Helium-aerated	1.08	1.21	-	0.89

* Corrosion caused by galvanic action alone.

Increase in weight caused by film formation.

Tests were all run at room temperature.

Specimen configuration - 1/2" x 6" x (0.040" - 0.060")

Table XI.
Titanium - Metal Couples in 1% Hydrochloric Acid

Metal	Duration of test (Hours)	Aeration	Av. Corrosion Rate (Mils per year)			Ratio
			Coupled	Uncoupled	Difference*	<u>Coupled</u> Uncoupled
Magnesium	18.5	Non-aerated	7060	4790	2270	1.47
Magnesium	42.5	Air-aerated	3080	2070	1010	1.49
Magnesium	15.5	Helium-aerated	7350	5750	1600	1.28
Zinc	21.5	Non-aerated	4060	701	3359	5.79
Zinc	240	Air-aerated	327	206	121	1.59
Zinc	240	Helium-aerated	345	280	65	1.23
Aluminum	720	Non-aerated	126	59.8	66.2	2.11
Aluminum	240	Air-aerated	418	233	185	1.80
Aluminum	240	Helium-aerated	292	190	102	1.54
Lead	240	Non-aerated	50.4	19.6	10.8	1.55
Lead	240	Air-aerated	73.7	42.1	31.6	1.75
Lead	240	Helium-aerated	38.5	25.1	13.4	1.53
Tin	720	Non-aerated	19.4	20.4	-	0.95
Tin	74	Air-aerated	309	195	114	1.58
Tin	240	Helium-aerated	72.1	58.7	13.4	1.23
Nickel	720	Non-aerated	9.36	8.86	0.50	1.06
Nickel	240	Air-aerated	34.5	40.8	-	0.85
Nickel	240	Helium-aerated	10.1	9.0	1.1	1.12
Copper	720	Non-aerated	116	51.7	64.3	2.25
Copper	117	Air-aerated	872	560	312	1.56
Copper	240	Helium-aerated	234	142	92	1.65

*Corrosion caused by galvanic action alone.

Tests were all run at room temperature.

Specimen configuration - 1/2" x 6" x (0.040" - 0.060")

Table XII.
Titanium - Metal Couples in 1% Sodium Hydroxide

Metal	Duration of test (Hours)	Aeration	Av. Corrosion Rate (Mils per year)			Ratio $\frac{\text{Coupled}}{\text{Uncoupled}}$
			Coupled	Uncoupled	Difference*	
Magnesium	744	Non-aerated	0.27	0.00	0.27	-
Magnesium	480	Air-aerated	0.00	0.00	0.00	-
Magnesium	240	Helium-aerated	0.00	0.00	0.00	-
Zinc	720	Non-aerated	0.00#	0.00#	0.00	-
Zinc	480	Air-aerated	3.88	3.47	0.41	1.12
Zinc	240	Helium-aerated	12.4	12.5	-	0.99
Aluminum	49	Non-aerated	2230	2450-	-	0.91
Aluminum	42	Air-aerated	2870	3270	-	0.88
Aluminum	72	Helium-aerated	1910	1810	100	1.05
Lead	240	Non-aerated	24.0	22.0	2.00	1.09
Lead	240	Air-aerated	92.3	98.7	-	0.93
Lead	240	Helium-aerated	21.2	15.1	6.1	1.40
Tin	480	Non-aerated	30.4	16.9	13.5	1.80
Tin	91	Air-aerated	54.2	80.0	-	0.68
Tin	240	Helium-aerated	36.2	17.7	18.5	2.04
Nickel	744	Non-aerated	0.01	0.01	0.00	1.00
Nickel	480	Air-aerated	0.01	0.01	0.00	1.00
Nickel	240	Helium-aerated	0.08	0.07	0.01	1.14
Copper	720	Non-aerated	0.98	0.83	0.15	1.18
Copper	240	Air-aerated	0.00	0.00	0.00	-
Copper	240	Helium-aerated	0.00	0.00	0.00	-

* Corrosion caused by galvanic action alone.

Increase in weight caused by film formation.

Tests were all run at room temperature.

Specimen configuration - 1/2" x 6" x (0.040" - 0.060")

Table XIII. Solution Potential of Metals in Synthetic Ocean Water

Metal	Duration of Test	Aeration	Corrosion Rate (m.p.y.)	Initial EMF(volts)	Average EMF(volts)
Magnesium	408 hrs.	Non-aerated	4.48	-1.36	-1.36
Magnesium	408 hrs.	Air-aerated	89.0	-1.38	-1.35
Magnesium	408 hrs.	Helium-aerated	31.3	-1.35	-1.36
Zinc	744 hrs.	Non-aerated	1.19	-0.796	-0.788
Zinc	744 hrs.	Air-aerated	5.90	-0.786	-0.796
Zinc	744 hrs.	Helium-aerated	1.10	-0.804	-0.789
Aluminum	528 hrs.	Non-aerated	0.00	-0.481	-0.692
Aluminum	528 hrs.	Air-aerated	1.31	-0.486	-0.619
Aluminum	528 hrs.	Helium-aerated	0.00	-0.491	-0.659
Tin	528 hrs.	Non-aerated	0.00	-0.287	-0.257
Tin	744 hrs.	Air-aerated	0.09	-0.329	-0.251
Tin	744 hrs.	Helium-aerated	0.02	-0.305	-0.298
Lead	528 hrs.	Non-aerated	0.44	-0.350	-0.236
Lead	528 hrs.	Air-aerated	0.83	-0.349	-0.237
Lead	528 hrs.	Helium-aerated	0.55	-0.361	-0.243
Copper	528 hrs.	Non-aerated	1.66	+0.054	+0.096
Copper	528 hrs.	Air-aerated	3.20	+0.004	0.000
Copper	528 hrs.	Helium-aerated	0.80	+0.009	+0.004
Nickel	744 hrs.	Non-aerated	0.00	-0.025	+0.179
Nickel	744 hrs.	Air-aerated	0.00	-0.028	+0.082
Nickel	744 hrs.	Helium-aerated	0.00	-0.067	+0.147
Titanium	744 hrs.	Non-aerated	0.02	-0.191	+0.180
Titanium	744 hrs.	Air-aerated	0.00	-0.205	+0.140
Titanium	744 hrs.	Helium-aerated	0.00	-0.128	+0.054

Table XIV.
Titanium-Magnesium Couples in Synthetic Ocean Water

Metal	Aeration	Av. Corrosion Rate (mils per year)		Average Current (Milliamps)	Open Circuit Potential (Volts)		EMF Relative to Saturated Calomel Half-Cell				
		Coupled	Uncoupled		Initial	Final	Coupled Initial	Coupled Final	Uncoupled Initial	Uncoupled Final	
Magnesium	Non-aerated	895	22.4	-	-	-1.344	#	-1.344	-1.354	-	-
Titanium	Non-aerated	0.00	0.04	-	-	-0.171	-0.039	-0.203	+0.012	-	-
Ti-Mg Coupled	Non-aerated	-	-	24.5	1.240	1.002*	-	-	-	-	-
Ti-Mg Uncoupled	Non-aerated	-	-	-	1.148	1.366	-	-	-	-	-
Magnesium	Air-aerated	1190	58.7	-	-	-1.394	#	-1.404	-1.374	-	-
Titanium	Air-aerated	0.00	0.00	-	-	-0.120	-0.822	-0.119	+0.018	-	-
Ti-Mg Coupled	Air-aerated	-	-	21.5	1.331	0.4725*	-	-	-	-	-
Ti-Mg Un- Coupled	Air-aerated	-	-	-	1.299	1.448	-	-	-	-	-

Duration of tests: Non-aerated - 168 Hr.
Air-aerated - 120 Hr.

Final potential could not be measured due to disintegration of sample.

* Final potential could not be measured out last measurement before failure of sample is recorded.

Table XV.
Titanium - Tin Couples in Synthetic Ocean Water

Metal	Aeration	Av. Corrosion Rate (mils per year)		Average Current Milliamps	Open Circuit Potential (Volts)		EMF Relative to Sat. Cal. Half-Cell			
		Coupled	Uncoupled		Initial	Final	Coupled Initial	Coupled Final	Uncoupled Initial	Uncoupled Final
Tin	Non-aerated	1.47	1.39	-	-	-	-0.225	-0.227	-0.223	-0.262
Titanium Sn-Ti	Non-aerated	0.02	0.00	-	-	-	-0.048	0.077	-0.065	-0.172
Coupled Sn-Ti	Non-aerated	-	-	0	0.198	0.298	-	-	-	-
Uncoupled	Non-aerated	-	-	-	0.148	0.464	-	-	-	-
Tin	Air-aerated	0.68	0.46	-	-	-	-0.256	-0.211	-0.246	-0.235
Titanium Sn-Ti	Air-aerated	0.00	0.00	-	-	-	-0.080	0.069	-0.089	0.091
Coupled Sn-Ti	Air-aerated	-	-	0	0.180	0.275	-	-	-	-
Uncoupled	Air-aerated	-	-	-	0.174	0.328	-	-	-	-

Duration of Tests: 720 hours

* Positive value indicates titanium was positive member of couple.

Table XVI.
Titanium - Nickel Couples in Synthetic Ocean Water

Metal	Aeration	Av. Corrosion Rate (mils per year)		Average Current (Milliamps)	Open Circuit Potential (Volts)		EMF Relative to Saturated Calomel Half-Cell (Volts)			
		Coupled	Uncoupled		Initial	Final	Coupled Initial	Coupled Final	Uncoupled Initial	Uncoupled Final
Nickel	Non-aerated	0.11	0.12	-	-	-	0.015	0.171	0.016	0.104
Titanium	Non-aerated	0.03	0.01	-	-	-	-0.024	0.160	-0.048	0.201
Ni-Ti	Non-aerated	-	-	0	-0.063	0.001	-	-	-	-
Ni-Ti	Non-aerated	-	-	-	-0.069	0.122	-	-	-	-
Nickel	Air-aerated	0.14	0.11	-	-	-	0.004	0.114	0.004	0.090
Titanium	Air-aerated	0.00	0.00	-	-	-	-0.093	0.123	-0.117	0.021
Ni-Ti	Air-aerated	-	-	0	-0.110	-0.086	-	-	-	-
Ni-Ti	Air-aerated	-	-	-	-0.134	-0.007	-	-	-	-

Duration of Tests: 720 hours

* Positive value indicates titanium was positive member of couple. Negative value indicates nickel was positive member.

Table XVII. Titanium-Zinc Couples in Synthetic Ocean Water

Metal	Aeration	Av. Corrosion Rate (mils per year)		Average Current Milliamps	Open Circuit Potential (Volts)		EMF Relative to Sat. Cal. Half-Cell Coupled (Volts)			
		Coupled	Uncoupled		Initial	Final	Initial	Final	Initial	Final
Zinc	Non-aerated	9.11	1.27	-	-	-	-0.823	-0.821	-0.827	-0.792
Titanium	Non-aerated	0.00	0.00	-	-	-	-0.140	-0.519	-0.157	0.145
Zn-Ti	Non-aerated	-	-	0.3	0.699	0.527	-	-	-	-
Zn-Ti	Uncoupled	-	-	-	0.693	0.934	-	-	-	-
Zinc	Air-aerated	8.7	8.2	-	-	-	-0.803	-0.833	-0.808	-0.797
Titanium	Air-aerated	0.00	0.00	-	-	-	-0.152	-0.468	-0.161	0.038
Zn-Ti	Air-aerated	-	-	0.4	0.684	0.435	-	-	-	-
Coupled	Air-aerated	-	-	-	0.670	0.842	-	-	-	-
Zn-Ti	Uncoupled	-	-	-	-	-	-	-	-	-

Duration of Tests: 720 hours.