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BATTELLE MEMORIAL INSTITUTE

THE THERMAL AND ELECTRICAL CONDUCTIVITIES
OF ZIRCONIUM AND ITS ALLOYS

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INTRODUCTION

For the engineering applications of zirconium and its alloys, it is necessary to know their thermal conductivities. Although direct measurement of thermal conductivity would be desirable in all cases, the measurements are time consuming. The Wiedemann-Franz-Lorentz relation indicates a way to circumvent this difficulty. This relation enables us, in principle, to compute the thermal conductivity from the electrical conductivity. The measurement of electrical conductivity is a relatively simple and accurate procedure.

The purpose of this report is to present an empirical formula, based on available experimental data, to correlate the thermal and electrical conductivities of zirconium and zirconium alloys.

SUMMARY

This report contains a compilation of data available at Battelle on the thermal and electrical conductivities of zirconium and a number of zirconium alloys. These data are contained in Tables 1, 2, and 3.

A calculation has been made to correlate thermal and electrical conductivities with a view toward predicting thermal conductivities from the more easily measured electrical conductivities.

A calculation by the method of least squares indicates that the relation

$$K = 0.0368 (\sigma - 0.00327) T + 0.0381$$

best fits the available data. In the equation, K is in watt cm.⁻¹ °C.⁻¹, σ is in (microhm-cm.)⁻¹, and T is the Kelvin temperature. This relation

enables us to predict thermal conductivities from electrical conductivities with a maximum probable error of about ± 5 per cent.

ZIRCONIUM ALLOYS INVESTIGATED

Table 1 is a compilation of information on the zirconium alloys investigated. Each specimen is numbered for convenience in later reference. The description, analysis, and fabrication history of each alloy are presented where available.

THERMAL-CONDUCTIVITY DATA

Table 2 presents the thermal-conductivity data obtained at Battelle on zirconium and its alloys. The values have been interpolated from the curves drawn through the experimental points. The method used for measuring thermal conductivity was that of Van Dusen and Shelton⁽¹⁾. The estimated accuracy of the results is about ± 3 per cent.

ELECTRICAL-RESISTIVITY DATA

Table 3 contains the experimental data obtained at Battelle on the electrical resistivity of zirconium and its alloys. Resistivities are tabulated in microhm-cm.

The resistivities were measured at 25°C. and 260°C. by measuring the current through and the potential drop across the samples. A few measurements were made at 142°C. to verify the linearity of the resistivity versus temperature curves in the temperature range 25°C. to 260°C. The estimated accuracy of the measurements is ± 1 per cent.

TABLE 1. DESCRIPTION OF ZIRCONIUM AND ZIRCONIUM ALLOY SPECIMENS

Specimen No.	Nominal Composition	Battelle Identification	Zirconium Source and Method of Melting	Analysis, %								Fabrication History
				C	N	Sn	Ti	Hf	Al	Fe	Ni	
1	100% Zirconium		Westinghouse Ingot D-216. Arc-melted ingot of WEM crystal bar. Produced from crystal-bar Lot CB-37; crystal bar tested 2 weeks at 600°F. TAM sponge was feed material in the de Boer process.	-	-	0.001	0.007	0.04	0.001	0.04	0.02	Ingot upset forged at 1250°F. Forged billet machined to obtain a thermal-conductivity sample.
2	5% Sn, Bal. Zr		Produced from Grade 1 low-hafnium crystal-bar zirconium. Double arc melted with chipping after first arc melt.	0.016 0.009 (Two ends of sample)	0.007 0.008	4.84 4.86	0.017 0.011	0.023 0.025	0.009 0.009	0.25 0.22	0.006 0.005	Ingot upset forged at 1650°F. to a 1-inch-square bar. Difficulty in forging made it necessary to increase fabrication temperature to 1650°F.
3	5% Sn, Bal. Zr	337	Induction melted in graphite from low-hafnium Bureau of Mines sponge.	-	-	-	-	-	-	-	-	Forged at 1800°F. in air.
4	4% U, Bal. Zr		Ingot U724. Produced from Grade 1 low-hafnium crystal-bar zirconium. Double arc melted with chipping operations after first arc melt.	0.05	0.007	3.61% Uranium	-	-	-	-	-	Ingot was upset forged at 1250°F. Forged billet rolled to sheet at 1250°F. 100-mil reduction per pass. Annealed at 1450°F.
5	3% U, Bal. Zr		No information.	-	-	-	-	-	-	-	-	No information.
6	14% U, Bal. Zr		No information.	-	-	-	-	-	-	-	-	No information.
7	0.07% Ta, Bal. Zr		Alloy received from Argonne National Laboratory, identified as SA 1568. Annealed.	0.07	0.0055	-	0.007	-	0.02	0.10	-	None available.
8	0.16% Ta, Bal. Zr		Alloy received from Argonne National Laboratory, identified as SA 1576.	0.02	0.015	-	0.005	-	0.06	0.10	-	None available.
9	0.16% Ta, Bal. Zr		Specimen 8 after annealing.	-	-	-	-	-	-	-	-	

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TABLE 1 (Continued)

Specimen No.	Nominal Composition	Battelle Identification	Zirconium Source and Method of Melting	Analysis, %								Fabrication History
				C	N	Sn	Ti	Hf	Al	Fe	Ni	
First Series, Tin-Zirconium Alloys												
10	100% Zr	781-T1	Arc-melted low-hafnium crystal-bar zirconium. Double arc melted using a tungsten electrode and helium atmosphere.	0.05	0.008	<0.05	<0.001	0.076	0.004	0.034	-	Ingot was upset forged and rolled to sheet at 1250°F. Reduction during rolling, 100-mil pass. Sheet annealed at 1450°F. and sand blasted.
11	1% Sn, Bal. Zr	779-B1	Same as No. 10.	0.025	0.007	1.01	<0.001	0.08	0.004	0.038	-	Same as No. 10.
12	1% Sn, Bal. Zr	779-T1	Same as No. 10.	0.025	0.007	1.01	<0.001	0.08	0.004	0.038	-	Same as No. 10.
13	3% Sn, Bal. Zr	777-B1	Same as No. 10.	0.036	0.005	2.98	<0.001	0.085	0.004	0.04	-	Same as No. 10.
14	5% Sn, Bal. Zr	780-B1	Same as No. 10.	0.035	0.004	4.78	<0.001	0.08	0.004	0.032	-	Same as No. 10.
Second Series, Tin-Zirconium Alloys												
15	100% Zr	864	Arc-melted Grade 1 crystal-bar zirconium. Double arc melt using partial helium atmosphere and thoriated tungsten electrode.	0.021	0.008	<0.05	0.002	0.027	0.011	0.18	-	Upset forged at 1450°F. in air. Rolled at 1450°F. in air with a 100-mil reduction per pass.
16	1% Sn, Bal. Zr	865-B	Same as No. 15.	0.023	0.005	1.03	<0.001	0.025	0.012	0.17	-	Same as No. 15.
17	1% Sn, Bal. Zr	865-T	Same as No. 15.	0.013	0.005	1.00	<0.001	0.022	0.009	0.155	-	Same as No. 15.
18	3% Sn, Bal. Zr	866-D3	Same as No. 15.	0.031	0.006	2.97	0.045	0.03	0.008	0.185	-	Same as No. 15.
19	5% Sn, Bal. Zr	867	Same as No. 15.	0.033	0.005	5.00	0.001	0.04	0.005	0.21	-	Same as No. 15.

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TABLE 1 (Continued)

Specimen No.	Nominal Composition	Battelle Identification	Zirconium Source and Method of Melting	Analysis, %							Fabrication History	
				C	N	Sn	Ti	Hf	Al	Fe		Ni
<u>Third Series, Tin-Zirconium Alloys</u>												
20	100% Zr	881	Arc-melted Grade 1 crystal-bar zirconium. Double arc melted using partial helium atmosphere and thoriated tungsten electrode.	0.014	0.006	<0.05	-	-	-	-	-	Upset forged in air at 1450°F. Rolled at 1450°F. in air with an 84-mil reduction per pass.
21	100% Zr	881-B	Same as No. 20.	0.014	0.006	<0.05	-	-	-	-	-	Same as No. 20.
22	1% Sn, Bal. Zr	878	Same as No. 20.	0.019	0.006	1.03	-	-	-	-	-	Same as No. 20.
23	3% Sn, Bal. Zr	882	Same as No. 20.	0.019	0.005	2.98	-	-	-	-	-	Same as No. 20.
24	5% Sn, Bal. Zr	888	Same as No. 20.	0.014	0.004	4.82	-	-	-	-	-	Same as No. 20.
<u>Fourth Series, Tin-Zirconium Alloys</u>												
25	100% Zr	928	Arc-melted Grade 1 crystal-bar zirconium. Double arc melted using partial helium atmosphere and thoriated tungsten electrode.	0.021	-	<0.05	-	-	-	-	-	Upset forged and rolled in air at 1450°F. 100-mil reduction per pass.
26	1% Sn, Bal. Zr		Same as No. 25.	0.007	-	1.05	-	-	-	-	-	Same as No. 25.
27	3% Sn, Bal. Zr	930	Same as No. 25.	0.033	-	3.02	-	-	-	-	-	Same as No. 25.
28	5% Sn, Bal. Zr	927	Same as No. 25.	0.014	-	4.94	-	-	-	-	-	Same as No. 25.

TABLE 1 (Continued)

Specimen No.	Nominal Composition	Battelle Identification	Zirconium Source and Method of Melting	Analysis, %							Fabrication History	
				C	N	Sn	Ti	Hf	Al	Fe		Ni
Hoover Plate Series												
29	100% Zr		Hoover plate induction melted in graphite crucible; bottom poured into graphite mold.	0.33	0.02	<0.05	0.005	0.8	0.025	0.10	-	Used in as-cast condition.
30	5% Sn, Bal. Zr		Same as No. 29.	0.37	0.037	6.20	0.004	0.8	0.03	0.13	-	Used as cast.
31	5% Sn, Bal. Zr		Same as No. 29.	0.37	0.037	6.20	0.004	0.8	0.03	0.13	-	Forged and rolled at 1450°F.
32	10% Sn, Bal. Zr		Same as No. 29.	0.34	0.026	8.94	0.004	0.8	0.035	0.13	-	Used as cast.
33	15% Sn, Bal. Zr		Same as No. 29.	0.35	0.027	10.8	0.004	0.8	0.03	0.14	-	Used as cast.
34	25% Sn, Bal. Zr		Same as No. 29.	0.30	0.029	24.6	0.004	0.79	0.035	0.14	-	Used as cast.
Iodide Crystal-Bar Series												
35	100% Zr		Grade 3 low-hafnium crystal-bar zirconium received from Foote. Bars were machined and re-evaluated by corrosion.	-	-	-	-	-	-	-	-	Used as iodide deposited, machined.
36	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
37	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
38	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
39	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
40	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
41	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
42	100% Zr		Same as No. 35.	-	-	-	-	-	-	-	-	Same as No. 35.
43	100% Zr	910-84W	Lot No. 2 high-hafnium crystal bar zirconium. Bar produced from sodium-reduced crude, probably made by TAM.	-	-	-	-	-	-	-	-	Cold rolled and machined.

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TABLE 2. EXPERIMENTALLY DETERMINED THERMAL CONDUCTIVITIES OF ZIRCONIUM AND ZIRCONIUM ALLOYS

Specimen No. (a)	Nominal Composition	K, Thermal Conductivity (b)								
		25°C. (c)	50°C.	100°C.	142°C.	150°C.	200°C.	250°C.	260°C.	300°C.
1	100% Zr	0.211	0.209	0.204	0.200	0.200	0.196	0.192	0.191	0.187
2	5% Sn, Bal. Zr	0.096	0.098	0.101	0.104	0.105	0.108	0.112	0.112	0.116
3	5% Sn, Bal. Zr	0.084	0.086	0.090	0.094	0.095	0.098	0.103	0.104	0.107
5	3% U, Bal. Zr	0.140	0.141	0.142	0.143	0.143	0.144	0.145	0.146	0.147
6	14% U, Bal. Zr	0.111	0.113	0.116	0.119	0.120	0.123	0.127	0.128	0.130
7	0.07% Ta, Bal. Zr	0.189	0.188	0.184	0.182	0.181	0.178	0.175	0.174	0.171
8	0.16% Ta, Bal. Zr	0.186	0.184	0.181	0.178	0.178	0.175	0.172	0.171	0.168

(a) Data on source, fabrication, and analysis of specimens are in Table 1.

(b) Watt-cm⁻¹ °C.⁻¹.

(c) Values at 25°C. were obtained by extrapolating the experimental curve.

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TABLE 3. EXPERIMENTALLY DETERMINED ELECTRICAL RESISTIVITIES OF ZIRCONIUM AND ZIRCONIUM ALLOYS

Specimen No. (a)	Nominal Composition	Resistivity (b)			ρ_0 (c)	$\rho_{0\alpha}$ (d)
		25°C.	142°C.	260°C.		
1	100% Zr	44.1	-	81.3	40.2	0.158
2	5% Sn, Bal. Zr	107.8	117.3	127.5	105.7	0.084
3	5% Sn, Bal. Zr	121	-	141	118.7	0.085
4	4% U, Bal. Zr	59.7	-	92.7	56.2	0.140
5	3% U, Bal. Zr	71.1	-	102.5	67.8	0.134
6	14% U, Bal. Zr	85.5	-	116.0	82.2	0.130
7	0.07% Ta, Bal. Zr	50.5	68.2	85.1	46.8	0.147
8	0.16% Ta, Bal. Zr	52.4	70.1	86.6	48.8	0.146
9	0.16% Ta, Bal. Zr	52.3	(Specimen 8 annealed)			
10	100% Zr	47.3	-	85.5	43.2	0.162
11	1% Sn, Bal. Zr	64.1	-	99.0	60.4	0.148
12	1% Sn, Bal. Zr	64.6	-	99.5	60.9	0.148
13	3% Sn, Bal. Zr	91.0	-	117.0	88.2	0.111
14	5% Sn, Bal. Zr	116.6	-	137.5	113.8	0.112
15	100% Zr	48.9	-	87.0	44.8	0.162
16	1% Sn, Bal. Zr	64.6	-	96.1	61.2	0.134
17	1% Sn, Bal. Zr	65.4	-	99.6	61.8	0.146
18	3% Sn, Bal. Zr	93.6	-	118.5	91.0	0.106
19	5% Sn, Bal. Zr	109.5	-	132.0	107.1	0.096
20	100% Zr	46.6	-	83.5	42.7	0.157
21	100% Zr	46.2	-	-	-	-
22	1% Sn, Bal. Zr	61.5	-	94.5	58.0	0.140
23	3% Sn, Bal. Zr	90.6	-	117.8	87.7	0.116
24	5% Sn, Bal. Zr	112.0	-	133.0	109.8	0.089
25	100% Zr	49.7	-	-	-	-
26	1% Sn, Bal. Zr	65.5	-	-	-	-
27	3% Sn, Bal. Zr	93.0	-	-	-	-
28	5% Sn, Bal. Zr	116.3	-	-	-	-
29	100% Zr	56.2	-	97.3	51.8	0.175
30	5% Sn, Bal. Zr	138.0	-	150.5	136.7	0.052
31	5% Sn, Bal. Zr	139.5	-	151.2	138.2	0.05
32	10% Sn, Bal. Zr	154.7	-	164.5	153.7	0.042
33	15% Sn, Bal. Zr	164.5	-	170.0	163.9	0.024
34	25% Sn, Bal. Zr	147.0	-	168.5	144.7	0.091
35	100% Zr	45.9	-	82.0	42.0	0.154
36	100% Zr	45.0	-	81.6	41.1	0.156
37	100% Zr	44.6	-	81.8	40.6	0.158
38	100% Zr	44.6	-	80.5	40.8	0.153
39	100% Zr	44.9	-	81.0	40.0	0.154
40	100% Zr	46.4	-	81.8	42.8	0.146
41	100% Zr	44.9	-	81.7	41.0	0.157
42	100% Zr	45.1	-	81.0	41.3	0.153
43	100% Zr	47.9	-	85.9	43.8	0.162

Footnotes are on following page.

Footnotes for Table 3.

- (a) Data on source, fabrication, and analysis of specimens are in Table 1.
- (b) Microhm-cm.
- (c) Resistivity at 0°C., calculated in microhm-cm.
- (d) α is the temperature coefficient of resistivity in °C.⁻¹, and is the average value from 25 to 260°C.

The resistivity at temperatures other than the measured ones may be calculated from the relation

$$\rho = \rho_0(1 + \alpha t),$$

where ρ_0 is the resistivity in microhm-cm. at 0°C., α is the temperature coefficient of resistivity, and t is the centigrade temperature. Values of ρ_0 and $\rho_0 \alpha$ have been calculated and tabulated in Table 3.

CORRELATION OF THERMAL AND ELECTRICAL CONDUCTIVITIES

The work of Smith and Palmer⁽²⁾ on copper-base alloys indicated that a relation of the form

$$K = A\sigma T + B$$

existed between thermal and electrical conductivities. Here, K is the thermal conductivity, σ is the electrical conductivity, T is the absolute temperature, and A and B are constants. Later work on aluminum alloys⁽³⁾, magnesium alloys⁽⁴⁾, and iron alloys⁽⁵⁾ successfully used the above relation. A recent paper by Bungardt and Kallenbach⁽⁶⁾ obtained a somewhat better representation for the data on aluminum and magnesium alloys using a relation of the form

$$K = A\sigma T + BT.$$

Simple electron theory predicts that the constant, A , should have a value of about 0.025 watt-microhm °C.⁻² for all metals. In practice, the constants in the equations above must be determined experimentally.

For zirconium and its alloys, however, neither of the above relations gives a good fit to the data. We have found that the best fit is obtained with a relation of the form

$$K = A\sigma T - BT + C.$$

This may be written in the form

$$K = A(\sigma - B/A) T + C$$

Now if we plot K versus $(\sigma - B/A) T$, we have a straight line of slope A and intercept C.

Using the available experimentally determined values of K and ρ for zirconium and six zirconium alloys, we have calculated the constants A, B, and C by the method of least squares. The results are shown graphically in Figure 1.

The calculation gives

$$K = 0.0308 (\sigma - 0.00327) T + 0.0381, \quad (1)$$

where

K is in watt cm⁻¹ °C.⁻¹,

σ is in (microhm-cm)⁻¹, and

T is the Kelvin temperature.

The root-mean-square deviation of experimental points from the calculated curve is

$$\pm 0.0033 \text{ watt cm}^{-1} \text{ }^{\circ}\text{C}^{-1}.$$

It is estimated that thermal conductivities calculated from Equation 1 should not be in error by more than ± 5 per cent.

Because of the limited temperature range of the data, it would not be wise to rely on Equation 1 for temperatures below 0°C. or above 300°C. Furthermore, it must be remembered that Equation 1 is based on a rather restricted series of alloys and may not be satisfactory for all zirconium alloys. Further measurements are now in progress to test this point.

No attempt has been made to explain the form of the empirical relationship on theoretical grounds.

FIGURE 1. THERMAL CONDUCTIVITY VERSUS $(\sigma - 0.00327) T$ FOR ZIRCONIUM AND SIX ZIRCONIUM ALLOYS

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Table 4 contains calculated values of the thermal conductivity at 25°C. and 260°C. for those alloys for which electrical data are available. For the alloys for which both electrical and thermal data are available, a comparison of observed and calculated values is given. The maximum difference between observed and calculated values of thermal conductivity is 3.6 per cent.

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TABLE 4. THERMAL-CONDUCTIVITY VALUES CALCULATED
FROM ELECTRICAL RESISTIVITIES

Specimen No. (a)	Nominal Composition	K, Thermal Conductivity (b)					
		25°C.			260°C.		
		Calc. (c)	Obs.	% Diff.	Calc. (c)	Obs.	% Diff.
1	100% Zr	0.216	0.211	2.4	0.186	0.191	2.6
2	5% Sn, Bal. Zr	0.093	0.096	3.1	0.113	0.112	0.9
3	5% Sn, Bal. Zr	0.084	0.084	0	0.101	0.104	2.9
4	4% U, Bal. Zr	0.162	-	-	0.162	-	-
5	3% U, Bal. Zr	0.137	0.140	2.1	0.145	0.146	0.7
6	14% U, Bal. Zr	0.115	0.111	3.6	0.126	0.128	1.6
7	0.07% Ta, Bal. Zr	0.190	0.189	0.5	0.177	0.174	1.7
8	0.16% Ta, Bal. Zr	0.183	0.186	1.6	0.174	0.171	1.8
9	0.16% Ta, Bal. Zr	0.183	-	-	-	-	-
10	100% Zr	0.202	-	-	0.176	-	-
11	1% Sn, Bal. Zr	0.151	-	-	0.140	-	-
12	1% Sn, Bal. Zr	0.150	-	-	0.140	-	-
13	3% Sn, Bal. Zr	0.109	-	-	0.125	-	-
14	5% Sn, Bal. Zr	0.087	-	-	0.104	-	-
15	100% Zr	0.196	-	-	0.164	-	-
16	1% Sn, Bal. Zr	0.150	-	-	0.156	-	-
17	1% Sn, Bal. Zr	0.149	-	-	0.150	-	-
18	3% Sn, Bal. Zr	0.106	-	-	0.123	-	-
19	5% Sn, Bal. Zr	0.092	-	-	0.109	-	-
20	100% Zr	0.205	-	-	0.182	-	-
21	100% Zr	0.207	-	-	-	-	-
22	1% Sn, Bal. Zr	0.157	-	-	0.158	-	-
23	3% Sn, Bal. Zr	0.109	-	-	0.124	-	-
24	5% Sn, Bal. Zr	0.090	-	-	0.108	-	-
25	100% Zr	0.193	-	-	-	-	-
26	1% Sn, Bal. Zr	0.148	-	-	-	-	-
27	3% Sn, Bal. Zr	0.107	-	-	-	-	-
28	5% Sn, Bal. Zr	0.097	-	-	-	-	-
29	100% Zr	0.171	-	-	0.154	-	-
30	5% Sn, Bal. Zr	0.075	-	-	0.094	-	-
31	5% Sn, Bal. Zr	0.074	-	-	0.094	-	-
32	10% Sn, Bal. Zr	0.068	-	-	0.085	-	-
33	15% Sn, Bal. Zr	0.064	-	-	0.082	-	-
34	25% Sn, Bal. Zr	0.071	-	-	0.082	-	-
35	100% Zr	0.208	-	-	0.185	-	-

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TABLE 4 (Continued)

Specimen No. (a)	Nominal Composition	K, Thermal Conductivity (b)					
		25°C.			260°C.		
		Calc. (c)	Obs.	% Diff.	Calc. (c)	Obs.	% Diff.
36	100% Zr	0.212	-	-	0.185	-	-
37	100% Zr	0.214	-	-	0.185	-	-
38	100% Zr	0.214	-	-	0.188	-	-
39	100% Zr	0.212	-	-	0.187	-	-
40	100% Zr	0.206	-	-	0.185	-	-
41	100% Zr	0.212	-	-	0.185	-	-
42	100% Zr	0.212	-	-	0.187	-	-
43	100% Zr	0.200	-	-	0.175	-	-

(a) Data on source, fabrication, and analysis of specimens are in Table 1.

(b) Watt cm⁻¹ °C.⁻¹.

(c) Calculated values obtained from the equation

$$K = 0.0308 (\sigma - 0.00327) T + 0.0381.$$

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