~~CONFIDENTIAL~~

UNCLASSIFIED

Argonne National Laboratory

HIGH TEMPERATURE STRENGTH ZIRCONIUM

AND TITANIUM BASE ALLOYS

FOR FUEL ELEMENT JACKETING

by

K. F. Smith and H. H. Chiswik

~~RESTRICTED DATA~~

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

UNCLASSIFIED

~~CONFIDENTIAL~~

DECLASSIFIED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

UNCLASSIFIED

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

ARGONNE NATIONAL LABORATORY

P. O. Box 299
Lemont, Illinois

ANL-5338

HIGH TEMPERATURE STRENGTH ZIRCONIUM AND TITANIUM
BASE ALLOYS FOR FUEL ELEMENT JACKETING

by

K. F. Smith and H. H. Chiswick

Final Report - Metallurgy Program 4.4.6

Portions of the material in this report have appeared
in the following Metallurgy Division Quarterly Reports:

ANL-5234	pp. 27-29	Oct., Nov., Dec., 1953
ANL-5257	pp. 17-18	Jan., Feb., Mar., 1954
ANL-5338	pp. 41-49	Apr., May., June, 1954

Price \$ 0.30

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

February 1956

CLASSIFICATION CANCELLED
DATE APR 2 1957
For The Atomic Energy Commission
H. R. Canale
Chief, Declassification Branch

Operated by The University of Chicago
under

Contract W-31-109-eng-38

UNCLASSIFIED

1 3085

TABLE OF CONTENTS

	<u>Page</u>
I. Introduction	3
II. Experimental Methods	4
III. Results and Discussion	5
IV. Conclusions	6
V. Acknowledgments	7

LIST OF TABLES

I. Tensile Data for Zirconium Alloys (Armour Research Foundation)	8
II. Tensile Data for Titanium Alloys (Armour Research Foundation)	9
III. Corrosion Rates of Zirconium and Titanium Alloys in Sodium at 660°C for 120 hours. (All Alloys Annealed at 650°C for 2 Days and Water Quenched)	10
IV. Corrosion Rates of Zirconium and Titanium Alloys in 680°F Degassed Water (All Alloys Annealed at 650°C for 2 days and Water Quenched)	11
V. Supplementary Corrosion Test on Titanium-8% Aluminum Alloy in Degassed Water (All Alloys Annealed at 650°C for 2 days and Water Quenched)	12
VI. Thermal Conductivities of Selected Alloys	12

LIST OF FIGURES

1. Tensile Strength of Zirconium and Titanium Alloys at 650°C .	13
2. Yield Strength of Zirconium and Titanium Alloys at 650°C . .	14
3. Yield and Tensile Strength of Zirconium and Titanium Alloys at 800°C	15

HIGH TEMPERATURE STRENGTH ZIRCONIUM AND TITANIUM BASE ALLOYS FOR FUEL ELEMENT JACKETING

by

K. F. Smith and H. H. Chiswik

INTRODUCTION

The successful development of liquid metal-cooled fast reactors for power production is strongly contingent upon the attainment of dimensional stability of the fuel assemblies. The use of alloying element additions, such as zirconium or plutonium, is expected to assist in promoting stability of fuel elements. However, the tendency in reactor design is to push operating temperatures to ever higher levels to take advantage of increased thermal efficiency in the steam turbine circuit. In combination with the economy inherent in less frequent processing and the resultant desire to operate to higher burnup, the trend to higher temperatures keeps the fuel element stability problem from receding very far from active consideration.

An alternate approach from alloying to improve the stability of a fuel element is to clad or to encase the fuel material in a jacket of sufficient strength to inhibit its tendency to distort in shape. Jacket strength of this order of magnitude is not difficult to realize without adding excessive structural material. Type 347 stainless steel restrains beta-treated uranium in thermal cycling into the gamma range in a thickness which adds only about 22 per cent to the structural volume of the fuel elements.* Using the strength of this material as an arbitrary criterion in this program, an attempt was made to develop zirconium- and titanium-base alloys of equivalent strength, the latter, unlike stainless steel, being metallurgically compatible with uranium in that they do not form low melting eutectics and/or no brittle intermetallic compounds with it.

As an accompaniment to the strength requirement, spot testing was carried out on several other critical properties, notably thermal conductivity and corrosion behavior in sodium and in pressurized water, to serve as rough screening guides as to the over-all usefulness of these alloys. Particular attention was paid to weldable type alloys.

*See ANL-5377, "Mechanical Stabilization of Uranium Fuel Elements," to be published.

4 EXPERIMENTAL METHODS

In a jacketing material to be used for the purpose of preventing distortion in uranium, the following properties are desirable:

1. Strength sufficient to overcome distortion in the core material without use of excessive thicknesses of jacketing material.
2. Good corrosion resistance in coolants.
3. Chemical compatibility with uranium - freedom from formation of brittle intermetallic compounds and low melting eutectics and with low inter-diffusion rates.
4. Ease of fabricability, including weldability without resort to special methods.
5. Thermal conductivity high enough to permit efficient removal of heat through the jacket.

Pure zirconium and pure titanium meet conditions 2 through 5 satisfactorily. Both are corrosion resistant to hot sodium, form no brittle intermetallic compounds with uranium, are fairly well fabricable, and although rather poor heat conductors, still are acceptable on that basis. However, in a pure state they lack strength at elevated temperatures. To improve their high temperature strength by alloying, a contract was entered into with Armour Research Foundation to prepare a number of alloys of compositions that appeared most promising on the basis of available information and to screen them with reference to their yield and tensile strengths. The spot checking for corrosion resistance and thermal conductivity was performed at Argonne, through the cooperation of the Reactor Engineering Division.

Both zirconium and titanium alloys are of four general types: (1) the alpha and beta isomorphous, with continuous solid solutions in both alpha and beta phases; (2) the beta isomorphous, with continuous solid solutions in the beta phase alone; (3) the beta eutectoid, in which the alpha-beta transformation temperature is lowered, and (4) the alpha type, in which the alpha-beta transformation temperature is raised. Types (3) and (4) are characterized by the existence of one or more intermetallic compounds.

For hot strength and weldability alloys of type (4) are preferable, aluminum and tin additions being prime examples. It is necessary to stay in the solid solution range with these materials to avoid loss of ductility due to the introduction of intermetallic phases. It was also considered desirable to include zirconium-titanium as a binary base, even though this system belongs to type (1), but the resulting ternary alloys proved later to be comparatively weak at elevated temperatures.

The test materials, as prepared at Armour,* were made from iodide zirconium and a good grade of sponge titanium as bases, and the alloy additions were of high purity. Titanium-base ingots weighing two kilograms were prepared, using double arc melting techniques. Zirconium-base ingots weighing 250 grams were melted a number of times in a non-consumable electrode arc furnace.

The titanium-base ingots were readily forged at temperatures of about 1175°C (2150°F). During forging, the zirconium alloys scaled to a much greater extent than did the titanium alloys and usually the scale was not adherent. Aluminum additions and larger titanium additions resulted in heavy scaling, although the zirconium-tin alloys were appreciably more oxidation resistant. Forging temperatures for the zirconium-base alloys varied from 1040°C to 1400°C (1900° to 2550°F), depending on the composition.

The tensile specimens prepared by Armour were 0.252-inch gage diameter by one-inch gage length. Annealing was performed in sealed Vycor bulbs. Specimens were pulled using a 60,000-pound Baldwin-Southwark tensile machine in conjunction with a Baldwin-Lima-Hamilton microformer extensometer.

The elevated temperature was supplied by a controlled Nichrome-wound furnace, thermocouples being attached to specimen shoulders. The inert atmosphere was supplied by a positive pressure of helium applied to the sealed furnace. Resulting contamination was very slight.

RESULTS AND DISCUSSION

The tensile data reported by Armour are reproduced in Tables I and II, with plots of selected compositions appearing in Figures 1-3. Compositions having less than 10% temperature ductility were arbitrarily considered to be of questionable use from the viewpoint of easy fabricability, although no attempts to roll these materials have been made. It should be pointed out in this connection, however, that in some of the alloys that developed good high temperature properties, the low ductility at room temperature might be improved by more suitable heat treatments; hence their discard from consideration cannot be considered as final.

The zirconium-aluminum and zirconium-tin binaries and the zirconium-aluminum-tin ternary are best according to yield and tensile strength criteria. All the titanium alloys have superior strength, but the 8 per cent aluminum alloy suffers in ductility. Comparative creep properties for two such alloys appear below.

*See Final Report, Project No. B 063, Armour Research Foundation, and "Elevated Temperature Strength of Selected Zirconium Base Alloys," R.J. Van Thyne and D. J. McPherson, Trans. ASM, v. 48, Reprint No. 46.

	<u>Ti - 7 Al</u>	<u>Ti - 7 Al - 3 Mo</u>
Stress for rupture in 100 hours (psi)	13,500	21,500
Stress for minimum creep rate of 1% in 100 hours (psi)	7,000	11,800

Corrosion data in 660°C sodium are shown in Table III. Short time tests such as these, lasting only 120 hours, can be expected to provide only a rough screening, and none of these alloy systems should be eliminated from consideration purely on the basis of these corrosion data. The zirconium-tantalum alloys appear to be somewhat more resistant, and the zirconium-titanium alloys slightly less resistant, than the general average. A trend toward weight losses in preference to gains is in evidence in most of the alloys containing titanium.

Tables IV and V show corrosion results in degassed water. Good corrosion resistance is indicated by the presence of a hard, adherent film and a low weight change. Some of the materials show promise in these short time tests, but long time tests on a large number of samples would be required before a critical evaluation can be made. The zirconium-tin and the titanium alloys appear to have the best chance for success.

Table VI gives the thermal conductivities for selected high strength zirconium and titanium alloys. It is evident that a serious impairment of conductivity has taken place as a result of alloying, with decreases ranging above 50 per cent. Thermal conductivity was measured on a comparison type of apparatus heated by NaK baths. These conductivities would be expected to be higher at service temperatures, but even then could scarcely be expected to be competitive with stainless steel, since the conductivity of the latter improves with rising temperature. Thus, a substantial price in thermal conductivity is paid in the use of these alloys for jacketing materials, particularly as temperature goals in reactor design are moved upward and heat transfer becomes of increasing moment.

CONCLUSIONS

It has been shown possible by means of alloying zirconium and titanium to obtain an order of high temperature strength which is at least comparable to that of some stainless steels, but only at a considerable cost in heat transfer. The following points are pertinent:

1. The following alloys have yield strengths in the temperature range 650° to 800°C equal to or greater than type 347 stainless steel, and have in excess of 10% room temperature elongation (Compositions are in weight per cent):

54

6

DECLASSIFIED

(a) Zirconium alloys:

3-4% Aluminum
7-10% Tin
(1.5 - 3%) Aluminum + (3 - 10%) Tin
5% Titanium + (3 - 15%) Tin

(b) Titanium alloys:

7% Aluminum
7% Aluminum + 0.5% Silicon
7% Aluminum + 3% Molybdenum (annealed only)

2. The zirconium-base alloys mentioned in 1 (a) above are not extensively attacked by sodium at 660°C but are not resistant to degassed water at 360°C, an exception to the latter being the tin alloys.
3. The titanium alloys listed in 1 (b) above are corrosion resistant under both conditions given in 2.
4. All the above alloys are weldable by inert arc methods. Their fabrication is expected to be difficult but possible.
5. The thermal conductivities of these alloys range from 0.019 to 0.022 cal-cm/cm²-sec.°C mean temperature of 130°C; this compares with 0.039 for type 347 stainless steel (same thermal units).

ACKNOWLEDGMENTS

The authors acknowledge with thanks the assistance of Messrs. D. O. Leeser, R. A. Stella, and C. R. Breden, of the Reactor Engineering Division, in carrying out the thermal conductivity and corrosion tests.

Mechanical property data were furnished by the Armour Research Foundation.

54 7 DECLASSIFIED

Table 1

TENSILE DATA FOR ZIRCONIUM ALLOYS (FROM ARMOUR RESEARCH FOUNDATION, FINAL REPORT, PROJ B 063)

Zirconium Base Alloy (wt %)	Tensile Strength (10 ³ psi)			Yield Strength (10 ³ psi)			Modulus of Elasticity (10 ⁶ psi)			Elongation (%)			Reduction of Area (%)			Footnote Number
	R T (1)	650°C(1)	800°C(2)	R T (1)	650°C(1)	800°C(2)	R T (1)	650°C(1)	800°C(2)	R T (1)	650°C(1)	800°C(2)	R T (1)	650°C(1)	800°C(2)	
Pure Zr	38.4	5.8		22.0	4.7	-	12	4.2	-	42	60		58	98	-	3
347 SS	-	51.2	23	-	41.0	14	-	22	-	-	46	75		71	-	
2 Al	92.6	36.8	18.0	82.0	28.4		13	7.2	-	16	57	62	22	94	99	8
		35.8	15.8		30.0	13.2		7	5.2		58	-		93	99	
3 Al	112.0	52.0	25.1	99.0	34.0	19.6	14	7	3.1	10	32	55	26	71	91	4
		51.6			34.0			8			49			79		
4 Al	124.6	56.0	-	107.0	36.0	-	13	6.5	-	6	58	-	13	98	-	3,5
5 Al	128.8	52.4	-	114.0	31.0	-	16	6.5	-	2	72	-	5	99	-	
5 Ti	52.2	24.2	3.9	33.0	-	2.8	9.5	-	3	42	60	-	-	96	98	
		19.7			17.4			4.6			90			95		
10 Ti	62.8	26.8	3.4	44.0	16.6	-	10.5	5.7	-	18	44	>250	37	97	99	7
15 Ti	89.2	18.4	-	60.0	16.0	-	10.5	3		12	78	-	26	99	-	3
		17.1			13.6			2.2			170			99		
25 Ti	122.4	4.4	-	67.0	4.0	-	12	3.8	-	6	>300	-	10	79	-	
45 Ti	143.6	4.2		106.0	3.2		11	2.7		6	>300		3	92		
5 Ta	87.0	24.8	7.7	67.0	22.4	4.8	13	6.3	3.4	12	34	48	37	99	95	3
10 Ta	128.6	30.6	3.5	106.0	27.2	2.6	13.5		3.8	2	33	> 50	8	98	93	4
15 Ta	118.2	39.0	4.8	92.0	36.0	3.2	13	8	3.4	2	17	77	4	50	99	4
20 Ta	-	36.4	-		25.0	-	-	5.3	-	-	34	-	-	90	-	
3 Sn	55.4	19.6	7.6	40.0	17.8	6.4	11.5	7.6	4.0	32	46	-	53	86	97	7
7 Sn	76.0	40.2	18.0	65.0	30.2	15.8	13.5	8	3.8	24	20	70	12	70	83	
		34.2			29.6			9.5			44			86		
10 Sn	95.0	47.8	27.7	75.0	36.0	24.0	12	9.5	4.4	19	33	74	25	60	94	3
1.5 Al-3 Sn	91.0	50.0	23.5	72.0	39.0	21.6	11	9	6	20	58	188	31	99	84	6
1.5 Al-7 Sn	-	62.6	24.2	96.0	48.0	19.2	-	7	5.6	-	44	77	-	60	99	
1.5 Al-10 Sn	-	48.0	24.4	-	36.0	20.6	-	-	5.2		35	>200	-	61	98	
2 Al-3 Sn	103.0	50.0	19.5	88.0	36.0	16.4	15	-	4.8	16	35	108	31	82	99	6
2 Al-7 Sn	-	68.0	21.2	>100.0	50.0	16.4	-	8	3.6		19	54		10	99	
2 Al-10 Sn	105.8	48.0	17.1	86.0	38.0	16.4	15	7	3.2	3	14	92	7	13	99	
2.5 Al-3 Sn	110.4	59.2	-	99.0	38.0		13	8	-	14	28	-	30	65	-	
3 Al-3 Sn	127.2	61.4	-	106.0	42.0	-	15	7	-	10	17	-	26	36	-	
5 Ti-3 Sn	64.0	22.5	-	47.0	20.4	-	12	6	-	18	52		34	91	-	
5 Ti-7 Sn	92.0	37.9	-	77.0	34.0	-	12	4.5	-	12	50	-	27	88	-	
5 Ti-10 Sn	117.2	47.4		103.0	34.8	-	12	5	-	4	82		9	93	-	
5 Ti-15 Sn	-	38.2	-	-	30.0	-	-	5	-	-	96	-	-	99	-	
5 Ti-2 Al	100.4	40.0	-	81.0	38.0	-	9	6	-	19	65		29	90	-	3
5 Ti-3 Al	123.0	30.4	-	108.0	24.0		13	3.5	-	4	102	-	9	99		
5 Ti-3 Cr	> 93.0	30.8	-	84.0	20.0	-	14	1.5		-	46		-	97	-	6
5 Ti-5 Ta	77.0	23.6	-	64.0	20.0	-	12	-	-	8	64	-	17	99	-	
3 Sn-2 Mo	81.2	27.6	-	60.0	22.0	-	13	7	-	14	30	-	24	99	-	
3 Sn-3 Cr	90.8	32.0	-	62.0	24.0	-	15	5	-	4		-	7	93		3
3 Sn-3 Ta	69.2	32.0	-	-	26.0	-	-	6.5	-	26	18	-	38	98	-	
5 Ti 3 Sn 1 Al	112.0	37.7	12.2	97.0	36.4	9.2	13	5.8	3.4	10	-	-	35	99	-	

- (1) Alloys annealed at 650°C for 2 days and water quenched
(2) Alloys annealed at 800°C for 1 day and water quenched
(3) Difficulties with test, but data considered valid
(4) Test data may be inaccurate, but enclosed for comparison only
(5) Broke outside gage length
(6) Broke during test
(7) Test performed at constant load rate
(8) Double annealing treatment

DECLASSIFIED

7
Table II

TENSILE DATA FOR TITANIUM ALLOYS (FROM ARMOUR RESEARCH FOUNDATION
FINAL REPORT, PROJ. B 063)

Titanium Base Alloy (wt %)	Tensile Strength (10^{-3} psi)			Yield Strength (10^{-3} psi)			Modulus of Elasticity (10^{-6} psi)			Elongation (%)			Reduction of Area (%)		
	R.T. (1)	650°C(1)	800°C(2)	R.T. (1)	650°C(1)	800°C(2)	R.T. (1)	650°C(1)	800°C(2)	R.T. (1)	650°C(1)	800°C(2)	R.T. (1)	650°C(1)	800°C(2)
7 Al	153.4	55.2	35.4	136.0	47.0	26.4	16	11	5.8	10	56	28	22	58	70
	160.2			143.0			16			13			22		
8 Al	125.8	74.6	28.5	-	46.0	26.0	15.5	13.5	7.7	0	32	38	4***	45	37
	96.0			-			14.5			0			4***		
7 Al-0.5 Si	132.6	77.6	27.0	126.0	67.0	24.6	16	11.5	6.5	16	-	16	26	63	22
	134.4			129.0			16			22			33		
7 Al-3 Mo	148.2	68.0	25.4	148.2	32.8**	21.6	17	7	3.4**	3	27	118	10	52	99
	148.8			-			19			***			-		
	146.4*			132.0			17			14			16		

*Annealing treatment: 875°C - 24 hr - Air Cooled; 650°C - 48 hr - Air Cooled.

**Difficulties with the test, but data considered valid.

***Brittle fracture.

(1)Alloys annealed at 650°C for 2 days and water quenched.

(2)Alloys annealed at 800°C for 1 day and water quenched.

10
Table III

CORROSION RATES OF ZIRCONIUM AND TITANIUM ALLOYS IN SODIUM
AT 660°C FOR 120 HOURS (ALL ALLOYS ANNEALED
AT 650°C FOR 2 DAYS AND WATER QUENCHED)

Alloy (wt %)	Corrosion Rate (mg/cm ² /mo)	Alloy (wt %)	Corrosion Rate (mg/cm ² /mo)
<u>Zirconium - Aluminum Alloys</u>		<u>Zirconium - Titanium Alloys</u>	
Zr-2 Al	- 32	Zr-5 Ti	+11.2
Zr-2 Al	+ 5.8	Zr-5 Ti	+ 9.6
Zr-3 Al	- 8.3	Zr-7 Ti	+29
Zr-4 Al	+ 6.4	Zr-7 Ti	- 9.6
Zr-4 Al	+ 3.5	Zr-10 Ti	-22
Zr-5 Al	+243*	Zr-15 Ti	-29
Zr-5 Al	+ 9.3	Zr-15 Ti	-43
<u>Zirconium - Tin Alloys</u>		Zr-25 Ti	- 7.7
Zr-3 Sn	+ 4.5	Zr-45 Ti	+12.8
Zr-3 Sn	+ 3.2	<u>Zirconium - Tantalum Alloys</u>	
Zr-7 Sn	+ 5.4	Zr-5 Ta	- 0.3
Zr-10 Sn	+ 0.3	Zr-5 Ta	+ 1.6
Zr-10 Sn	0.0	Zr-10 Ta	- 0.3
<u>Titanium - Aluminum Alloys</u>		Zr-10 Ta	+ 1.3
Ti-8 Al	- 8.0	Zr-15 Ta	+ 1.3
Ti-7 Al	- 9.6	Zr-15 Ta	+ 1.9
Ti-7 Al	- 5.1	Zr-20 Ta	+ 6.1
Ti-7 Al-3 Mo	- 5.4	Zr-20 Ta	0.0
Ti-7 Al-3 Mo	- 7.7		
Ti-7 Al- 1/2 Si	- 8.0		
Ti-7 Al- 1/2 Si	- 6.4		

*Questionable. No information on zirconium ternaries was obtained.

54 - 10

DECLASSIFIED

Table IV

CORROSION RATES OF ZIRCONIUM AND TITANIUM ALLOYS IN 360°C DEGASSED WATER
(ALL ALLOYS ANNEALED AT 650°C FOR 2 DAYS AND WATER QUENCHED)

Composition	Test Period (hr)	Corrosion Rate (mg/cm ² /mo)	Comments
Zr-2 Al	48	-2110	Heavy, loose, flaking, white coating.
Zr-3 Al	48	+ 518	Heavy, adherent, white coating, partly off on one end.
Zr-4 Al	48	- 30	Heavy, loose, flaking, white coating.
Zr-5 Al	48	+ 147	Heavy, loose, flaking, white coating.
	48	- 657	Heavy, loose, gray coating. Sample pitted.
Zr-10 Ti	48	+ 26.5	Adherent black coating with gray spots. Heavy, loose, flaking, gray coating.
	329	- 22.5	
Zr-15 Ti	48	+ 30	Adherent lustrous black coating. White spots on each end.
	329	- 3.09	Heavy, loose, flaking, gray and black coating.
Zr-25 Ti	48	+ 22.1	Adherent gray and black coating.
	329	+ 4.64	Adherent black coating with gray spots.
Zr-45 Ti	48	+ 5.30	Adherent blue-black coating.
	329	+ 2.70	Adherent dull black coating.
Zr-3 Sn	48	± 0.00	Adherent lustrous black coating.
	329	+ 0.515	Adherent lustrous black coating.
Zr-7 Sn	48	- 4.42	Adherent lustrous black coating.
	329	+ 0.515	Adherent lustrous black coating.
Zr-10 Sn	48	± 0.00	Adherent lustrous black coating.
	329	+ 1.03	Adherent mottled gray-black coating.
Zr-5 Ta	48	-2060	Heavy, loose, white coating.
Zr-10 Ta	48	+ 8.83	Adherent lustrous black coating. Small white spot at previous crack on one end.
	329	+ 6.44	Slightly loose white coating.
Zr-15 Ta	48	-1030	Heavy, loose, flaking, gray coating.
Zr-20 Ta	48	± 0.00	Adherent lustrous black coating.
	329	+ 3.09	Adherent lustrous gray speckled coating.
Ti-8 Al	48	± 0.00	Adherent blue, red and straw tarnish.
	329	± 0.00	Adherent, faintly iridescent, dark gray coating.
Ti-7 Al	48	+ 1.36	Adherent blue and dark straw tarnish.
	329	± 0.00	Adherent, faintly iridescent, blue-black coating.
Ti-7 Al-3 Mo	48	- 2.04	Adherent blue and dark straw tarnish.
	329	+ 0.298	Adherent dark blue tarnish.
Ti-7 Al-1/2 Si	48	- 2.04	Adherent blue and dark straw tarnish.
	329	± 0.00	Adherent, faintly iridescent, blue-black coating.

54

11

DECLASSIFIED

Table V

SUPPLEMENTARY CORROSION TEST ON TITANIUM-8% ALUMINUM ALLOY
IN DEGASSED WATER (ALL ALLOYS ANNEALED AT 650°C
FOR 2 DAYS AND WATER QUENCHED)

Temp (°C)	Time (Hr)	Rate (mg/cm ² /mo)	Comments
93	186	+1.22	Original appearance.
260	230	-0.621	Lustrous purple-blue coating.
260	712	+0.124	Faint gray coating over lustrous purple-blue tarnish.
260	714	-0.020	No change in appearance.
260	1481	-0.060	Adherent dark blue-gray coating.
360	334	+0.263	Adherent dark blue-gray coating.
360	671	0.000	Adherent dark blue-gray coating.
360	1481	+0.047	Adherent smooth, dark blue-gray and iridescent green coating.
360	713	0.000	Adherent smooth, dark blue-gray and iridescent green coating.

Table VI

THERMAL CONDUCTIVITIES OF SELECTED ALLOYS

Material	Mean Temperature		Thermal Conductivity	
	°C	°F	Cal-cm/cm ² -sec-°C	BTU-ft/ft ² -hr-°F
Ti	room	room	0.041	9.9 ⁽³⁾
Zr ⁽²⁾	100	212	0.046	11.2
Ti-7 Al- 1/2 Si	135	275	0.0206	5.0
Ti-7 Al	130	270	0.0211	5.1
Zr-10 Sn	131	267	0.0190	4.6
Zr-3 Al	133	271	0.0198	4.8
Zr-7 Sn	134	272	0.0224	5.4
347 SS	100	212	0.039	approx. 9.3 ⁽¹⁾

(1) ASM Metals Handbook, 1948. p. 566.

(2) Hafnium-containing crystal bar.

(3) Reactor Handbook, Vol. 3, p. 395.

FIGURE 1. TENSILE STRENGTH OF Zr AND Ti ALLOYS AT 650°C

54 13
DECLASSIFIED

FIGURE 2. YIELD STRENGTH OF Zr AND Ti ALLOYS AT 650°C

FIGURE 3. TENSILE AND YIELD STRENGTH OF Zr AND Ti ALLOYS AT 800°C