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UNITED STATES ATOMIC ENERGY COMMISSION

SCALING OF ZIRCONIUM AND ZIRCONIUM ALLOYS

Technical Progress Report No. 1

By

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A ECU-3661

First

TECHNICAL PROGRESS REPORT

SCALING OF ZIRCONIUM AND ZIRCONIUM ALLOYS

By

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R. E. Swift

Conducted By

DEPARTMENT OF MINING & METALLURGICAL ENGINEERING
UNIVERSITY OF KENTUCKY

In Cooperation With

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ABSTRACT

Zirconium-base binary alloys were prepared using the elements molybdenum, iron, cobalt, chromium, nickel, copper, silver, tantalum, columbium, platinum, palladium, osmium, iridium, rhodium, ruthenium, vanadium, silicon, manganese, tin, lead, tungsten, antimony, germanium, aluminum, titanium, magnesium, zinc, lanthanum, and barium. Also, zirconium-base ternary alloys were prepared using the elements copper, nickel, columbium, tantalum, vanadium, tin, antimony, and tungsten. The maximum total alloy content of the alloys was five per cent. The zirconium used was low-hafnium sponge, and the alloys were prepared by arc melting in an argon atmosphere.

The alloys were tested for scaling resistance at the temperatures 1200°, 1500°, and 1800°F in a multi-specimen furnace for periods up to about 300 hours. Scaling propensity of the alloys was evaluated on the basis of the weight increase per unit area as compared to that of unalloyed zirconium.

The binary alloys containing nickel and copper showed the greatest scaling resistance of all the binary alloys at all temperatures. Ternary Alloys showed little or no improvement over the most scaling resistant binary alloys.

The number of alloys more resistant than unalloyed zirconium was about the same at 1200° and 1500°F, but was considerably more at 1800°F.

In general, there was some change in the order of relative scaling propensity based on the average weight increase per average unit area per hour at the the three temperatures.

A logarithmic plot of weight increase versus time for most of the alloys showed a sharp increase in the scaling rate after various periods of time, whereas very few showed a decrease.

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I. INTRODUCTION

AECL-3561

This report covers research performed on Contract AT (33-3)-1, U. S. Atomic Energy Commission, for the period March 1956 to September 1957. The work was accomplished in the Department of Mining and Metallurgical Engineering of the University of Kentucky in cooperation with the Kentucky Research Foundation. Dr. L. R. Standifer, Chief of the Technical Branch of the U. S. Atomic Energy Commission, Lockland Branch, Cincinnati, Ohio, is the Technical Administrator for the contract.

With the advent of the field of atomic energy, research on the metal zirconium received considerable impetus due to certain attractive properties which it possesses. The most important of the properties pertaining to this field is a neutron-absorption cross section of 0.18 barns which is lower than that of most constructional metals. Another advantageous property of zirconium is its extreme stability at room temperature in the presence of air, oxygen, nitrogen, and most acids. However, at moderately elevated temperatures this stability decreases and zirconium will then react readily with oxygen and hydrogen and, at somewhat higher temperatures, with nitrogen.

Factors which suggest that zirconium might have good oxidation resistance at elevated temperatures are listed by Gulbransen and Andrew¹ as: "(1) the high melting point, 1852°C; (2) the high melting point of the oxide, approximately 2675°C; (3) the low volatility of the oxide; (4) the high degree of thermodynamic stability of the oxide and its low decomposition pressure; and (5) the possible formation of a continuous oxide film since the specific volume ratio of the oxide to the metal is greater than unity. Unfavorable factors are: (1) the metal reacts to form nitrides, hydrides, and carbides; (2) the oxide is soluble at elevated temperatures in the metal; and (3) the oxide ZrO_2 undergoes crystal-structure transformations at high temperatures."

Research has been conducted by several investigators on the high temperature scaling behavior of zirconium in various gases. Hayes and Roberson² report that in oxygen and air zirconium forms a blue-black scale which later turns to a white scale. In nitrogen a thin golden scale is formed on zirconium above 800°C. Belle and Mallett³ and Gulbransen and Andrew¹ report the scale formed in oxygen to be monoclinic ZrO_2 whereas Cubicciotti⁴ found the scale to be a mixture of both monoclinic and tetragonal ZrO_2 . Studies by Phalnikar and Baldwin⁵ on scales formed in air showed a mixture of monoclinic and tetragonal ZrO_2 and ZrN . A large dimensional change with time occurred coinciding with the appearance of a white scale between 850° and 1050°C. The reaction rate followed approximately the parabolic rate law for a time and then increased sharply.

Garibotti, Green, and Baldwin⁶ performed research on zirconium scaled in air, nitrogen, oxygen, and mixtures of nitrogen and oxygen. In pure oxygen or nitrogen there was no change in the color of the scale. However, mixtures of the two resulted in color changes similar to those observed in air. No difference was found between the black and white scale, both consisting of monoclinic and tetragonal ZrO_2 . They also determined that the presence of both oxygen and nitrogen was necessary for the sudden change in the scaling rate. The reason presented by Baldwin and Phalnikar⁵ for this is that the nitrogen dissolves in the ZrO_2 and, since nitrogen is quadrivalent, it would create defects in the oxygen ion structure. This would permit a higher diffusion rate of the oxygen through the oxide to the metal interface.

A few studies have been made on the effect of alloy elements on the scaling behavior of zirconium. Litton and Ogburn⁷ prepared binary zirconium-base alloys by arc melting in a copper crucible and by induction melting in a graphite crucible. The results of their work are shown in Table I. Arc-melted alloys containing Mo, Ni, W, Ta, and Al and induction-melted alloys containing W, Cr, Be, Al, Ta, and Ni were more resistant to oxidation than the pure zirconium. The induction-melted alloys contained about 0.2 to 0.3% carbon and showed inferior oxidation resistance in comparison with the arc-melted alloys.

A preliminary study of about 25 zirconium alloy systems prepared by induction melting in graphite crucibles was made by Anderson, Hayes, Roberson, and Kroll⁸. They found that binary zirconium-base alloys containing Fe, Ni, and Ag and ternary zirconium-base alloys containing Cu plus Fe, Co, or Ni showed improvement over zirconium at 1200°F. Table II gives a summary of their results of scaling tests at 1200°F on zirconium alloy systems for 24 hours.

Hickman and Gulbransen⁹ made a study of the oxides of the binary alloys 20% Zr-Cu, 60% Zr-Co, and 70% Zr-Ni and found no presence of zirconium dioxide up to 700°C. The thermodynamic data indicate that ZrO_2 should be observed. The proposed explanation for its nonexistence was that the rates of formation and diffusion of zirconium ions may be much lower than those of cobalt, copper, and nickel ions.

TABLE I

OXIDATION RESISTANCE OF ZIRCONIUM ALLOYS AT 750°C (1382°F)
(Litton & Ogburn)⁷

Arc Melted		Induction Melted	
Intended Comp., (balance Zr)	Weight Gain in 2 hrs. (mg/sq. dm.)	Intended Comp. (balance Zr)	Weight Gain in 6 hrs. (mg/sq. dm.)
100% Zr	415	100% Zr	3,300
1% Mo	368	2.25 At. % O ₂	4,200
2.5% Mo	536	5% W	2,600
5.0% Mo	957	5% Mo	*
10.0% Mo	634	5% Cr	3,198
1.0% Ni	219	5% Cb	*
2.5% Ni	223	5% V	*
5.0% Ni	181	5% Pt	*
10.0% Ni	220	5% Be	1,660
1.0% W	227	5% Si	*
2.5% W	251	1% Al	*
5.0% W	209	3% Al	1,610
10.0% W	491	5% Al	413
1.0% Ta	433	5% Ta	1,450
2.5% Ta	620	10% Ta	5,100
5.0% Ta	314	20% Ta	11,100
10.0% Ta	263	5% Ni	*
17.5% Ta	*	5% Ti, 15% W	*
2.0% Al	*	5% Ti, 15% Cr	*
4.0% Al	550	5% Ti, 15% Ta	*
6.0% Al	287	5% Ti, 15% Mo	*
1.0% Al, 50% Ti	*	1% Ni	1,844
4.0% Al, 50% Ti	*	2.5% Ni	575
6.0% Al, 50% Ti	4,680	5.0% Ni	1,690
		7.5% Ni	3,120
		10.0% Ni	1,109
		50% Ti	*
		1% Al, 50% Ti	*
		3% Al, 50% Ti	*

*Alloy Disintegrated

TABLE II

RESISTANCE OF ZIRCONIUM ALLOYS TO AIR AT 1200°F.
(Anderson, Hayes, Roberson, & Kroll)⁸

<u>Element</u>	<u>Limit of Addition (%)</u>	<u>Weight Gain (mg/dm/day)</u>
Al	10	*
Be	5	*
B	5	*
Ce	5	*
Cr	10	600-1500
Co	46	600-1500
Zr-base alloys containing Co. & Cr		*
Co content	4	
Cr content	5	
Cb	12	*
Cu	15	600-1500
Zr-ternary alloys of Cu and Fe, Co, or Ni		less than 600
Cu content	5	
Fe, Co, or Ni content	5	
Fe	60	less than 600
Mn	25	*
Mo	10	*
Ni	10	less than 600
Si	5	*
Ag	10	less than 600
Ta	30	*
Th	5	*
Sn	10	*
Ti	90	*
W	10	*
V	10	*
Zr	-	600-1500

* Alloy disintegrated in less than 24 hours

II. PURPOSE AND SCOPE

The primary objective of this contract was to investigate the effects of alloying elements on the scaling resistance of low-hafnium sponge zirconium with the view of developing an alloy to withstand exposures on the order of 200 hours in dry air at 1800°F. The alloys prepared were also tested at 1200° and 1500°F to determine those which were more resistant to scaling than pure zirconium at these temperatures. Zirconium-base alloys were made with 29 elements with the intended alloy content at a maximum of 5%. A list of these alloys is given in Table III.

The scaling resistance was based on the average weight increase per unit area per unit time. The scaling resistance of duplicate specimens of alloys was compared with that of a zirconium standard specimen.

III. EQUIPMENT

A. Arc-Melting Furnace

The arc-melting furnace used for melting the zirconium-base alloys is illustrated in Figure 1. * The tungsten tip of the electrode is brazed to a bar of copper which, in turn, is screwed into the water-cooled electrode. This permits easy removal of the tungsten tip so that it can be dressed up by grinding after each melt. The square copper hearth has a capacity of approximately 150 grams of zirconium. The copper hearth is soldered in the water-cooled copper crucible for easy removal. The power supply for the furnace consists of three 400-ampere Hobart motor-generator units connected in parallel to the furnace. A voltmeter is connected across the electrode and crucible so that the arc voltage can be observed while melting. A manifold is attached to the furnace by rubber tubing at the argon inlet so that the furnace can be connected either to an argon tank or to a mechanical vacuum pump. A mercury trap containing approximately 1 inch of mercury is attached to the argon outlet to provide a positive pressure of argon in the furnace during melting.

B. Scaling Furnace

The scaling furnace used for testing the scaling resistance of the zirconium-base alloy specimens is illustrated in the line drawing of Figure 2. The essential components are the scaling furnace proper with rotating top, balance, air drier, pre-heat furnace, power transformers, and a temperature controlling and recording potentiometer.

The heating chamber of the scaling furnace consists of two concentrically positioned refractory cores in which are mounted coiled

*Modification of drawing taken from: Maynor, Barrett & Swift; W. A. D. C. TR 54-109, "Scaling of Titanium and Titanium Alloys", April, 1954.

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FIG. 2 LINE DRAWING OF SCALING AND PRE-HEAT FURNACES

Nichrome-V heating elements. The specimens to be scaled are suspended from the top by Nichrome ribbons which are held in place by split plugs. A total of 25 specimens can be scaled in the furnace at the same time. The top is mounted on a vertical shaft located in the center of the furnace and is slowly rotated one revolution per minute. Two thermocouples are located in the heating chamber at positions 90 degrees apart and can be placed alternately in the controlling circuit by means of a toggle switch.

Desiccated and metered air is furnished to the heating chamber by a variable-capacity blower. Preheating of the air to about 500°F is accomplished by passing it through about 35 feet of resistance-heated Nichrome-V tubing. The air is dried by passing through a cannister containing approximately 50 pounds of silica gel which is removable for regeneration.

A Volland Visigram analytical balance, sensitive to 0.1 mg, is situated on a platform above the rotating top of the scaling furnace. A length of stainless steel wire is suspended from one end of the beam to hold the specimen ribbons during weighing. The Visigram feature employs the chainomatic principle with a direct reading counter which greatly facilitates weighings in the 0 to 1000 mg range.

IV. EXPERIMENTAL PROCEDURE

A. Preparation of Zirconium-base Alloys

The zirconium sponge used for the production of zirconium-base alloys was purchased from the Carborundum Metals Company, Inc., Akron, New York. Reactor Grade, or low hafnium sponge was used, with the following typical analysis.¹⁰

<u>Element</u>	<u>Weight %</u>	<u>Element</u>	<u>Weight %</u>
Hafnium	0.01	Magnesium	0.060
Aluminum	0.0075	Manganese	0.005
Boron	0.0001	Nickel	0.007
Chlorine	0.06	Titanium	0.005
Chromium	0.010	Vanadium	0.005
Iron	0.100	Carbon	0.02
Lead	0.005	Nitrogen	0.010

The sponge was sized by screening to -3 to +20 mesh, washed in methyl alcohol to remove contaminants and moisture, and then evacuated in a filter flask with a vacuum pump overnight. The zirconium sponge was then sealed in jars until the alloys were weighed to minimize moisture pickup.

The alloying elements used for the production of alloys were obtained in the purest commercial grades available in convenient form. The zirconium sponge and alloying element were weighed out to the nearest milligram in an amount to make the total weight of the alloy not over 120 to 130 grams. The sponge plus alloying element was then put into a compacting mold having a cross section of 1.5 inches square, the alloying element being distributed as much as possible among the sponge. This was pressed with a hydraulic press under a force of approximately 30 tons, obtaining a compact measuring 1.5 inches by 1.5 inches by about 0.75 inch. The compacting of the charge permitted all of it to be put into the crucible at the same time instead of adding it while melting, or melting only part of the charge and then adding the remainder.

The compacted charge was placed in the square hearth of the copper crucible and a piece of magnesium ribbon tied to the tungsten tip with thread to facilitate starting the arc. The crucible was placed in the furnace and the furnace sealed. The furnace was then evacuated for about one hour, giving a vacuum of 1 to 3 microns of mercury. The vacuum pump was isolated from the furnace and argon flushed through the system for about 2 minutes. The furnace was re-evacuated to 3 to 5 microns and then argon passed through it at a pressure of 1 inch of mercury above atmospheric pressure. The motor-generators were started and the arc struck by lowering the electrode until the magnesium ribbon touched the charge. The potential between the electrode and charge was maintained between 20 and 30 volts and the current used varied between 360 and 720

amperes. The time of melting for the majority of melts was about 2 minutes. For the first alloys produced the compacted charge was placed flat in the crucible hearth and then, after melting, the ingot was turned over for the next melt. This procedure was modified by standing the charge on edge for each melt and melting through the cross section. The final melt of each alloy was then placed flat and melted only long enough to remove any cold shuts in the ingot which resulted from the preceding melt. This yielded an ingot which was free of any major defects and was suitable for rolling without machining. It is believed that very little contamination resulted from alloying of the tungsten electrode with the charge because of the very slight deterioration of the electrode after each melt.

The rolling of the zirconium alloy ingots was conducted on a Stanat rolling mill. The ingots were heated in a Hevi-Duty salt pot furnace containing E. F. Houghton & Company's "Liquid Heat 235" which is a mixture of lithium, sodium, and potassium carbonates with a melting point of 750°F and a working range of 800° to 1700°F. The advantages of using this salt for heating the ingots were a fast heating rate and a reduction in the contamination of the ingots. The disadvantages were the low maximum working temperature and the inability of the salt pot furnace to maintain a temperature of about 1500° - 1600°F while the pot was uncovered during the rolling operation. The rolling temperatures given in Table III were the temperatures of the salt bath at the start and finish of the rolling operation. The ingots were held in the molten salt for 30 seconds to 1 minute with tongs until they reached the temperature of the salt as observed by their color, and then passed through the rolls. Reductions per pass ranged from 0.030 to 0.040 inch at the start to 0.005 to 0.010 inch at the finish of the rolling operation, the ingots being reheated between each pass. The ingots were rotated 90 degrees between each pass until they measured approximately 2.5 inches by 2.5 inches and then were rolled in the same direction to the final dimensions of about 2.5 inches by 5.5 inches by 0.09 inch. Table III shows the relative amount of surface cracking on the finished plate of each alloy due to rolling. Alloys were made containing 5% Fe and 5% Co but were discarded because of excessive cracking of the ingots during rolling.

TABLE III
PREPARATION OF ZIRCONIUM-BASE ALLOYS

PREPARATION OF ERGONOMY BASE ALLOYS					Amount of
Alloy*	Number of Melts	Total Time of Melting (Min.)	Rolling Temperature**		Surface Cracks from Rolling
			Start	Finish	
<u>Group I</u>					
2 Mo	6	9 1/2	1500	1380	None
5 Mo	4	10 1/2	1620	1400	None
2 Fe	3	7	1650	1490	None
2 Co	3	5 1/2	1520	1310	None
1 Cr	4	8	1500	1410	None
5 Cr	5	10 1/2	1610	1540	Many
1 Ni	6	14	1520	1360	None
5 Ni	3	7 1/2	1500	1425	Few
2 Ag	3	4 1/2	1500	1380	None
5 Ag	5	11 1/2	1460	1340	None
1 Cu	5	13	1300	1250	None
5 Cu	3	6 1/2	1350	1250	Few
<u>Group II</u>					
2 Ta	6	12	1460	1360	None
5 Ta	4	7	1500	1420	None
2 Cb	5	10	1430	1350	None
5 Cb	5	9 1/2	1490	1360	None
2 Pt	3	6	1410	1360	None
2 Pd	3	5	1520	1430	None
2 Os	4	6 1/2	1600	1480	None
2 Ir	3	8	1400	1340	None
2 Rh	6	5	1440	1380	None
2 Ru	4	13	1440	1380	None
2 V	3	6 1/2	1460	1410	None
5 V	3	8	1600	1485	Few
<u>Group III</u>					
1 Si	3	5	1570	1550	Many
2 Mn	7	15 1/2	1560	1450	None
5 Mn	3	7 1/2	1640	1430	None
2 Sn	4	9	1520	1450	None
5 Sn	3	7	1580	1480	None
2 Pb	3	5	1470	1440	None
5 Pb	3	5 1/2	1505	1465	None
2 W	6	10 1/2	1560	1530	None
5 W	9	13 1/2	1630	1565	None
2 Sb	3	7	1525	1475	None
5 Sb	3	6	1580	1540	Many
2 Ge	3	6 1/2	1570	1560	Many

(continued on next page)

TABLE III (Continued)

Alloy*	Number of Melts	Total Time of Melting (Min.)	Rolling Temperature** Start	Finish	Amount of Surface Cracks from Rolling
Group IV					
2 Al	3	4 1/2	1650	1550	Many
2 Ti	5	6	1540	1510	None
5 Ti	5	6 1/2	1520	1510	None
2 Mg ***	5	9	1620	1560	None
2 Zn ***	3	6	1570	1560	None
5 La	3	6 1/2	1620	1550	Few
2 La	3	4	1620	1560	None
2 Ba ***	6	10 1/2	1620	1560	None
Group V					
1.0 Cu-1.0 Ni	3	6 1/2	1600	1540	None
2.5 Cu-2.5 Ni	3	4	1610	1550	None
1.0 Cb-1.0 Ta	4	7 1/2	1560	1540	None
2.5 Cb-2.5 Ta	5	6 1/2	1600	1550	None
1.0 V - 1.0 Sn	3	3 1/2	1590	1550	None
2.5 V - 2.5 Sn	3	4	1660	1550	None
1.0 Cb-1.0 Sn	4	6 1/2	1530	1520	None
2.5 Cb-2.5 Sn	4	5 1/2	1540	1540	None
1.0 Cu-1.0 Sb	3	5	1600	1520	None
2.5 Cu-2.5 Sb	3	5 1/2	1590	1510	Many
1.0 Cu-1.0 W	8	14	1620	1550	None
2.5 Cu-2.5 W	9	18 1/2	1630	1580	Few

* Intended Composition (% of alloying element)

** Temperature of salt bath at the start and at the finish of the rolling operation.

***These alloys exhibited extreme volatilization during melting due to the low boiling point of the alloying elements.

The rolled plates of the zirconium alloys were radiographed to determine gross segregation of the alloying elements. The binary zirconium-base alloys which were found to be inhomogeneous by radiography after rolling were 2% and 5%Ta and 2% and 5% W. The rolled plates of these alloys were sandblasted, pickled in a $\text{HF-HNO}_3\text{-H}_2\text{O}$ solution, washed in distilled water and alcohol and cut up with a power shear. They were then remelted for as many times as thought necessary for complete solution of the alloying elements and then rolled. All four of the alloys were free of gross segregation after the second rolling.

After radiographing the alloy plates they were straightened by clamping them between two steel plates and heating in an electric furnace for 0.5 hour at 1000°F . Specimens were cut from the alloy plates and ground on a Doall Precision Grinder to the approximate dimensions of 1.0 inch by 1.0 inch by 0.05 to 0.07 inch. To suspend the specimens on the nichrome ribbons 0.125 inch holes were drilled in the specimens 0.125 inch from the edge. The specimens were then abraded on No. 1 metallographic emery paper. Figure 3 illustrates the steps in the preparation of the alloy specimens.

B. Method of Performing Scaling Tests

The zirconium-base alloys were tested for resistance to scaling at the temperatures of 1200° , 1500° , and 1800°F by determining the weight increase with time of duplicate specimens of each alloy. Prior to inserting the specimens in the scaling furnace, they were measured to the nearest one thousandth of an inch with micrometers. Three measurements were taken along the length, width, and thickness and the values averaged. The specimens were degreased with carbon tetrachloride, hung on the nichrome ribbons which had previously been weighed with the Voland balance, and then the weight of the specimen and ribbon was determined. These weighings were made with the balance off the scaling furnace.

Temperature calibration of the scaling furnace was carried out in the following manner: The furnace was allowed to preheat for approximately eight hours at the temperature of the tests to allow thermal equilibrium to be reached. There were two thermocouples in the hot zone of the furnace which could be connected alternately to the controller-recorder potentiometer. Thermocouple No. 1 was fixed permanently so that its end was positioned about 0.5 inch below the level of the lower edges of the specimens. Thermocouple No. 2 was adjustable and during the preheat period its end was positioned at a level corresponding to that of the center of the specimens. This couple was connected both to the controller-recorder potentiometer and to a portable potentiometer during the preheat period. After the furnace had reached the temperature of the test, couple No. 1 was connected to the controller-recorder potentiometer and its approximate temperature obtained. The controller-recorder potentiometer was then adjusted to control the furnace at this temperature. The temperature of couple No. 2, which was at the level of the specimens, was obtained

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Fig. 3 Steps in the Preparation of the Scaling Specimens.
("A", zirconium sponge; "B", compacted sponge; "C", melted sponge;
"D", rolled ingot; "E", scaling specimens)

with the portable potentiometer. Any necessary fine adjustments were made on the controller-recorder potentiometer to keep the temperature at the No. 2 couple at that of the test. The temperature was controlled to within about $\pm 10^{\circ}\text{F}$ by the recording potentiometer. Before inserting the specimens into the furnace the couple whose level corresponded to that of the center of the specimens was lowered below the level of the lower edge of the specimens, in order to avoid contact between the thermocouple and the specimens during the rotation of the latter.

The air pre-heat furnace and air pump were turned on at the same time as the scaling furnace. The air was pumped into the scaling furnace at the rate of 1.7 cubic feet per minute at a temperature of about 500°F . Just prior to inserting the specimens in the furnace, a freshly regenerated cannister of silica gel was placed in the air drier. During the course of the scaling test this cannister of silica gel was replaced when silica gel with indicator in the air circuit changed color. The frequency of replacement of regenerated silica gel depended on the relative humidity of the air.

Due to the fact that approximately 2 minutes was required for the weighing of each specimen, the specimens were put in the furnace at intervals of 2 minutes, thus causing each specimen to be scaled for the same length of time at each weighing. This was done for all scaling tests except for those of Groups I and II alloys at 1800°F . During the weighing operation, the air flow to the furnace and the rotation of the top were discontinued. To weigh the specimens one half of the split plug holding the specimen ribbon was removed and the ribbon raised, by means of forceps, so that the wire from the balance beam could be inserted in the hole in the ribbon. The weight of the specimen was then determined at the time designated for that particular specimen, the weighings being made at intervals of 2 minutes. After the weight of the last specimen was obtained, the flow of air to the furnace and rotation of the top was resumed.

In some cases, during the weighing of the specimens, one or both specimens of an alloy were observed to lose weight as a result of spalling of the scale or to drop from the ribbon. Then the final weight of the alloy was taken as that of the last preceding weighing.

V. EXPERIMENTAL RESULTS

The intended compositions of the alloys tested for scaling resistance are listed by groups in Table III. Duplicate specimens of the alloys in each group were tested together in the scaling furnace at 1200° , 1500° , and 1800°F along with a zirconium standard specimen.

The data obtained from the scaling tests of the zirconium-base alloys are given in Tables IV to XIII. Tables IV, VI, VIII, X, and XII show the cumulative weight increase of two specimens of each alloy. The average cumulative weight increase per average unit original area of the two specimens at 1200° , 1500° , and 1800°F is given in Tables V, VII, IX, XI, and XIII.

In determining the weight increase of the specimens, the weight increase of the Nichrome ribbons was included. Weighings were made of the specimen ribbons before and after scaling of the Group I alloys. The average weight increases of the ribbons were 1.2 mg at 1200°F, 4.4 mg at 1500°F, and 3.9 mg at 1800°F. On the basis of these figures, by including the weight increases of the ribbons with that of the specimens, the weight increases per unit area would be affected to the extent of only 0.09, 0.31, and 0.27 mg/cm², respectively.

The weight increase per unit original area as a function of time is given graphically in Figures 4 to 8 for the alloys at the three temperatures. Figure 9 shows a comparison between the scaling propensity of the zirconium standards used in the scaling runs of the alloys at the different temperatures employed. Portions of the curves at the extreme left on the graphs for the temperatures 1200° and 1500°F were plotted, but are not shown in order to conserve space.

Table XIV lists the alloys in the order of increasing weight increase per unit area per hour at the three temperatures. The general characteristics of the scaled specimens which did not drop from the ribbons are given in terms of the adherence or cracking of the scale and distortion of the specimens.

A. Group I - Binary Zirconium-Base Alloys

The alloys which were more resistant to scaling than the zirconium standards at all temperatures were those containing nickel and copper. Other alloys which were more resistant to scaling than zirconium were 2 and 5% Ag at 1200°F, and 2% Fe, 5% Ag, and 2% Co at 1800°F. Alloying of zirconium with molybdenum and chromium decreased its scaling resistance at the three temperatures.

The 2% Ag alloy at 1800°F had a decrease in the scaling rate which indicates a possible loss in weight due to spalling of scale.

Figure 10 is a photograph of the scaled specimens of Group I alloys illustrating the various degrees of scaling and distortion of the specimens when removed from the furnace.

B. Group II - Binary Zirconium-Base Alloys

As shown in Figure 5, none of the Group II alloys were more resistant to scaling than the zirconium standard at 1200° and 1500°F. However, at 1800°F the curves of all the alloys except 2 and 5% Ta and 2 and 5% V were below that of zirconium; the latter two alloys lasting only 1 to 2 hours before disintegrating. The 5% Cb alloy curve is below the curve for zirconium but has a steeper final slope. It also disintegrated in a shorter time than the zirconium.

C. Group III - Binary Zirconium-Base Alloys

Referring to Figure 6 for the Group III alloys, only 2% W had a lower weight increase than zirconium at 1200°F, and then only until after about 80 hours.

At 1500°F none of the alloys showed improvement over the zirconium standard.

At 1800°F the alloys containing 5% Sn, 2% Mn, and 2 and 5% W showed improvement over zirconium. The 5% Mn alloy initially had a lower weight pickup than zirconium but its scaling rate increased rapidly after 2 hours and disintegrated before zirconium.

D. Group IV - Binary Zirconium-Base Alloys

At 1200°F none of the alloys showed any improvement over the zirconium standard. (Note: During this scaling test, the power supply to the scaling furnace was interrupted for 1.5 hours and the temperature dropped to about 700°F; however, the temperature was brought back to normal in approximately one-half hour.)

At 1500°F, 2% Ba and 2% Mg showed practically the same scaling rate as the zirconium standard. Specimens of 5% Ti and 2% Ti disintegrated before 1 and 2 hours, respectively.

All the alloys except 2% Zn showed improvement over zirconium at 1800°F. The alloys 5% Cu and 5% Ni, belonging to Group I, were re-run with this group for a period of about 300 hours. The 5% Ni alloy had better scaling resistance; however, as shown in Table X, one specimen of the 5% Cu alloy had over twice the total weight increase of the other.

The alloys 2% Zn, 2% Ba, and 2% Mg exhibited extreme volatilization of the alloying element during melting and probably had very little of the alloying elements remaining in them. However, they were

tested to determine if the residual alloying elements would improve the scaling resistance of zirconium. Only at 1800°F did the alloys containing magnesium and barium show some improvement in scaling resistance as compared with zirconium at the same temperature.

E. Group V - Ternary Zirconium-Base Alloys

The choice of combination of the alloying elements in this group was based on the relative effects they produced on the scaling resistance of zirconium in the binary alloys. Elements which increased the resistance in binary alloys were combined with each other, such as to make up the copper-nickel ternary alloys. Elements which decreased the resistance were combined, such as to make up the vanadium-tin ternary alloys. Elements which increased the scaling resistance were combined with those which decreased it, such as to make up the copper-antimony ternary alloys.

The alloying element additions were 1% and 2.5% of each in the low and high content alloys, respectively, in order to determine the effect of substitution of one half the percentage of one element with another. Exceptions to this rule are the ternary alloys containing 1% Cu and 1% Ni since the binary alloys of these elements contained only 1% each of the alloying elements.

The ternary alloys which showed improvement over the zirconium standards at all temperatures were the copper-nickel, copper-tungsten, and copper-antimony alloys. Mention should be made here of the anomalous behavior of antimony in its binary and ternary alloys. The binary alloys were among the least resistant to scaling but when antimony was combined with copper in the ternary alloys these alloys were among the more resistant.

WEIGHT INCREASE PER UNIT ORIGINAL AREA AS A FUNCTION OF TIME FOR ZIRCONIUM ALLOYS AT 1200°, 1500° AND 1800°F.
GROUP I

FIG. 4

152 022

WEIGHT INCREASE PER UNIT ORIGINAL AREA AS A FUNCTION OF TIME FOR ZIRCONIUM ALLOYS AT 1200°, 1500° AND 1800°F.
GROUP II

FIG. 5

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WEIGHT INCREASE PER UNIT ORIGINAL AREA AS A FUNCTION OF TIME FOR ZIRCONIUM ALLOYS AT 1200°, 1500° AND 1800°F.
GROUP III

FIG. 6

152 024

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WEIGHT INCREASE PER UNIT ORIGINAL AREA AS A FUNCTION OF TIME FOR ZIRCONIUM ALLOYS AT 1200°, 1500° AND 1800°F.

GROUP IV

FIG. 7

FIG. 8

WEIGHT INCREASE PER UNIT ORIGINAL AREA AS A FUNCTION OF TIME FOR ZIRCONIUM STANDARDS AT 1200°, 1500° AND 1800°F.

Fig. 9

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Fig. 10 Specimens of Group I Alloys Scaled at 1200, 1500, and 1800°F.

152 028

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Table IV

CUMULATIVE WEIGHT INCREASE OF SPECIMENS OF GROUP I ALLOYS AT 1200, 1500 AND 1800°F

Cumulative Time (Hours)		Cumulative Weight (mg) of Specimens																1200°F (648.8°C)																Zr Stand.
		2%Mo		5%Mo		2%Fe		2%Co		1%Cr		5%Cr		1%Ni		5%Ni		2%Ag		5%Ag		1%Cu		5%Cu										
A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B									
1	9.9	9.7	20.2	18.7	9.6	9.7	7.9	7.1	8.3	7.5	9.8	10.1	6.2	6.0	5.6	5.1	5.3	5.4	5.7	6.0	5.6	5.2	5.5	5.0	6.7									
3	16.8	17.1	34.4	34.3	18.0	17.3	14.1	14.3	15.4	14.7	19.8	20.2	12.0	12.8	11.0	10.8	11.7	11.3	10.2	11.8	12.1	11.1	10.7	9.9	13.1									
5	19.6	20.2	40.4	39.6	19.6	19.0	15.3	15.9	17.1	16.6	35.4	36.7	14.2	14.4	12.5	12.0	13.3	13.2	12.5	13.0	12.7	12.5	11.1	10.9	13.7									
7	20.6	22.5	46.2	46.6	22.0	20.5	17.3	17.8	17.6	18.3	54.9	56.2	14.5	15.2	13.0	13.8	14.5	13.5	12.9	14.3	14.8	14.8	12.7	12.8	15.7									
13	26.2	26.6	59.4	60.4	26.2	25.5	21.3	21.6	21.9	21.7	122.2	125.3	18.4	18.4	16.3	16.4	17.0	16.8	16.9	17.0	16.8	17.1	13.7	14.4	17.5									
19	29.8	30.8	70.0	68.2	29.2	28.8	24.8	25.6	26.5	25.3	195.2	202.2	23.4	23.9	20.0	19.7	21.1	20.7	19.7	19.8	21.2	20.9	17.8	17.9	21.8									
31	37.1	36.2	89.2	85.0	33.2	33.5	25.7	27.2	28.8	25.3	342.6	356.5	24.9	23.1	19.7	20.4	21.8	21.9	23.2	21.8	23.5	22.8	20.3	19.0	23.4									
43	45.1	44.9	111.4	106.2	37.2	37.4	31.3	32.1	35.9	32.7	493.7	512.8	27.8	28.7	24.2	25.1	25.9	26.8	26.3	26.0	27.3	27.0	21.9	22.4	29.6									
55	57.6	56.7	129.8	126.1	43.2	42.7	38.1	43.6	41.7	40.4	643.5	670.9	30.8	29.9	25.6	26.5	30.1	30.3	28.4	28.4	29.2	28.4	24.5	23.9	32.3									
70	81.5	79.6	155.4	148.4	56.0	56.4	61.1	64.7	62.1	48.4	834.6	868.0	33.9	33.0	28.6	28.3	36.1	35.7	31.3	31.5	31.2	30.8	26.1	26.0	40.1									
89	129.6	118.1	198.7	183.0	84.9	81.1	91.8	97.3	70.0	65.5	1108.0	1187.6	40.1	39.3	29.3	30.2	47.9	45.5	38.6	38.5	36.0	34.0	27.6	28.7	55.0									
101	159.3	145.0	214.5	204.2	102.2	99.2	112.6	117.1	86.7	78.1	1274.3	1330.8	47.6	45.8	31.5	32.0	62.1	56.4	46.1	46.2	39.4	37.4	28.8	29.4	68.1									
118	191.3	185.9	244.7	234.1	130.4	127.3	139.5	144.9	117.2	104.1	65.1	62.2	33.9	32.3	75.6	66.4	53.9	54.8	50.2	47.0	29.7	30.4	87.9											
140	262.2	244.0	295.2	285.9	176.0	168.0	182.0	186.3	175.9	157.1	90.8	84.1	35.7	35.8	95.3	89.2	66.0	65.9	70.4	66.0	33.6	33.5	130.1											
164	318.5	300.9	340.1	331.1	220.2	211.9	222.9	225.4	237.9	215.0	118.4	111.4	37.0	37.1	107.2	103.6	74.2	73.6	84.1	81.8	35.3	35.3	170.1											
194	392.3	373.4	394.4	388.0	277.1	266.1	270.8	273.1	316.7	291.4	149.2	141.7	40.6	41.0	123.1	121.2	82.2	81.2	97.5	97.7	38.7	38.5	223.8											
1500°F (815.6°C)																																		
1	47.2	47.9	78.6	78.9	34.6	33.1	28.3	27.0	34.4	33.0	38.3	39.7	26.3	26.0	22.1	23.4	37.2	35.4	25.5	25.6	24.8	26.4	22.9	22.5	29.8									
2	67.4	66.6	160.8	159.4	41.6	40.2	34.6	32.2	41.4	41.6	87.8	88.5	32.5	32.2	26.5	28.6	55.2	59.1	34.4	35.6	30.3	30.8	25.9	26.6	37.4									
5	218.4	178.4	380.1	376.8	58.4	57.4	47.7	46.9	61.5	59.0	486.0	493.9	46.5	45.1	38.7	39.4	139.1	134.5	92.3	98.1	44.0	44.1	41.3	44.3	54.2									
10	289.5	318.2	683.1	695.0	94.0	78.9	65.2	66.8	87.2	83.5	1167.2	700.5	58.0	57.6	49.0	50.4	323.0	309.7	219.3	234.4	54.2	54.8	57.2	61.3	73.2									
19			1190.9	1204.4	273.3	183.2	122.0	134.1	166.1	158.4			78.1	77.7	63.6	64.4	665.1	647.9	502.1	521.6	67.5	69.9	78.1	86.2	121.6									
26			1480.2	1489.9	476.1	314.2	208.6	240.2	296.5	254.2			105.9	102.0	77.0	77.5	944.9	924.3	758.6	778.8	80.7	79.9	89.4	99.2	195.6									
35					762.0	499.8	379.6	446.9	547.6	448.1			157.2	149.4	93.8	93.3	1289.8	1267.6	1096.2	1109.7	95.1	91.6	100.0	109.2	363.6									
43					1048.0	681.1	583.3	686.3	791.0	675.7			228.5	214.4	110.4	108.8	1593.4	1557.9	1395.0	1399.2	113.3	107.9	107.4	118.0	543.4									
1800°F (982.2°C)																																		
Hrs.	2%Mo		Hrs.	5%Mo		Hrs.	2%Fe		Hrs.	2%Co		Hrs.	1%Cr		Hrs.	5%Cr		Hrs.	1%Ni		Hrs.	5%Ni												
1.14	139.2	137.3	1.27	580.8	540.2	1.36	171.0	220.7	1.46	114.6	113.2	1.56	431.2	587.7	1.63	703.0	838.5	1.69	132.2	116.0	1.75	80.5	75.9											
3.01	437.3	478.3	3.08	2111.7	2017.9	3.13	356.3	492.1	3.18	194.9	178.7	3.28	1334.0	1649.8	3.34	2119.9	2175.1	3.41	187.8	171.7	3.45	101.5	98.0											
5.02	1757.9	1798.0				5.14	683.2	820.1	5.20	344.4	317.6							5.32	312.5	298.8	5.40	120.9	115.6											
						6.65	883.6	1051.6	6.89	507.7	474.8							6.98	475.6	475.6	7.10	134.1	129.6											
Hrs.	2%Ag		Hrs.	5%Ag		Hrs.	1%Cu		Hrs.	5%Cu		Hrs.	Zr Stand.																					
1.80	904.0	1028.0	1.85	116.4	102.2	1.90	146.2	144.9	1.97	137.0	158.8	1.99	473.7																					
3.49	1653.3	1729.4	3.54	282.2	218.5	3.59	289.7	250.3	3.67	168.4	180.5	3.73	758.0																					
5.45	1864.6	1932.2	5.51	528.9	539.7	5.58	574.7	495.1	5.65	174.2	198.1	5.71	1274.7																					
7.21	1967.5	1984.0	7.35	722.5	800.2	7.49	859.9	787.2	7.59	187.1	210.6																							

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Table V.

AVERAGE CUMULATIVE WEIGHT INCREASE PER AVERAGE ORIGINAL UNIT AREA OF SPECIMENS OF GROUP I ALLOYS AT 1200, 1500 AND 1800°F.

1200°F (648.8°C)													
Average Surface Area (cm ²) of Specimens													Zr Stand.
2%Mo	5%Mo	2%Fe	2%Co	1%Cr	5%Cr	1%Ni	5%Ni	2%Ag	5%Ag	1%Cu	5%Cu		
14.78	14.88	14.16	13.33	14.93	14.08	14.84	14.81	14.71	14.92	14.31	14.59		14.66
Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)													
0.7	1.3	0.7	0.6	0.5	0.7	0.4	0.4	0.4	0.4	0.4	0.4		0.5
1	1.2	2.3	1.3	1.1	1.0	0.8	0.7	0.8	0.7	0.8	0.7		0.9
3	1.4	2.7	1.4	1.2	1.1	1.0	0.8	0.9	0.9	0.9	0.8		1.0
5	1.5	3.1	1.5	1.3	1.2	1.0	0.9	1.0	0.9	1.0	0.9		1.1
7	1.8	4.0	1.9	1.6	1.5	1.2	1.1	1.2	1.2	1.2	1.0		1.3
13	2.1	4.7	2.1	1.9	1.8	1.6	1.4	1.4	1.3	1.5	1.2		1.6
19	2.5	5.9	2.4	2.0	1.8	1.6	1.4	1.5	1.5	1.7	1.4		1.7
31	3.1	7.3	2.7	2.4	2.3	1.9	1.7	1.8	1.8	1.9	1.5		2.1
43	3.9	8.3	3.1	3.1	2.8	2.1	1.8	2.1	1.9	2.1	1.7		2.3
55	5.5	10.9	4.0	4.7	3.4	2.3	1.9	2.5	2.1	2.2	1.8		2.8
70	8.4	13.4	5.9	7.1	4.6	2.7	2.0	3.2	2.6	2.5	1.9		3.8
89	10.3	14.8	7.2	8.7	5.6	3.2	2.2	4.1	3.1	2.7	2.0		4.7
101	12.8	16.8	9.1	10.8	7.5	4.3	2.3	4.9	3.7	3.4	2.1		6.1
116	17.2	20.2	12.2	13.9	11.2	5.9	2.4	6.3	4.5	4.8	2.3		8.9
140	21.0	23.3	15.3	16.9	15.2	7.8	2.5	7.2	5.0	5.8	2.4		11.7
164	25.9	27.0	19.2	20.5	20.4	9.8	2.8	8.3	5.5	6.9	2.7		15.3
1500°F (815.6°C)													
Average Surface Area (cm ²) of Specimens													
14.84	14.91	14.52	14.59	14.86	14.10	14.85	14.80	14.72	14.88	14.27	14.61		14.70
Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)													
3.2	5.3	2.3	1.9	2.3	2.8	1.8	1.5	2.5	1.7	1.8	1.6		2.0
2	4.5	10.8	2.8	2.3	2.8	2.2	1.9	3.9	2.4	2.1	1.8		2.5
5	13.4	25.5	4.0	3.2	4.1	3.1	2.6	9.3	6.4	3.1	3.0		3.7
10	20.5	46.2	6.0	4.5	5.8	3.9	3.4	21.5	15.2	3.8	4.1		5.0
19		80.4	15.8	10.1	11.0	5.3	4.3	44.6	34.4	4.8	5.7		8.3
26		99.6	27.2	17.5	18.6	7.0	5.2	63.5	51.7	5.6	6.5		13.3
35			43.5	29.7	33.5	10.3	6.4	86.9	74.1	6.6	7.2		24.7
43			59.6	42.9	49.7	14.9	7.4	107.2	103.9	7.8	7.8		37.0
1800°F (982.2°C)													
Average Surface Area (cm ²) of Specimens													
14.78	14.91	14.71	13.99	14.90	14.64	14.82	14.81	14.67	14.86	14.25	14.83		13.86
Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)													
Hrs 2%Mo	Hrs 5%Mo	Hrs 2%Fe	Hrs 2%Co	Hrs 1%Cr	Hrs 5%Cr	Hrs 1%Ni	Hrs 5%Ni	Hrs 2%Ag	Hrs 5%Ag	Hrs 1%Cu	Hrs 5%Cu	Hrs Zr Stand.	
1.14 9.4	1.27 37.6	1.36 13.3	1.46 8.1	1.56 34.2	1.63 52.7	1.69 8.4	1.75 5.3	1.80 65.9	1.85 7.4	1.90 10.2	1.97 10.0	1.99 34.1	
3.01 31.0	3.08 138.5	3.13 28.8	3.18 13.4	3.28 100.1	3.34 146.7	3.41 12.1	3.45 6.7	3.49 115.3	3.54 16.8	3.59 18.9	3.67 11.4	3.73 54.6	
5.02 120.3		5.14 50.4	5.20 23.7			5.32 20.6	5.40 8.0	5.45 129.4	5.51 38.0	5.58 37.5	5.65 12.5	5.71 91.8	
		6.65 65.7	6.89 35.1			6.98 32.1	7.10 8.9	7.21 134.7	7.36 51.2	7.49 57.8	7.59 13.4		

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Table VI

CUMULATIVE WEIGHT INCREASE OF SPECIMENS OF GROUP II ALLOYS AT 1200, 1500 AND 1800°F.

Cumulative Time (Hrs)	Cumulative Weight Increase (mg) of Specimens																Zr Stand.												
	2%V		5%V		2%Ta		5%Ta		2%Cb		5%Cb		2%Pt		2%Pd			2%Os		2%Ir		2%Rh		2%Ru					
1	10.5	9.2	20.1	20.2	9.8	7.9	12.3	11.7	6.3	6.9	12.5	11.5	3.8	3.2	3.2	3.1	6.7	7.0	4.8	4.6	5.1	4.1	5.5	5.0	3.8				
3	22.4	18.7	43.6	38.5	20.9	19.1	24.7	24.3	15.5	14.5	24.1	24.7	7.8	6.4	7.8	7.2	11.4	11.4	10.3	8.8	9.5	9.3	9.9	10.7	9.0				
7	39.9	36.5	75.4	63.8	33.5	34.0	48.4	40.8	24.8	24.7	42.2	42.6	13.9	13.0	12.0	12.3	23.0	23.5	14.4	13.8	14.5	14.2	14.7	15.2	12.4				
19	76.2	79.3	128.9	116.1	52.5	51.4	61.9	63.9	41.3	41.0	90.2	90.6	20.1	19.8	17.3	17.5	65.3	66.2	21.2	20.8	20.7	18.9	26.3	25.5	19.3				
31	106.6	112.8	162.5	148.1	61.8	60.3	73.7	76.0	57.5	56.2	140.0	141.6	26.6	27.8	20.1	21.7	113.1	115.2	28.0	26.4	25.9	26.4	45.7	43.1	22.6				
47	150.8	157.0	208.0	193.8	79.8	84.1	91.6	93.6	92.0	91.3	190.7	191.4	40.2	55.9	30.6	33.7	188.5	190.0	40.9	39.6	41.3	46.4	85.0	85.9	32.9				
55	166.1	172.4	224.5	208.2	88.2	93.7	97.7	100.7	110.6	108.1	198.1	199.4	77.7	74.3	35.6	42.7	226.0	228.6	49.5	46.4	52.0	59.1	105.3	104.1	36.7				
81	214.9	213.8	281.3	249.1	109.7	126.6	129.6	136.0	176.8	172.0	222.4	210.5	124.3	122.5	70.8	86.6	348.1	353.5	94.4	86.8	97.1	100.4	170.7	167.7	52.4				
104	259.3	264.9	290.6	278.2	133.8	157.0	151.4	158.8	240.5	234.7			167.6	164.7	105.9	119.1	458.0	463.3	134.8	129.4	133.1	136.2	232.1	226.1	68.1				
121	292.9	273.0	312.9	299.1	151.0	175.3	172.4	178.3	274.4	276.3			197.9	196.5	131.5	142.5	537.5	540.8	165.8	159.7	159.9	162.1	273.9	268.7	84.1				
140	335.7	312.9	338.4	323.7	169.5	199.5	192.3	202.0	372.5	325.2			238.6	234.3	162.0	170.5	629.1	634.3	202.0	196.1	192.9	195.9	324.2	318.1	113.1				
168	395.1	373.0	377.3	360.7	198.5	237.4	228.5	238.3	391.0	379.9			290.4	290.0	203.0	210.5	752.3	752.6	259.1	248.4	243.2	238.9	396.5	391.1	164.1				
194	543.1	428.3	414.3	396.1	228.5	270.1	259.0	272.3	444.4	437.4			346.9	346.1	243.6	250.2	837.8	823.9	313.3	302.0	289.3	284.5	470.3	459.2	215.6				
1500°F (815.6°C)																													
1	222.0	238.2	436.2	433.9	70.6	69.9	154.7	149.0	49.2	50.2	83.3	81.9	31.3	30.8	27.2	25.8	36.6	36.5	30.9	31.5	29.5	30.7	32.5	32.8	30.5				
3	590.2	704.9			117.1	118.0	341.9	321.9	77.5	81.1	190.2	179.5	44.0	44.2	37.8	37.6	113.8	118.0	45.1	45.8	44.7	46.7	50.6	49.5	44.2				
7					263.9	273.3	607.5	575.4	188.8	191.6	559.1	529.3	65.6	66.8	52.0	54.0	520.4	527.5	69.2	70.8	70.7	77.7	185.1	186.0	62.9				
18					870.2	871.4			1076.4	1131.4			246.3	250.0	187.4	159.8	1598.9	1504.7	289.1	283.6	425.9	534.2	1000.3	1138.0	112.0				
31					1426.6	1443.1							822.1	778.5	682.8	616.0			804.4	879.2	1125.1	1284.8			331.0				
42					1830.7	1850.7							1365.4	1248.1	1128.7	1097.7			1281.5	1475.6	1718.1	1913.0			630.5				
1800°F (982.2°C)																													
Hrs.	2%V		Hrs.	5%V		Hrs.	2%Ta		Hrs.	5%Ta		Hrs.	2%Cb		Hrs.	5%Cb		Hrs.	2%Pt		Hrs.	2%Pd		Hrs.	2%Os		Hrs.	2%Ir	
1.05	530.9	539.6	1.06	768.2	823.3	1.07	262.2	249.2	1.08	298.3	298.5	1.08	99.0	99.1	1.08	150.7	149.2	1.08	113.0	111.9	1.10	94.7	94.8	1.10	111.1	115.8	1.09	106.7	112.3
						1.98	538.6	553.2	1.98	566.0	547.3	1.98	132.5	131.7	1.98	226.1	228.1	1.99	184.5	170.4	2.00	116.4	117.8	2.00	185.0	201.4	2.02	170.2	178.5
						3.77	1146.1	1235.5	3.78	960.6	937.4	3.78	238.7	221.3	3.78	535.8	535.5	3.78	462.8	394.9	3.73	170.7	168.8	3.77	441.6	500.7	3.78	356.9	373.0
						5.28	1861.6	1917.7				5.25	399.9	347.3	5.26	1109.9	1127.7	5.26	879.3	744.9	5.27	247.9	233.8	5.27	751.5	824.2	5.28	562.0	580.7
						6.77	2473.1	2526.6				6.72	665.1	599.4				6.72	1486.3	1246.5	6.72	347.3	325.5	6.72	1119.9	1228.6	6.73	803.2	846.9
												8.18	1039.4	917.1				8.12	1478.7	1500.4	8.13	469.2	450.7	8.13	1549.3	1666.1	8.15	1075.1	1143.4
																		9.59	631.9	626.8	9.64	2059.5	2176.8				9.75	1493.7	1598.2
Hrs.	2%Rh		Hrs.	2%Ru		Hrs.	Zr Stand.																						
1.08	102.3	104.8	1.08	122.8	122.3	1.05	188.8																						
2.00	134.4	135.8	2.00	180.8	178.3	2.00	363.2																						
3.77	207.3	202.2	3.80	412.6	386.0	3.77	796.4																						
5.25	308.3	290.8	5.25	763.9	694.8	5.25	1312.9																						
6.72	441.4	400.8	6.72	1201.8	1085.9	6.73	2023.4																						
8.13	612.3	534.3	8.12	1612.8	1486.7																								
9.79	931.4	767.9																											

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Table VII

AVERAGE CUMULATIVE WEIGHT INCREASE PER AVERAGE ORIGINAL UNIT AREA OF SPECIMENS OF GROUP II ALLOYS AT 1200, 1500, and 1800°F.

1200°F (648.8°C)													
2%V	5%V	2%Ta	5%Ta	2%Cb	5%Cb	2%Pt	2%Pd	2%Os	2%Ir	2%Rh	2%Ru	Zr	Stand.
Average Surface Area (cm ²) of Specimens													
14.47	14.09	14.96	14.95	14.27	14.93	14.37	14.48	14.81	14.42	14.47	14.17	14.72	
Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)													
0.7	1.4	0.8	0.8	0.5	0.8	0.2	0.2	0.5	0.3	0.3	0.4	0.3	
1.4	2.9	1.3	1.6	1.1	1.6	0.6	0.5	0.8	0.7	0.7	0.7	0.6	
2.6	4.9	2.3	2.7	1.7	2.8	0.9	0.9	1.6	1.0	1.0	1.1	0.8	
5.5	8.7	3.5	4.2	2.9	6.1	1.4	1.2	4.4	1.5	1.4	1.8	1.5	
7.6	11.0	4.1	5.0	4.0	9.4	1.9	1.5	7.7	1.9	1.8	3.1	1.7	
10.6	14.2	5.5	6.2	6.4	12.8	4.1	2.2	12.8	2.8	3.0	6.0	2.2	
11.7	15.3	6.1	6.6	7.7	13.2	5.3	2.7	15.4	3.3	3.9	7.4	2.5	
14.8	18.1	7.9	8.9	12.2	14.5	8.6	5.5	23.7	6.3	6.8	12.0	3.6	
17.5	20.2	9.7	10.4	16.7		11.6	7.8	31.2	9.2	9.3	16.2	4.6	
19.5	21.7	10.9	11.7	19.3		13.7	9.5	36.4	11.3	11.1	19.2	5.7	
22.4	23.5	12.4	13.2	22.9		16.4	11.5	42.7	13.8	13.4	22.7	7.7	
26.5	26.2	14.6	15.6	27.0		20.2	14.3	50.8	17.6	16.7	27.8	11.1	
30.5	28.7	16.6	17.7	30.9		24.1	17.1	56.1	21.4	19.8	32.8	14.6	
1500°F (815.6°C)													
Average Surface Area (cm ²) of Specimens													
14.42	14.09	14.97	14.93	14.26	14.93	14.37	14.47	14.80	14.38	14.47	14.18	14.67	
Average Cumulative Weight Increase (mg) per Average Original Unit Area													
16.0	30.9	4.7	10.2	3.5	5.5	2.2	1.8	2.5	2.2	2.1	2.3	2.1	
44.9		7.9	22.2	5.6	12.4	3.1	2.6	7.8	3.2	3.2	3.5	3.0	
		18.0	39.6	13.3	36.5	4.6	3.7	35.4	4.9	5.1	13.1	4.3	
		58.2		77.4		17.3	12.0	104.9	19.9	33.2	75.4	7.6	
		95.9				55.7	44.2		58.4	83.3		22.6	
		123.0				90.9	76.9		95.8	125.5		43.0	
1800°F (982.2°C)													
Average Surface Area (cm ²) of Specimens													
14.43	14.09	14.96	14.94	14.26	14.97	14.35	14.49	14.82	14.40	14.46	14.16	14.71	
Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)													
Hrs 2%V	Hrs 5%V	Hrs 2%Ta	Hrs 5%Ta	Hrs 2%Cb	Hrs 5%Cb	Hrs 2%Pt	Hrs 2%Pd	Hrs 2%Os	Hrs 2%Ir	Hrs 2%Rh	Hrs 2%Ru	Hrs Zr	Stand.
1.05 37.1	1.06 57.2	1.07 17.1	1.08 19.6	1.08 7.0	1.08 10.0	1.08 7.8	1.10 6.5	1.10 7.7	1.09 7.6	1.08 7.2	1.08 8.7	1.05 12.8	
		1.98 36.5	1.98 37.3	1.98 9.3	1.98 15.2	1.99 12.4	2.00 8.1	2.00 13.0	2.02 12.1	2.00 9.3	2.00 12.7	2.00 24.7	
		3.77 79.6	3.78 63.5	3.78 16.1	3.78 35.8	3.78 29.5	3.78 11.7	3.77 31.8	3.78 25.4	3.77 14.2	3.80 28.2	3.77 54.1	
		5.28 123.0		5.25 26.2	5.25 74.7	5.25 56.2	5.27 16.6	5.27 53.2	5.28 39.7	5.25 20.7	5.25 51.5	5.25 89.3	
		6.77 163.8		6.72 44.4		6.72 94.9	6.72 23.2	6.72 79.2	6.73 57.3	6.72 29.1	6.72 80.8	6.73 137.6	
				8.18 78.6		8.12 112.6	8.13 31.8	8.13 108.5	8.15 77.1	8.13 39.6	8.12 109.6		
						9.59 43.4	9.64 143.0	9.75 107.4	9.79 58.8				

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Table VIII

CUMULATIVE WEIGHT INCREASE OF SPECIMENS OF GROUP III ALLOTS AT 1200, 1500 AND 1800°F.

Cumulative Weight Increase (mg) of Specimens

Cumulative Time (Hrs)	2%Mn		5%Mn		2%Sn		5%Sn		2%Pb		5%Pb		2%W		5%W		2%Sb		5%Sb		1%Si		2%Ge		Zr. Stand
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
1200°F (648.8°C)																									
1	5.6	7.3	10.2	9.8	5.7	6.2	5.6	5.6	12.4	6.6	6.3	5.4	5.6	5.4	5.0	5.1	5.0	5.6	14.2	16.7	7.1	8.5	9.7	10.1	5.6
3	9.8	12.0	15.9	15.9	10.0	10.0	9.0	10.0	14.2	10.8	10.8	10.5	12.7	11.6	10.1	10.5	9.7	9.9	101.5	112.4	13.9	17.1	14.8	14.8	9.1
7	15.0	15.9	20.9	21.1	18.7	19.0	21.6	21.7	15.9	20.4	22.0	23.9	20.0	20.0	16.2	16.7	21.1	22.6	349.0	424.0	39.1	44.0	22.6	22.1	15.8
11	19.3	18.5	25.2	25.1	29.6	29.5	41.1	43.5	24.6	33.8	38.6	42.2	24.2	24.5	20.1	21.0	40.4	38.9	665.0	725.0	72.0	77.8	27.6	27.3	19.8
19	23.2	23.3	29.4	28.5	58.7	58.0	112.4	120.6	48.6	63.6	82.8	88.4	28.4	28.6	23.4	24.6	134.9	146.4	1287.2	1551.4	137.4	147.6	58.9	56.0	21.6
27	24.9	27.7	31.5	33.5	96.5	96.6	232.8	246.8	83.4	99.7	131.6	137.4	32.1	31.9	26.8	28.3	347.6	318.2			201.4	213.5	91.0	88.4	24.1
44	36.2	39.1	48.1	55.3	185.1	183.6	615.7	620.6	163.1	176.8	243.7	246.7	39.8	39.2	37.4	40.7	895.2	1031.2			336.8	356.5	170.0	165.6	31.2
55	43.0	44.8	57.6	68.2	240.1	237.6	791.8	717.2	214.8	228.6	317.8	320.1	44.5	44.1	46.8	48.3					418.0	442.2	218.7	213.1	37.4
74	57.6	57.5	74.2	93.9	331.5	329.2	1276.8	1194.2	296.3	309.5	429.1	428.7	50.7	50.4	69.5	64.0					539.1	570.8	293.4	286.2	48.4
93	82.4	78.3	95.1	123.1	427.0	423.6	1380.0	1493.1	379.6	394.0	540.0	538.4	57.9	57.0	98.5	88.9					658.0	702.7	368.3	359.8	56.2
108	110.0	108.7	110.0	145.0	495.3	492.8			443.4	458.6	620.4	611.8	64.3	64.5	115.0	110.1					742.9	792.3	422.8	413.7	66.2
129	171.7	168.5	148.4	185.7	617.9	614.5			559.2	571.0	759.5	747.7	79.9	78.4	149.1	148.9					866.9	759.8	518.4	506.4	92.6
148	217.6	213.4	176.3	219.7	709.1	708.4			847.6	855.5	863.0	852.6	89.9	88.7	171.2	171.9					912.4	855.4	689.6	673.9	121.5
170	277.2	273.8	225.5	269.2	830.7	829.8			760.9	760.9	997.0	986.0	110.1	108.7	202.5	205.7					933.1	850.0	681.4	663.4	175.6
194	336.2	332.1	271.0	317.0	941.4	940.6			860.4	856.7	1115.8	1101.7	131.7	128.7	226.9	232.3					761.2	740.9			224.1
1500°F (815.6°C)																									
1	35.4	34.5	35.7	35.7	37.5	38.3	88.4	89.9	36.8	35.7	35.8	35.7	38.8	38.1	32.8	34.0	126.8	110.5	427.6	438.0	60.4	57.7	350.5	364.5	32.8
2	43.4	42.5	40.3	39.9	72.6	77.0	246.4	258.7	45.4	44.7	47.1	51.6	46.2	45.2	40.4	40.1	480.3	450.5	1183.5	1188.8	125.3	121.1	786.3	820.3	38.6
4	51.1	51.3	49.9	47.3	256.5	270.2	583.3	594.9	72.4	73.4	131.0	142.8	62.8	60.2	51.4	52.1	1205.3	1277.6	1532.1	1980.0	259.3	254.6			49.0
6	58.6	59.0	55.9	53.5	429.0	447.2	812.2	820.2	109.8	111.6	252.4	262.0	100.6	81.7	59.1	60.5	1702.3	1812.9			400.0	396.3			56.4
10	76.9	76.1	70.3	62.9	927.3	938.5	1188.4	1179.2	267.8	300.8	521.9	522.4	303.4	241.7	68.7	71.0					736.0	730.4			67.8
18	196.6	155.5	97.9	82.5	1404.9	1394.5	1689.6	1722.2	725.4	756.9	876.3	855.0	602.1	531.5	91.7	94.2					1115.2	1095.3			88.4
24	604.1	460.1	171.7	138.3							986.6	914.1	158.3	168.4											142.1
30	1008.1	774.3	258.4	199.3							1237.7	1159.1	233.1	242.2											204.1
37			402.3	321.5							1520.6	1439.4	337.1	351.3											313.4
46			590.9	487.1							1874.2	1784.9	517.3	536.0											503.3
1800°F (982.2°C)																									
1	127.4	122.1	149.3	135.7	844.8	921.2	948.2	681.0	623.1	605.5			181.3	195.4	167.3	166.0	1054.9	1037.4	350.4	324.1	325.7	321.4	388.4	366.0	245.4
2	234.8	209.3	348.9	285.1	1644.0	1622.2	912.7	951.1	1828.2	1856.8			320.5	332.1	290.0	294.0	1931.7	1957.0	758.5	730.4	737.4	729.5	879.1	789.9	468.1
3	400.4	327.0	837.6	713.3	1656.8	1635.5	1076.5	1102.2					414.3	429.0	461.1	467.3	1975.8	2086.1	1180.1	1194.4	1181.5	1142.2	1591.7	1305.1	764.7
4	619.9	486.8			1660.3	1635.6	1205.7	1221.0					539.5	549.4	666.7	699.9			1548.5	1588.2					1111.0
5	1015.9	735.6					1311.8	1316.4					712.2	648.3	945.2	789.5			1846.0	1868.2					1631.1
6.5							1463.7	1441.7					901.8	892.8											
8.5							1697.3	1675.4																	

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Table IX

AVERAGE CUMULATIVE WEIGHT INCREASE PER AVERAGE ORIGINAL UNIT AREA OF SPECIMENS OF GROUP III ALLOYS AT 1200, 1500 AND 1800°F.

	2%Mn	5%Mn	2%Sn	5%Sn	2%Pb	5%Pb	2%W	5%W	2%Sb	5%Sb	1%Si	2%Ga	Zr. Stand.		
1200°F (848.8°C)															
Average Area (cm ²) of Specimens															
	14.12	14.08	14.02		14.21	12.67		14.20	15.12	14.52	14.62	14.52	14.59	14.53	14.62
Cumulative Time (Hrs.)	Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)														
1	0.5	0.7	0.4		0.4	0.7		0.4		0.3	0.4	1.1	0.5	0.7	0.4
3	0.8	1.1	0.7		0.7	0.9		0.8		0.7	0.6	7.4	1.1	1.0	0.6
7	1.1	1.5	1.3		1.5	1.5		1.3		1.1	1.5	26.6	2.8	1.5	1.1
11	1.3	1.8	2.1		3.0	2.3		2.8		1.6	1.4	53.1	5.1	1.9	1.3
19	1.6	2.1	4.2		8.2	4.4		6.0		1.9	1.7	9.5	102.3	9.8	1.5
27	1.9	2.3	6.9		16.5	7.0		9.5		2.1	1.9	22.6	14.2	8.2	1.6
44	2.7	3.7	13.2		19.2	12.5		17.3		2.6	2.9	65.8	23.8	13.6	2.1
55	3.1	4.5	17.1		28.8	18.2		22.5		2.9	3.5		29.5	16.9	2.5
74	4.1	6.0	23.6		62.7	22.0		30.1		3.3	4.8		38.0	22.0	3.2
93	5.7	7.7	30.4		76.8	27.9		37.9		3.8	6.6		46.6	27.1	3.8
106	7.7	9.1	35.3			32.5		43.4		4.3	8.0		52.6	30.9	4.5
129	12.0	11.8	44.0			40.5		53.1		5.2	10.4		55.8	37.4	6.3
146	15.3	14.1	50.6			46.8		60.4		5.9	12.1		60.6	42.1	8.3
170	19.5	17.6	59.3			54.3		69.8		7.2	14.3		65.8	48.4	12.0
194	23.7	20.9	67.2			60.9		78.1		8.5	16.1			53.8	15.3
1500°F (815.6°C)															
Average Area (cm ²) of Specimens															
	14.09	14.39	14.33		14.17	14.66		14.25	15.14	14.53	14.62	14.59	14.45	14.58	14.67
Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)															
1	2.5	2.5	2.6		6.3	2.5		2.5		2.3	2.2	4.0	8.1	30.0	24.5
2	3.0	2.8	5.2		17.8	3.1		3.5		2.8	2.6	8.4	31.8	82.1	27.6
4	3.6	3.4	18.4		41.6	5.0		9.6		4.1	3.8	17.6	54.9	121.5	
6	4.1	3.8	30.8		57.6	7.6		18.0		6.0	4.1	3.8	27.3	120.2	
10	5.4	4.6	65.1		83.5	19.4		36.6		18.2	4.8	4.8	50.3		
16	12.5	6.3	97.7		120.4	50.6		61.0		37.4	6.4	6.0	75.8		
24	37.8	10.7			121.6			62.8		11.2	9.7				
30	63.2	15.9						79.2		16.4	13.9				
37		25.2						97.8		23.7	21.4				
46		37.5						120.8		36.2	34.3				
1800°F (982.2°C)															
Average Area (cm ²) of Specimens															
	14.10	14.09	14.02		14.15	14.65		14.28	15.12	14.54	14.59	14.49	14.57	14.60	14.64
Average Cumulative Weight Increase (mg) Per Average Original Unit Area (cm ²)															
8.9	10.1	63.0		47.0	41.9	12.5		11.5		16.8	71.7	23.3	22.2	25.8	16.8
15.8	22.5	116.5		65.9	125.7	21.4		20.1		33.3	133.3	51.4	50.4	67.2	33.3
25.8	55.0	117.4		77.0		29.7		31.9		52.2	139.2	81.9	79.8	99.2	52.2
39.3		117.5		85.7		38.3		47.7		75.9		108.2		75.9	
62.1				92.9		48.0		59.7		111.4		126.2			111.4
				102.3		59.1									
				112.1											

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TABLE X

CUMULATIVE WEIGHT INCREASE OF SPECIMENS OF GROUP IV ALLOYS AT 1200, 1500, AND 1800°F.

Cumulative Weight (mg) of Specimens																																
Cumulative Time (Hrs)	2% Mg		2% Zn		2% Al		2% Ti		2% V		2% La		2% Ba		2% Ce		2% Cu		2% Sn		Zr Stand.											
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B												
1200°F (648.8°C)																																
1	8.4	9.1	11.2	10.5	57.8	51.4	42.3	42.4	179.2	178.6	9.8	8.8	8.5	7.5	14.0	12.6																
2	14.1	14.1	15.1	13.9	219.1	200.4	63.8	64.1	326.9	333.2	14.7	14.0	13.1	12.7	24.0	23.3																
3	18.9	17.1	18.8	17.4	277.9	244.5	89.6	89.7	627.6	623.9	20.3	19.0	17.2	16.5	34.5	32.7																
13	23.1	22.7	23.3	22.2	591.6	565.1	144.0	144.8	1239.5	1231.4	25.8	26.6	22.5	21.5	49.9	47.7																
23	25.5	24.7	43.5	44.9	909.5	897.3	244.7	238.8			32.5	33.3	27.9	27.8	65.1	65.1																
34	31.1	30.1	66.0	67.4	1307.0	1256.1	401.2	390.3			60.3	61.7	58.8	58.8	134.5	130.1																
51	37.0	35.7	111.8	118.7	1605.7	1610.6	628.2	618.1			86.1	88.1	99.5	99.5	190.4	172.3																
72	41.4	42.9	174.7	181.9			924.2	918.1			86.1	88.1	99.5	99.5	190.4	172.3																
94	48.0	47.1	211.5	220.5			1089.5	1082.5			103.2	105.6	125.9	125.9	200.9	195.8																
109	64.1	61.3	299.9	210.1			1368.0	1245.0			135.3	135.3	140.1	138.8	198.0	185.1																
126	80.0	73.6	359.7	373.6			1529.8	1509.3			157.3	157.3	161.2	159.3	229.6	229.0																
150	113.8	102.4	454.5	467.1			1765.8	1719.7			223.0	223.0	229.7	229.7	301.8	301.8																
174	155.5	142.3	547.2	557.2							250.6	250.6	252.8	252.8	382.9	382.9																
194	190.0	179.9	618.8	629.5									250.6	252.8	382.9	382.9																
1500°F (815.6°C)																																
1	35.2	35.3	41.5	42.7	37.6	39.2	521.6	594.4			52.6	53.7	48.9	41.6	99.5	98.3																
2	49.7	48.0	56.8	59.6	47.1	49.6					87.7	87.6	60.1	64.8	155.2	154.0																
3	55.9	57.1	63.8	72.4	58.7	64.0					123.7	123.3	67.4	65.2	215.2	215.3																
4	66.4	67.0	87.8	89.8	77.0	88.0					153.5	152.9	74.6	74.9	273.2	270.1																
5	91.1	93.1	161.8	172.8	128.6	155.3					232.9	231.8	93.7	102.5	373.5	369.6																
9	151.2	159.0	422.3	447.2	302.1	276.8					369.7	368.2	146.7	162.5	554.7	548.7																
14	238.0	251.8	866.9	739.4							545.3	545.3	608.7	608.7	461.1	461.1																
21	474.2	490.3											608.7	608.7	461.1	461.1																
28	605.3	622.5											608.7	608.7	461.1	461.1																
36	733.6	734.3											608.7	608.7	461.1	461.1																
48	923.1	976.2											608.7	608.7	461.1	461.1																
1800°F (982.2°C)																																
1	331.9	300.2	339.7	306.6	142.8	115.1	559.9	618.4	652.7	660.2	394.5	397.7	300.6	274.4	288.1	270.3	142.0	141.0	88.9	81.9	228.1	228.1	142.0	141.0	88.9	81.9	228.1	228.1	142.0	141.0	88.9	81.9
2.5	608.6	626.5	850.1	1027.1	320.3	249.8	1034.8	1243.2	1050.5	937.8	599.5	829.2	564.1	564.9	569.9	547.1	201.3	171.1	98.2	96.9	840.1	840.1	201.3	171.1	98.2	96.9	840.1	840.1	201.3	171.1	98.2	96.9
4	1055.3	1302.8	1828.5	1538.4	508.0	475.4	1538.4	1538.4	1538.4	1538.4	1114.0	1648.9	955.2	1021.7	1190.6	1128.1	332.1	158.8	111.7	112.6	1632.3	1632.3	332.1	158.8	111.7	112.6	1632.3	1632.3	332.1	158.8	111.7	112.6
6																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
8																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
11																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
21																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
31																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
46																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
64																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
83																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
105																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
121																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
149																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
177																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
221																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
263																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						
313																	361.8	203.3	128.2	128.3			361.8	203.3	128.2	128.3						

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Table XI

AVERAGE CUMULATIVE WEIGHT INCREASE PER AVERAGE ORIGINAL UNIT AREA OF SPECIMENS OF GROUP IV ALLOYS AT 1200, 1500 AND 1800°F.

	2%Mg	2%Zn	2%Al	2%Ti	5%Ti	2%La	2%Ba	5%La	5%Cu	5%Ni	Zr Stand.
1200°F (648.8°C)											
Average Area (cm ²) of Specimens											
	14.67	14.83	14.49	14.87	14.76	14.63	14.48	14.78			14.77
Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)											
Cumulative Time (Hours)											
1	0.6	0.7	3.8	2.9	12.1	0.6	0.6	0.9			0.6
3	1.0	1.0	14.5	4.3	22.7	1.0	0.9	1.6			0.8
6	1.2	1.2	24.9	6.0	42.4	1.3	1.2	2.3			1.1
12	1.6	1.9	39.9	9.7	93.2	1.8	1.5	3.3			1.4
22	1.7	3.0	62.4	16.2		2.3	1.9	4.5			1.7
34	2.1	4.5	88.5	28.6		3.0	2.6	6.4			2.0
51	2.5	7.7	111.0	41.9		4.2	4.0	9.0			2.3
72	2.9	12.0		62.0		6.0	6.9	11.9			2.7
84	3.2	14.6		72.3		7.2	8.9	13.4			2.8
109	4.3	20.6		90.5		9.4	13.1	17.6			3.6
126	5.2	24.9		102.2		10.9	16.1	20.5			4.2
150	7.4	31.1		117.2		13.1	20.1	24.7			5.6
174	10.2	37.2				15.4	24.4	27.1			7.6
194	12.6	42.1				17.2	27.5				9.1
1500°F (815.6°C)											
Average Area (cm ²) of Specimens											
	14.64	14.81	14.50	14.87	14.74	14.64	14.48	14.78			14.68
Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)											
1	2.5	2.8	2.6	57.7	—	3.6	3.1	6.7			2.8
2	3.3	3.9	3.3			6.2	4.0	10.5			3.4
3	3.9	4.8	4.2			8.4	4.6	14.7			4.1
4	4.6	6.0	5.7			10.5	5.2	18.4			4.8
6	6.3	11.3	9.6			15.9	6.8	25.1			6.5
9	10.6	29.4	16.5			24.2	11.2	37.3			10.1
14	20.1	54.3				39.4	20.7				19.1
21	32.9						31.2				31.5
28	41.6						42.5				39.8
36	50.1						52.4				47.8
48	66.2						70.9				64.6
1800°F (982.2°C)											
Average Area (cm ²) of Specimens											
	14.66	14.81	14.38	14.87	14.77	14.62	14.49	14.50	14.65	12.44	14.70
Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)											
1	21.6	24.8	9.0	39.5	45.1	27.1	19.8	18.6	9.7	6.8	19.2
2.5	44.2	67.8	19.8	60.0	67.3	48.9	39.0	38.5	12.7	7.8	57.1
4	81.4	124.8	34.2	76.6	92.9	94.5	68.2	79.9	14.4	9.0	110.4
6				97.4	120.0		117.0		15.9	10.2	
8				121.2	158.0				17.1	11.1	
11				153.6					18.9	12.4	
21									22.6	15.6	
31									25.1	18.2	
46									30.4	21.4	
54									33.6	22.8	
83									44.8	27.5	
105									53.2	30.9	
131									64.4	35.6	
149									72.1	39.7	
177									84.4	48.8	
221									126.4	68.8	
263									134.7	86.3	
313										107.0	

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Table XII

CUMULATIVE WEIGHT INCREASE OF SPECIMENS OF GROUP V ALLOYS AT 1200, 1500, and 1800°F.

Cumulative Time (Hours)	Cumulative Weight Increase (mg) of Specimens																									
	1%Cu A	1%Ni B	2.5%Cu A	2.5%Ni B	1%Cb A	1%Ta B	2.5%Cb A	2.5%Ta B	1%V A	1%Sn B	2.5%V A	2.5%Sn B	1%Cb A	1%Sn B	2.5%Cb A	2.5%Sn B	1%Cu A	15Sb A	2.5%Cu B	2.5%Sb A	1%W B	1%Cu A	2.5%W B	2.5%Cu A	B	
1200°F (648.8°C)																										
1	12.0	11.9	10.7	9.1	31.3	30.6	34.9	35.0	19.3	19.6	25.0	23.3	16.4	15.8	12.7	14.0	10.8	11.0	10.3	10.6	11.6	11.9	11.9	9.7	9.2	
3	15.6	13.9	11.7	13.9	42.5	43.2	44.5	44.8	34.5	34.9	35.8	34.0	26.0	25.1	23.3	23.4	13.4	13.0	13.0	13.7	15.8	16.1	12.6	13.1	14.4	
6	21.4	18.4	16.2	17.6	56.2	55.7	55.8	56.6	52.8	54.5	50.8	47.2	48.2	46.8	42.3	42.2	13.0	18.6	18.8	19.4	25.3	25.7	21.2	21.6	25.4	
12	27.9	23.0	19.3	21.3	74.7	73.4	83.4	83.8	92.5	95.5	84.1	82.9	91.7	93.6	80.0	79.9	13.3	26.3	23.6	24.2	31.4	30.7	24.8	25.9	32.0	
23	30.8	27.4	22.7	24.4	109.8	110.1	137.1	138.1	175.0	180.5	143.3	143.2	173.5	177.2	153.0	153.1	27.4	33.7	24.8	25.9	34.9	34.8	29.1	27.6	35.9	
30	35.3	31.1	38.1	27.6	138.4	138.7	170.6	170.0	234.9	243.8	187.3	186.8	226.1	231.0	200.9	202.4	37.2	44.1	26.6	27.7	38.0	37.6	29.7	29.8	37.8	
36	41.4	33.4	30.4	30.7	161.2	164.9	193.6	197.2	288.8	297.2	214.1	222.0	272.0	282.4	232.2	246.5	45.7	56.0	28.1	29.7	41.5	40.6	32.1	31.8	42.1	
48	42.6	37.6	32.8	33.9	211.0	212.8	249.4	255.3	407.3	422.0	292.4	300.8	362.9	373.5	315.1	327.6	58.4	63.3	29.0	30.4	45.5	45.4	32.8	33.5	45.1	
60	44.8	37.9	33.3	34.7	251.9	255.9	294.0	300.5	525.5	549.5	362.7	378.3	436.8	450.8	381.7	388.4	65.7	71.0	30.6	32.9	51.9	50.0	35.8	35.7	51.2	
73	46.9	41.9	38.4	38.4	296.9	299.1	340.8	347.4	651.8	694.8	441.8	461.3	516.6	527.5	437.3	422.2	73.4	85.5	34.9	37.0	63.5	60.8	39.6	40.6	62.3	
98	51.1	45.4	41.9	42.5	381.2	380.8	428.3	437.5	893.3	967.8	609.5	631.8	668.8	679.7			89.6	94.6	36.0	40.3	74.3	70.3	41.2	42.9	76.1	
121	56.0	50.5	44.9	45.5	452.8	450.2	494.4	506.3	1093.5	1197.0	754.2	777.0	793.9	805.2			100.4	104.8	36.4	40.8	83.8	79.6	42.7	45.1	97.0	
145	57.6	52.4	47.2	48.6	523.7	518.9	558.4	571.3	1301.9	1421.7	902.4	922.0	918.0	929.0			110.1	116.8	39.0	43.9	99.1	96.0	46.7	48.4	134.8	
169	63.6	55.9	50.4	50.1	609.0	591.7	639.6	659.9	1517.4	1536.8	1062.5	1084.4	1038.1	1057.5			122.4	128.9	41.8	47.1	113.1	113.9	49.0	51.1	163.0	
192	65.6	59.9	53.7	53.8	705.9	682.8	729.1	699.0			1227.9	1268.4	1196.3	1195.3			155.2									
1500°F (815.6°C)																										
1	25.9	26.5	23.1	24.1	102.1	101.1	147.3	151.0	104.9	112.7	139.8	123.8	58.0	57.4	68.4	60.4	34.0	24.2	24.2	25.8	27.1	28.0	24.0	23.8	31.0	
2	31.0	31.3	27.6	29.2	140.5	137.4	259.5	265.1	231.1	243.6	256.6	217.0	167.3	162.2	172.1	162.8	28.8	34.6	36.4	35.8	42.7	42.5	37.0	36.0	48.8	
4	37.4	38.7	36.7	36.6	259.9	247.7	477.8	486.8	503.1	520.6	543.1	480.1	437.3	421.2	412.0	392.6	35.2	42.3	42.8	43.5	52.0	52.0	45.0	44.0	59.2	
6	46.9	47.3	44.1	46.8	408.6	393.6	699.7	707.4	778.7	801.8	879.4	804.3	736.3	708.9	643.9	629.6	42.5	49.0	48.3	50.3	59.9	58.7	50.8	49.0	68.5	
9	54.6	52.9	53.4	55.4	653.9	641.6	1048.9	1018.0	1208.9	1289.4	1427.8	1386.8	1293.8	1232.8	828.2	849.1	48.9	54.2	52.5	54.8	65.1	67.1	56.3	55.5	75.4	
12	60.0	60.1	60.0	63.2	882.8	885.9	1274.1	1238.8	1657.1	1821.2	1964.8	1953.4	1852.8	1742.9			33.4	51.0	60.3	63.9	82.7	84.0	61.9	61.0	81.3	
18.25	73.1	73.7	75.0	75.6	1311.4	1299.4							2512.3	2495.1			61.5	66.5	63.8	70.3	93.6	95.9	66.2	67.4	104.1	
22	79.5	81.0	83.2	83.1	1516.1	1568.6											66.3	78.1	75.6	83.9	120.4	122.6	76.5	77.6	149.2	
28	93.4	94.7	97.1	98.0													76.9	91.3	81.3	97.9	157.1	155.8	84.2	85.6	222.2	
34	108.9	111.0	110.3	109.8													91.9	114.7	93.1	124.5	238.2	240.3	96.8	97.6	475.8	
46	142.9	145.5	138.7	133.6													133.9									
1800°F (982.2°C)																										
1	259.4	144.0	116.7	134.5	248.1	197.1	583.9	534.0	1193.1	1204.9	1368.5	1331.8	645.6	496.1	737.9	763.3	633.8	300.2	123.3	123.5	169.8	164.7	165.3	159.1	235.0	
2	366.9	213.6	155.0	187.7	620.1	479.9	2055.6	2338.3					1287.0	1234.2	1728.5	1778.2	1087.8	986.5	158.9	162.9	231.8	237.1	206.9	202.8	527.8	
3	447.9	273.5	205.2	241.6	1071.0	918.7	2613.8	2641.1					1876.7	2114.6			1328.2	1322.3	184.8	199.2	321.2	331.7	239.2	236.2	822.7	
4	518.9	345.6	271.6	308.1	1375.7	1256.0							2456.0	2628.7			1514.6	1542.8	209.0	230.1	444.7	444.8	272.3	269.1	1153.8	
5	607.5	434.2	364.9	389.6	1704.7	1594.5											1687.2	1717.7	227.6	261.8	665.0	568.9	315.0	308.9	1565.9	
6	733.3	552.4	496.1	491.4	2178.0	2093.6											1874.1	1898.2	258.7	372.3	842.7	700.6	371.7	353.7	1846.9	
7	889.3	692.1	642.4	611.7	2453.8	2405.9											2045.2	2051.2	283.5	639.9	921.3	811.3	423.9	404.7	2031.8	
9	1201.9	1087.6	987.2	890.7													2317.0	2312.0	346.3	1408.8	1144.8	994.1	536.5	519.9		
12	1603.1	1699.0	1484.1	1296.7													2450.7	2479.1	634.6	1991.6	1504.0	1167.0	688.0	685.0		

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Table XIII

AVERAGE CUMULATIVE WEIGHT INCREASE PER ORIGINAL UNIT AREA OF SPECIMENS OF GROUP V ALLOYS AT 1200, 1500 AND 1800°F.

	1%Cu- 1%Ni	2.5%Cu- 2.5%Ni	1%Cb - 1%Ta	2.5%Cb - 2.5%Ta	1%V - 1%Sn	2.5%V - 2.5%Sn	1%Cb - 1%Sn	2.5%Cb - 2.5%Sn	1%Cu - 1%Nb	2.5%Cu - 2.5%Nb	1%W- 1%Cu	2.5%W- 2.5%Cu	Zr Stand.
1200°F (648.8°C)													
	Average Surface Area (cm ²) of Specimens												
	14.72	14.48	14.71	14.77	14.58	14.42	14.63	10.49	13.52	14.12	14.91	14.33	14.47
Cumulative Time Hours)	Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)												
1	0.8	0.7	2.1	2.4	1.3	1.7	1.1	1.3	0.8	0.7	0.8	0.7	0.6
3	1.0	0.9	2.9	3.0	2.4	2.4	1.7	2.2	1.0	0.9	1.1	0.9	1.0
6	1.4	1.2	3.8	3.8	3.7	3.4	3.3	4.0	1.2	1.2	1.4	1.2	1.4
12	1.7	1.4	5.0	5.7	6.5	5.8	6.3	7.6	1.4	1.4	1.7	1.5	1.8
23	2.0	1.6	7.5	9.3	12.2	9.9	12.0	14.6	2.0	1.7	2.1	1.8	2.2
30	2.3	1.9	9.4	11.5	16.4	12.9	15.6	19.2	2.6	1.8	2.3	2.0	2.5
36	2.6	2.1	11.1	13.2	20.1	15.1	19.0	22.8	3.3	1.9	2.5	2.1	2.6
48	2.7	2.3	14.4	17.1	28.5	20.5	25.2	30.7	4.2	2.1	2.8	2.2	2.9
60	2.8	2.4	17.3	20.1	36.9	25.7	30.4	36.7	4.8	2.1	3.1	2.3	3.1
73	3.0	2.7	20.3	23.3	46.2	31.3	35.7	41.0	5.3	2.3	3.4	2.5	3.5
98	3.3	2.9	25.9	29.3	63.9	43.0	48.1		6.5	2.6	4.2	2.8	4.3
121	3.6	3.1	30.7	35.9	78.6	53.1	54.7		7.2	2.7	4.9	3.0	5.3
145	3.8	3.2	35.4	38.3	93.5	63.2	63.2		8.0	2.8	5.5	3.1	6.7
169	4.1	3.5	40.8	44.0	104.8	74.4	71.6		8.9	3.0	6.6	3.3	9.3
192	4.3	3.7	47.2	48.4		86.5	81.8		9.8	3.2	7.6	3.5	12.7
1500°F (815.6°C)													
	Average Surface Area (cm ²) of Specimens												
	14.67	14.48	14.72	14.86	14.49	14.52	14.68	10.44	13.52	14.10	14.91	14.28	14.43
	Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)												
1	1.8	1.6	6.9	10.0	7.5	9.0	3.9	6.2	1.8	1.8	1.9	1.7	2.1
2	2.1	2.0	9.4	17.7	16.4	16.3	11.2	18.0	2.1	2.0	2.2	2.0	2.6
4	2.6	2.5	17.2	32.5	35.3	35.2	29.3	38.5	2.6	2.6	2.9	2.6	3.4
6	3.2	3.1	27.2	47.3	54.5	58.0	49.3	61.0	3.1	3.1	3.5	3.1	4.1
9	3.7	3.8	44.0	69.5	86.2	86.9	86.2	80.3	3.6	3.5	4.0	3.5	4.6
12	4.1	4.3	60.1	84.5	120.0	134.9	122.7		4.0	3.8	4.4	3.9	5.2
18.25	5.0	5.2	88.7				170.9		4.5	4.4	5.6	4.3	6.3
22	5.5	5.7	104.8						4.9	4.8	6.4	4.7	7.2
28	6.4	6.7							5.8	5.7	8.2	5.4	10.3
34	7.5	7.6							6.8	6.4	10.5	6.0	15.4
46	9.8	9.4							9.2	7.7	16.1	6.8	33.0
1800°F (982.2°C)													
	Average Surface Area (cm ²) of Specimens												
	14.81	14.47	14.81	14.84	14.50	14.69	14.78	10.45	14.89	14.32	14.96	14.39	14.39
	Average Cumulative Weight Increase (mg) per Average Original Unit Area (cm ²)												
1	13.6	8.7	15.0		37.7	91.9	38.6	71.8	28.0	8.6	11.2	11.3	16.3
2	19.6	11.8	37.1	148.0			85.3	167.8	69.7	11.2	15.7	14.2	36.7
3	24.4	15.4	67.2	177.0			135.0		89.0	13.4	21.8	16.5	57.2
4	29.2	20.0	86.9				172.1		102.6	15.3	29.7	18.8	80.5
5	35.2	26.1	111.4						114.3	17.1	41.9	21.7	108.8
6	43.4	34.1	144.3						128.6	22.0	51.6	25.2	128.4
7	53.4	43.3	184.1						137.5	32.3	57.9	28.8	141.2
9	76.7	64.9							155.4	61.3	71.5	36.7	
12	111.5	96.1							185.5	91.7	89.3	47.7	

TABLE XIV
ZIRCONIUM-BASE ALLOYS LISTED IN ORDER OF INCREASING AVERAGE
WEIGHT INCREASE PER AVERAGE ORIGINAL UNIT AREA PER HOUR

1200°F				1500°F				1800°F			
Alloy	Total Time (Hours)	Average Weight Increase (mg/cm ² /hr)	Char. of Scale*	Alloy	Total Time (Hours)	Average Weight Increase (mg/cm ² /hr)	Char. of Scale	Alloy	Total Time (Hours)	Average Weight Increase (mg/cm ² /hr)	Char. of Scale*
5%Cu	194	0.014	AX	2.5%W-2.5%Cu	46	0.15	AX	5%Ni (IV) ***	313.0	0.34	CZ
5%Ni	194	0.014	AX	5%Ni	43	0.17	AX	5%Cu (IV) ***	263.0	0.51	CZ
2.5%Cu-2.5%Sb	192	0.016	AX	2.5%Cu-2.5%Sb	46	0.17	BX	5%Ni (I)	7.1	1.25	AX
2.5%W-2.5%Cu	192	0.018	AX	5%Cu	43	0.18	AX	5%Cu (I)	7.6	1.77	AX
2.5%Cu-2.5%Ni	192	0.019	AX	1%Cu	43	0.18	AY	2.5%W-2.5%Cu	12.0	3.98	BZ
1%Cu-1%Ni	192	0.022	AX	2.5%Cu-2.5%Ni	46	0.20	BX	2%Pd	9.6	4.52	CZ
5%Ag	194	0.028	AX	1%Cu-1%Ni	46	0.20	BY	1%Ni	7.0	4.59	BZ
1%Cu	194	0.035	CX	1%Cu-1%Ni	46	0.21	BX	2%Co	6.9	5.10	BZ
1%W-1%Cu	192	0.040	AX	1%Ni	43	0.35	BY	2%Rh	9.8	6.00	CZ
2%Ag	194	0.043	AX	1%W-1%Cu	46	0.85	BZ	5%Ag	7.4	6.92	CZ
2%W	194	0.044	AX	Zr (V)	46	0.72	BZ	1%W-1%Cu	12.0	7.44	CZ
Zr (IV)	194	0.047	AX	Zr (III)	46	0.75	BZ	2.5%Cu-2.5%Sb	12.0	7.64	CZ
1%Ni	194	0.051	AX	5%W	46	0.79	CY	1%Cu	7.5	7.72	CZ
1%Cu-1%Ni	192	0.051	AX	5%Mn	46	0.81	CZ	2.5%Cu-2.5%Ni	12.0	8.00	CZ
2%Mg	194	0.065	AX	Zr (I)	43	0.88	CZ	2%Al	4.0	8.55	-
Zr (V)	192	0.068	AX	2%Co	43	1.01	BZ	2%W	6.5	9.13	-
Zr (III)	194	0.072	AX	Zr (II)	42	1.02	BZ	1%Cu-1%Ni	12.0	9.28	CZ
Zr (I)	194	0.079	AX	1%Cr	43	1.15	BZ	2%Co	8.2	9.61	-
Zr (III)	194	0.079	AX	Zr (IV)	46	1.34	CZ	2%Fe	6.7	9.88	CZ
5%W	194	0.082	BX	2%Mg	48	1.38	CZ	2%Ir	9.8	11.02	CZ
2%Ta	194	0.088	AX	2%Fe	43	1.39	CZ	5%W	5.0	11.93	-
2%Pd	194	0.088	AX	2%Ba	48	1.48	CZ	2%Mn	5.0	12.43	-
2%La	194	0.089	BY	2%Pd	42	1.83	CZ	5%Sn	8.5	13.19	CZ
5%Ta	194	0.092	AX	2%Al	9	1.84	-	2%Ru	8.1	13.50	-
2%Fe	194	0.099	BX	2%Mo	10	2.05	-	1%Cu-1%Ni	12.0	13.79	CZ
2%Rh	194	0.102	BX	2%Mn	30	2.11	-	2%Pt	8.1	13.87	-
1%Cr	194	0.105	AX	2%Pt	42	2.17	CZ	2%Ti	11.0	13.96	-
2%Co	194	0.106	AX	5%Ag	43	2.18	CZ	5%Co	5.3	14.10	-
5%Mn	194	0.108	BY	2%Ir	42	2.28	CZ	2%Os	9.6	14.83	CZ
2%Ir	194	0.110	BX	2%Ag	43	2.49	CZ	Zr (I)	5.7	16.10	-
2%Mn	194	0.122	BX	2%W	46	2.63	CZ	5%Ta	3.8	16.80	-
2%Pt	194	0.124	AX	2%La	14	2.82	-	5%Mn	3.0	18.35	-
2%Mo	194	0.134	BX	2%Ta	42	2.93	CZ	2%Ag	7.2	18.68	CZ
5%Mo	194	0.139	BX	2%Rh	42	2.99	CZ	2%Ba	6.0	19.50	-
2%Ba	194	0.142	CX	2%Pb	16	3.16	-	5%Ti	8.0	19.75	-
5%V	194	0.148	BX	5%Pb	16	3.80	-	5%La	4.0	19.97	-
5%La	186	0.148	BY	5%Mo	26	3.83	-	Zr (V)	7.0	20.17	-
2%V	194	0.157	BX	2%Zn	14	3.87	CZ	2%Mg	4.0	20.38	-
2%Co	194	0.159	CZ	5%La	9	4.15	-	Zr (III)	6.7	20.45	-
2%Ru	194	0.169	BY	2%Ru	18	4.19	-	Zr (III)	5.0	22.28	CZ
5%Co	81	0.179	-	2%Co	18	4.30	-	1%Co-1%Ta	7.0	23.45	-
2%Zn	194	0.217	BY	1%Si	16	4.74	-	2%La	4.0	23.63	-
1%Co-1%Ta	192	0.246	BY	1%Co-1%Ta	22	4.76	CZ	2%Mo	5.1	23.75	-
2.5%Co-2.5%Ta	192	0.252	CY	5%Co	7	5.21	-	2%Ta	6.8	24.19	-
2%Co	194	0.266	CY	5%Ta	7	5.66	-	5%Co	5.0	25.63	CZ
2%Os	194	0.289	CZ	2%Os	18	5.83	-	Zr (IV)	4.0	27.59	-
2%Pb	194	0.302	CX	2%Sn	18	6.11	-	2%Sn	4.0	29.38	CZ
2%Sn	194	0.346	CX	5%Cr	10	6.62	-	1%Si	3.0	30.15	-
5%Pb	194	0.402	CY	2.5%Co-2.5%Ta	12	7.04	CZ	1%Cr	5.2	34.30	-
1%Co-1%Sn	192	0.426	CY	5%Sn	16	7.52	CZ	2%Ge	3.0	34.37	-
2.5%V-2.5%Sn	192	0.451	CZ	2.5%Co-2.5%Sn	9	8.93	CZ	2%V	1.1	35.33	-
1%Si	107	0.492	CZ	1%Co-1%Sn	18.25	9.37	-	2%Zn	4.0	40.13	-
2.5%Co-2.5%Sn	73	0.562	CZ	1%V-1%Sn	12	10.00	-	1%Co-1%Sn	4.0	43.00	-
1%V-1%Sn	169	0.620	CZ	2.5%V-2.5%Sn	12	11.24	-	5%Cr	3.3	43.90	-
2%Ti	150	0.781	-	2%V	3	15.00	-	5%Mo	3.1	45.00	-
5%Cr	101	0.917	-	2%Si	6	20.03	-	2%Si	3.0	46.40	CZ
5%Sn	94	1.075	CZ	2%Ge	2	27.54	-	5%V	1.1	54.48	-
2%Si	44	1.498	CZ	5%Si	4	28.35	-	2.5%Co-2.5%Ta	3.0	59.00	-
2%Al	51	2.176	-	5%V	1	30.90	-	2%Pb	2.0	62.84	-
5%Si	19	5.107	CZ	2%Ti	1	57.69	-	1%V-1%Sn	1.0	82.71	-
5%Ti	12	7.764	-	5%Ti	-	-	-	2.5%Co-2.5%Sn	2.0	83.91	CZ
								2.5%V-2.5%Sn	1.0	91.89	-
								5%Pb	-	-	-

* A - Tightly adherent scale
B - Slightly cracked scale
C - Severely cracked scale
X - No distortion of specimen
Y - Slight distortion of specimen
Z - Severe distortion of specimen

** Disintegrated in less than one hour.

*** Rerun with Group IV Alloys.

VI. DISCUSSION OF EXPERIMENTAL RESULTS

A comparison of the weight increase of the zirconium standards used in the scaling tests at 1200°, 1500°, and 1800°F shows close agreement except for the standard of the Group IV alloys at 1500°F. No definite explanation can be given for the relatively wide discrepancy.

In general, the specimens of the alloys which had the greatest scaling rates also had wider divergencies between the weight increases of the two specimens. Also, the degree of divergence increased as the temperature was increased.

As shown in Figures 4 to 8, most of the curves exhibited a sharp increase in the scaling rate at various periods of time. In general, the alloys that had the greatest or least scaling rates did not have a break in their curves. This is similar to the results obtained by Garibotti, Green, and Baldwin⁶ on pure zirconium scaled in air. They found that at the lower and higher temperatures, logarithmic curves of weight increase versus time did not deviate from a straight line, whereas at intermediate temperatures they showed a sharp increase in the scaling rate.

In general, if an alloy having a low content increases the scaling resistance, then a larger content increases the scaling resistance still more. Conversely, if an alloy having a low content decreases the scaling resistance, then a larger content decreases the scaling resistance even further. The higher the temperature the more exceptions there are to these rules.

The ternary alloys did not show substantial improvement in scaling resistance over the binary alloys of 5% Cu and 5%Ni. The ternary alloy containing 2.5% of each of these elements had lower scaling resistance at all three temperatures than did their 5% binary alloys. The substitution of 2.5% Cu for 2.5% W to make the 2.5% Cu-2.5% W ternary alloy made a large improvement over the 5% W binary alloy, and at 1500°F this ternary alloy was the most scaling resistant of all the alloys. Also, the substitution of 2.5% Cu for 2.5% Sb to make the 2.5% Cu-2.5% Sb ternary alloy, produced an alloy which apparently has very good scaling resistance even though antimony decreased the scaling resistance of zirconium when in the form of binary zirconium-base alloys. However, at 1800°F there was a very wide divergence in the weight increases of the individual specimens, as shown in Table XII, and one specimen had considerably more distortion and cracking of the scale than the other. Time did not permit a retesting of this alloy at 1800°F, but this will be done in the future.

The alloying elements which lowered the scaling resistance of zirconium in the binary alloys, in most cases lowered the scaling resistance even further when combined into their ternary alloys.

More of the alloys had less weight increase than the zirconium standards at 1800°F than at 1200° and 1500°F, as can be seen in Table XIV. The reason for this behavior is not known for certain but may possibly pertain to the alpha-beta transition which, for pure zirconium, occurs at 1584°F (862°C). Since oxygen is more soluble in alpha than in beta zirconium (alpha - 7% and beta - 2%, by weight) then it would be expected that an element which stabilized the beta phase would reduce the amount of dissolved oxygen. Some elements which depress the alpha to beta transition of zirconium or are eutectoid formers are Cb, Ta, Ag, Co, Cr, Cu, Fe, Mn, Mo, Ni, V, and W.¹¹ Of these elements, when made into zirconium-base binary alloys, only Mo, V, and Cr increased the weight increase per cm² per hour and binary alloys containing Ta had about the same values as zirconium at 1800°F.

Attempts were made to correlate the relative effects of the alloying elements on the scaling resistance of zirconium with some of the physical and thermodynamic properties which were available on the elements and their oxides. However, due to the very many variables which must be considered in the scaling of the pure zirconium, let alone alloys of zirconium, no definite pattern could be established. More detailed studies will be made of some of the alloys in the future to gain a better understanding of their scaling mechanisms.

VII. CONCLUSIONS

It is apparent that the addition of alloying elements will increase, decrease, or produce essentially no effect upon the scaling rate of zirconium within the temperature range of 1200° to 1800°F. More of the alloys tested had greater resistance to scaling than zirconium at 1800°F than at the lower temperatures. A change in the percentage of the alloy content generally had the effect of either increasing or decreasing the scaling resistance even further.

The elements which decreased the scaling rate of zirconium to a large extent could not be determined decisively except by actual experimentation. The greatest hope for improvement of the scaling resistance of zirconium appears to exist in the use of copper and nickel, alone or in combination with other elements which decrease the scaling rate. However, other unsuspected possibilities may exist, similar to the ternary alloys containing copper and antimony, which will give considerable improvement.

VIII. FUTURE WORK

The experimental work expected to be accomplished in the future is as follows:

1. Preparation and testing for scaling resistance of additional ternary and possibly quaternary zirconium-base alloys. Particular emphasis will be placed on alloys containing copper and nickel.

2. Investigations of the scales of selected alloys by X-ray diffraction, metallography, and hardness tests in an attempt to determine the mechanism of the scaling of the alloys.
3. Any other studies which are mutually agreed upon by the contractor and investigators.

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