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THERMAL CONDUCTIVITY OF TANTALUM, TUNGSTEN, RHENIUM, Ta-10W, T_{111}, T_{222}, W-25Re IN THE TEMPERATURE RANGE 1500-2800°K

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TECHNICAL REPORT AFML-TR-66-367

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Air Force Materials Laboratory
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THERMAL CONDUCTIVITY OF TANTALUM, TUNGSTEN, RHENIUM, Ta-10W, T_{111}, T_{222}, W-25Re IN THE TEMPERATURE RANGE 1500-2800°K

C. K. Jun and M. Hoch

FOREWORD

This report was prepared by the Materials Science Program, University of Cincinnati, under USAF Contract AF 33(615)-1759. The contract was initiated under Project No. 7367, "Research on Characterization and Properties of Materials," Task No. 736704, "Extreme High Temperature Research Studies, Techniques, and Measurements." The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, Mr. Hyman Marcus, Project Engineer.

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This report covers work conducted from April 1, 1965, through September 30, 1966. The manuscript was released by the authors in November 1966 as an RTD Technical Report.

This technical report has been reviewed and is approved.

Hyman Marcus

HYMAN MARCUS, Actg. Chief
Thermo & Chemical Physics Branch
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ABSTRACT

The thermal conductivity K of tantalum, tungsten, rhenium, Ta-10W, T_{111}, T_{222}, and W-25Re alloys was measured in the temperature range 1500-2800°K. The data are consistent and in agreement with theoretical considerations.

For Ta,

$K=(.718\pm.006)-(.435\pm.208)\times10^{-4}T$ watt/cm°K $1500<T<2700$°K.

For Ta-10W,

$K=(.720\pm.004)-(.655\pm.082)\times10^{-4}T$ watt/cm°K $1500<T<2700$°K.

For T_{111},

$K=(.749\pm.005)-(.675\pm.141)\times10^{-4}T$ watt/cm°K $1500<T<2800$°K.

For T_{222},

$K=(.770\pm.003)-(.910\pm.103)\times10^{-4}T$ watt/cm°K $1500<T<2000$°K.

For Re,

$K=(.601\pm.005)-(.712\pm.154)\times10^{-4}T$ watt/cm°K $1500<T<2400$°K.

For W-25Re,

$K=(.701\pm.007)-(.304\pm.270)\times10^{-4}T$ watt/cm°K $1500<T<2600$°K.

TABLE OF CONTENTS

NOMENCLATURE

K = thermal conductivity in watt/sec°K

ε = total emittance

σ = Stefan-Boltzmann radiation constant

T_o = temperature in °K, at center of flat circular surface

a = radius of the specimen in cm

L = half height of the specimen (center to end) in cm

ΔT = temperature difference (T_a-T_o) between center and edge on the flat circular surface of the specimen

K_o, K_o' = constant, characteristic of the length to diameter ratio of the specimen

Cp = specific heat, cal/g/°K

θ = time in seconds

A = area of the sample

m = mass of the sample in grams

d = density, g/cc

$C° = K_o + 0.1 \frac{\pi}{2} \cdot \frac{a}{L} \cdot K_o'$ a constant

r = independent radial variable

INTRODUCTION

There is a great need for accurate thermophysical data on the high temperature refractory metals and their alloys. Our paper reports measurements on the thermal conductivity of tantalum, tungsten, rhenium, and Ta-10W, T_{111}, T_{222}, and W-25Re alloys in the temperature range 1500-2800°K.

EXPERIMENTAL METHOD

Thermal Conductivity

The temperature distribution on the flat surface of a cylindrical disc heated in vacuum by induction has been used by Hoch, Nitti, Gottschlich, and Blackburn(1)* to determine the thermal conductivity of solid materials. The following equation applies:

$$K = \frac{\varepsilon \cdot \sigma \cdot T_o^4 \cdot a \cdot L}{4 \cdot \Delta T \cdot L \cdot K_o + .2\pi \cdot K_o' \cdot a \cdot \Delta T} = \frac{\varepsilon\sigma T_o^4}{4(\frac{dT}{dr^2}) \cdot a^2} \cdot \frac{a}{C^\circ} \qquad (1)$$

This method has been applied earlier to various materials [Vardi and Hoch(2), Hoch and Vardi(3), Jun and Hoch(4), and Hoch and Jun(5)].

Determination of Total Emittance

When a specimen is heated to high temperature and then let cool in vacuum, the specimen loses heat from the surface to the surroundings only by radiation. From the power balance, Hoch, et al.(6,7,8) derived the relationship:

$$\frac{Cp}{\varepsilon} \cdot \frac{d(1/T^3)}{d\theta} = \frac{3\sigma A}{m} \qquad (2)$$

Equation 2 yields Cp/ε.

The last equation requires the knowledge of the specific heat to obtain the total emittance. The following specific heat equations, derived in an earlier paper(9), were used.

For Ta, Ta-10W, T_{111}, and T_{222},

$$Cp = 3.17\times10^{-2}+5.073\times10^{-6}T \text{ cal/g°K}.$$

For W and W-25Re,

$$Cp = 3.022\times10^{-2}+5.368\times10^{-6}T+2.43\times10^{-10}T^2 \text{ cal/g°K}.$$

For rhenium,

$$Cp = 3.023\times10^{-2}+5.81\times10^{-6}T \text{ cal/g°K}.$$

EQUIPMENT AND EXPERIMENTAL PROCEDURE

The equipment and experimental procedure have been described earlier(2,6).

MATERIALS

The tantalum and tungsten were obtained from the Fansteel Metallurgical Corporation, North Chicago, Illinois. The Ta-10W, T_{111}, and T_{222} samples were supplied by the Thermophysics Branch, AFML, RTD. The rhenium, W-25Re samples were supplied by General Electric Company, NMPO, Cincinnati, Ohio.

Compositional analysis on the various samples is given in Table 1, which also gives the grain size of the samples used. The sample dimensions and the ratio of specific heat to total emittance is given in Table 2.

EXPERIMENTAL RESULTS

The experimental results on the various samples are given in Tables 3-9. In Figure 1, all the data obtained on tantalum are represented. The best straight line obtained by least squares analysis gives

$$K = (.718\pm.006)-(.435\pm.208)\times10^{-4}T \text{ watt/cm°K}.$$

It has to be pointed out that all five samples of tantalum were machined in our shop from the same 1" diameter tantalum rod. The samples were used differently, heated to high temperature, and several of them used in the study to show that Cp/ε(5,6,7) is constant and finally in the thermal conductivity measurements shown here. As one can observe in Table 2, an extremely large grain growth has occurred during these runs. The data presented in Figure 1 were obtained by two experimenters; samples 1, 4, and 5 by one, and samples 2 and 3 by the other. Keeping all this in mind, one can see that the data are fairly consistent.

In Figure 2 we have plotted the thermal conductivity of the tantalum base alloys. They all have a thermal conductivity a little less than tantalum and their slopes are parallel to each other. The only larger than expected fluctuation is observed in the Ta-10W in which sample No. 1 was first run, afterwards heated to 2700°K and the other points, marked sample No. 2 taken. This seems to indicate that sample No. 1 was not in equilibrium. The data can be represented as

$$\text{Ta-10W} \quad K = (.720\pm.004)-(.655\pm.082)\times10^{-4}T \text{ watt/cm°K.}$$

$$T_{111} \quad K = (.749\pm.005)-(.675\pm.141)\times10^{-4}T \text{ watt/cm°K.}$$

$$T_{222} \quad K = (.770\pm.003)-(.910\pm.103)\times10^{-4}T \text{ watt/cm°K.}$$

In Figure 3 we show the data on pure rhenium, tungsten, and W-25Re alloy. The tungsten samples 1, 2, and 3 were all machined from the same tungsten piece. Sample No. 1 was repolished and machined to obtain sample No. 2, after which it was again repolished to obtain sample No. 3. In the W-25Re material, sample No. 2 is a powdered metallurgy sample and sample No. 1 is an arc-cast sample; the difference between the two shows up mainly in the density.

$$\text{For rhenium} \quad K = (.600\pm.005)-(.712\pm.154)\times10^{-4}T \text{ watt/cm°K.}$$

$$\text{W-25Re} \quad K = (.701\pm.007)-(.304\pm.270)\times10^{-4}T \text{ watt/cm°K.}$$

DISCUSSION OF THE RESULTS

The variation of the thermal conductivity temperature can be evaluated theoretically using the equation given by Mott and Jones(10),

$$\frac{R}{T} = A(1+2\alpha_L\gamma T)$$

where R is the resistance, α_L is the linear thermal expansion coefficient, and γ is the Grüneisen constant. A is a constant. If all the conduction is electronic, then the electrical resistivity and thermal conductivity are related by the Wiedeman-Franz-Lorenz relation, $K\cdot R/T = L_o$. These relationships give

$$K = \frac{L_o}{A}\cdot\frac{1}{1+2\alpha_L\gamma T} \simeq \frac{L_o}{A}(1-2\alpha_L\gamma T).$$

Using the values 1.75 for γ, and $1 \times 10^{-5}/°K$ for the linear thermal expansion coefficient, we find that between 1500-2500°K the thermal conductivity should decrease by 3.5%.

The thermal conductivity of the tantalum alloys is somewhat lower than that of pure tantalum, as required by theory. The decrease in K between 1500 and 2500°K is 6% for Ta, 9% for Ta-10W and T_{111}, and 12% for T_{222}, which is in agreement with theory.

The thermal conductivity of tungsten drops extremely rapidly between 1500-2100°K and only drops very little between 2100-2600°K. Why the rapid drop in tungsten thermal conductivity between 1500-2100°K (which has also been observed by other investigators) cannot be explained at this moment. The thermal conductivity of rhenium drops 12% in agreement with theory. The crystal structure of rhenium is hexagonal, and therefore, should have two distinct values for the thermal conductivity. The axial ratio of rhenium is close to ideal and therefore we have assumed that the two thermal conductivities would not be too different from each other. The material used in this investigation was cut from a sheet which was probably rolled. Therefore, the measurements give an average thermal conductivity. The W-25Re alloy has a thermal conductivity much lower than that of tungsten, as expected, its decrease between 1500-2500°K is 4%. Thus the addition of 25 wt. % Re modifies the W material in so far as thermal conductivity behavior is concerned.

Further investigation may be necessary to explain the behavior of the thermal conductivity of tungsten and especially to find out the minimum alloying which is required to eliminate the rapid decrease in thermal conductivity.

TABLE 1. CHEMICAL COMPOSITION OF THE SAMPLES USED

(Everything in ppm, except where noted.)

Impurity	Tantalum 1	Tantalum 2, 3	Tantalum 4, 5	Ta-10W	T_{111}	T_{222}
C	19	137, 30*	.5	25	22	95
H	17	2.7	0.9	ND**	5	12
N	17	16	18	ND	23	ND
O	17	655,114,12*	36	20	34	6
W				9.0%	7.8%	8.5%
Hf					2.0%	2.5%

Impurity	W	Re	W-25Re No. 1	W-25Re No. 2
C	7	47	23	25
H	<.5			2
N	<5		<5	ND
O	<5	11,16	14	22
Re			25.04%	24.5%
Fe			0.001%	

* Data indicates segregation

** Not detected

TABLE 2. DIMENSIONS, GRAIN SIZE AND RATIO OF SPECIFIC HEAT TO TOTAL EMITTANCE FOR THE SAMPLES USED

Material	Sample	Dia. cm	Height cm	Mass gm	Density gm/cm^3	Avg. Grain Dia. mm	Cp/ε cal/gm°K
Ta	1	2.4892	.3927	31.8141	16.65	.26	.210±.010
	2	2.2232	.2125	13.7184	16.63		.195±.006
	3	2.2232	.2018	13.0145	16.62	1.04	.195±.006
	4	1.9075	.2316	11.0043	16.63	1.23	.210±.010
	5	1.9062	.2273	10.7614	16.60	1.86	.219±.008
Ta-10W	1	2.1265	.3254	19.5351	16.91		.210±.008
	2	2.1251	.3145	18.8511	16.91		.209±.006
T_{111}	1	2.5476	.2504	22.6110	16.73		.199±.005
	2	2.5476	.2504	22.6110	16.73		.209±.013
T_{222}	1	2.2524	.3320	27.8949	16.81		.197±.004
	2	2.2524	.3320	27.8949	16.81		.210±.004
Re	1	1.0711	.1582	2.9890	20.97	.020	.175±.012
W-Re	1	1.9196	.0766	4.3870	19.73	.216	.252±.004
	2	1.9208	.2103	11.6877	19.19	.041	.198±.003
W	1	2.5339	.2999	28.5044	18.89		.142±.004
	2	2.4785	.2714	24.9065	19.03		.153±.002
	3	2.0801	.2700	17.6461	19.23	.035	.182±.005

TABLE 3. THERMAL CONDUCTIVITY OF TANTALUM

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1	1578	21	.780	.617
	1746	34	.722	.584
	1841	42	.722	.590
	1942	52	.723	.597
	2007	59	.726	.606
2	1700	41.2	.799	.691
	1759	48.7	.775	.678
	1869	61.2	.784	.693
	1985	81.2	.752	.675
	2225	138.2	.697	.643
	2334	173.8	.672	.627
	2398	203.4	.640	.603
3	1660	38.6	.817	.703
	1828	59.9	.773	.680
	2043	109.3	.662	.598
	2269	149.8	.734	.680
	2391	224.2	.604	.567
	2490	264.3	.603	.574
4	1563	21	.765	.603
	1585	21	.809	.640
	1712	28	.826	.665
	1714	28	.829	.668
	1811	38	.762	.621
	1817	37	.793	.646
	1907	44	.809	.667
	2020	61	.734	.613
	2142	68	.833	.707
5	1665	26.5	.785	.601
	1816	36.5	.806	.630
	1923	47.5	.779	.616
	2043	63.5	.742	.597
	2162.5	78.5	.754	.615
	2260	95.5	.739	.610
	2468	142	.707	.597
	2542	159	.710	.605
	2671	193	.713	.616

TABLE 4. THERMAL CONDUCTIVITY OF Ta-10W

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1	1514	18	.696	.546
	1648	24	.732	.585
	1753	33	.682	.552
	1807	40	.635	.518
	1857	45	.630	.516
	1938	56	.600	.496
	1973	57	.634	.526
	2072	63	.697	.586
	2130	76	.645	.547
2	1731	29	.753	.610
	1868	40.7	.727	.599
	1990.5	54.9	.695	.581
	2075	65.4	.689	.582
	2238	90.7	.672	.580
	2496	147	.642	.571
	2619	190	.602	.542
	2742	233	.589	.538

TABLE 5. THERMAL CONDUCTIVITY OF T_{111}

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1	1652	43.8	.745	.628
	1816	65.4	.729	.627
	1912	82.7	.709	.617
	1990.5	98.1	.702	.617
	2103.5	128.4	.669	.596
	2324.5	195.1	.656	.600
	2430	237.2	.644	.596
	2520	277.6	.637	.596
	2604	333.9	.604	.570
	2671	366.4	.609	.579
	2756	430	.588	.565
2	1524	26	.852	.675
	1585	33	.785	.627
	1685	39	.848	.686
	1800	57	.756	.620
	1808	58	.756	.622
	1915	71	.777	.647
	1962	86	.707	.592
	2022	104	.660	.557
	2082	112	.689	.586

TABLE 6. THERMAL CONDUCTIVITY OF T_{222}

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1	1660	34	.725	.618
	1798	48	.707	.613
	1990.5	74	.688	.611
	2110.5	100	.644	580
	2231	126	.639	.584
	2291.5	152.5	.587	540
	2390	178.4	.594	.553
	2486.5	217.9	.570	.536
	2598.5	259	.571	.545
2	1509	20	.835	.650
	1662	32	.766	.609
	1716	36	.775	.621
	1784	45	.725	.585
	1842	51	.727	.591
	1925	61	.725	.596
	1933	63	.713	.587
	2052	82	.696	.581
	2111	92	.695	.584

TABLE 7. THERMAL CONDUCTIVITY OF TUNGSTEN

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1	1513	19	1.032	1.183
	1536	20	1.042	1.197
	1578	23	1.009	1.169
	1678	32	.912	1.072
	1748	37	.945	1.122
	1835	47	.903	1 088
	1898	54	.899	1.092
	1930	63	.824	1.008
2	1571.5	21	1.103	1.182
	1640	26	1.056	1.144
	1675	30	.996	1.084
	1719.5	34.5	.962	1.055
	1745.5	37.5	.940	1.036
	1835.5	46	.937	1.048
	1905	55.5	.901	1 017
3	1836	30.5	1.011	.950
	1948	39.5	.989	.946
	2206	70	.918	.911
	2350	93	.890	.902
	2463	119	.839	.866
	2608	146	.860	.905

TABLE 8. THERMAL CONDUCTIVITY OF RHENIUM

Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1577	12	.512	.483
1667	15.5	.495	.473
1766	19.5	.496	480
1837.5	23.5	.482	.472
1930	29	476	471
2065	40 5	446	450
2142.5	47.5	.441	450
2166	50	.438	448
2226	53.5	.456	.471
2294	67	.411	428
2397	84.5	.388	.411

TABLE 9. THERMAL CONDUCTIVITY OF W-25Re

Sample	Temp°K	ΔT°K	K/ε cal/sec cm°K	K watt/cm°K
1*	1616.5	52	1.069	.702
	1710	68	1.027	.682
	1887	107	.965	660
	1928	114	.987	.680
	2034	146	.955	.668
	2074	154.5	.976	.687
2**	1625	27	.767	.640
	1669	29.5	.781	.657
	1720	36	.722	.612
	1802.5	43	.729	.627
	1804.5	42.5	.741	.637
	1917	57.5	.697	.610
	1925.5	56	.723	.638
	2002.5	67.5	.707	.626
	2043.5	76.5	.677	.603
	2088	81	.697	.626
	2097	83	.692	.623
	2128	95	.641	.580
	2283	118	.684	.631
	2415	149	.678	.639
	2553	187	.674	.648

* arc cast
** powdered metallurgy

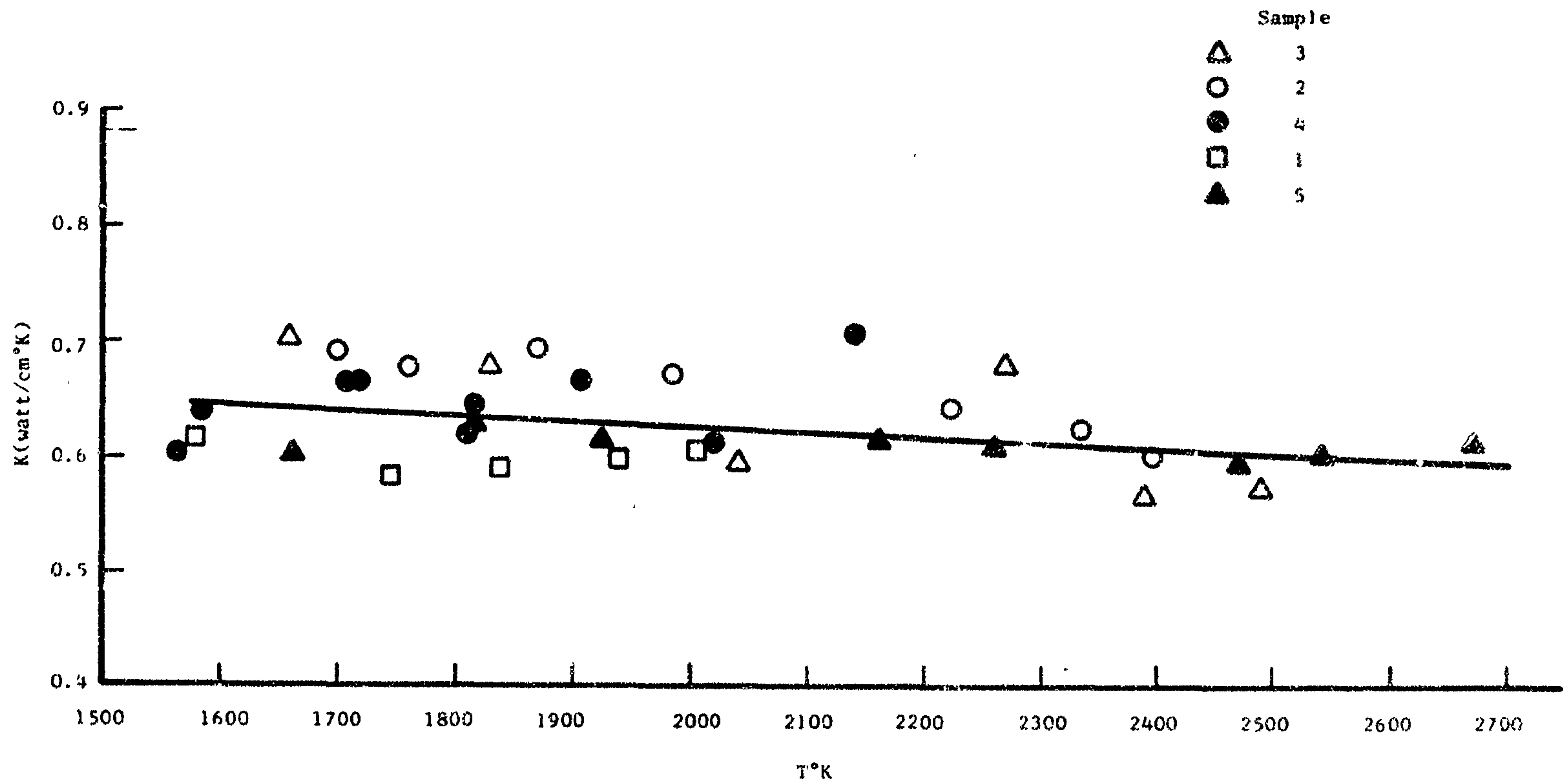

FIGURE 1. THERMAL CONDUCTIVITY OF TANTALUM

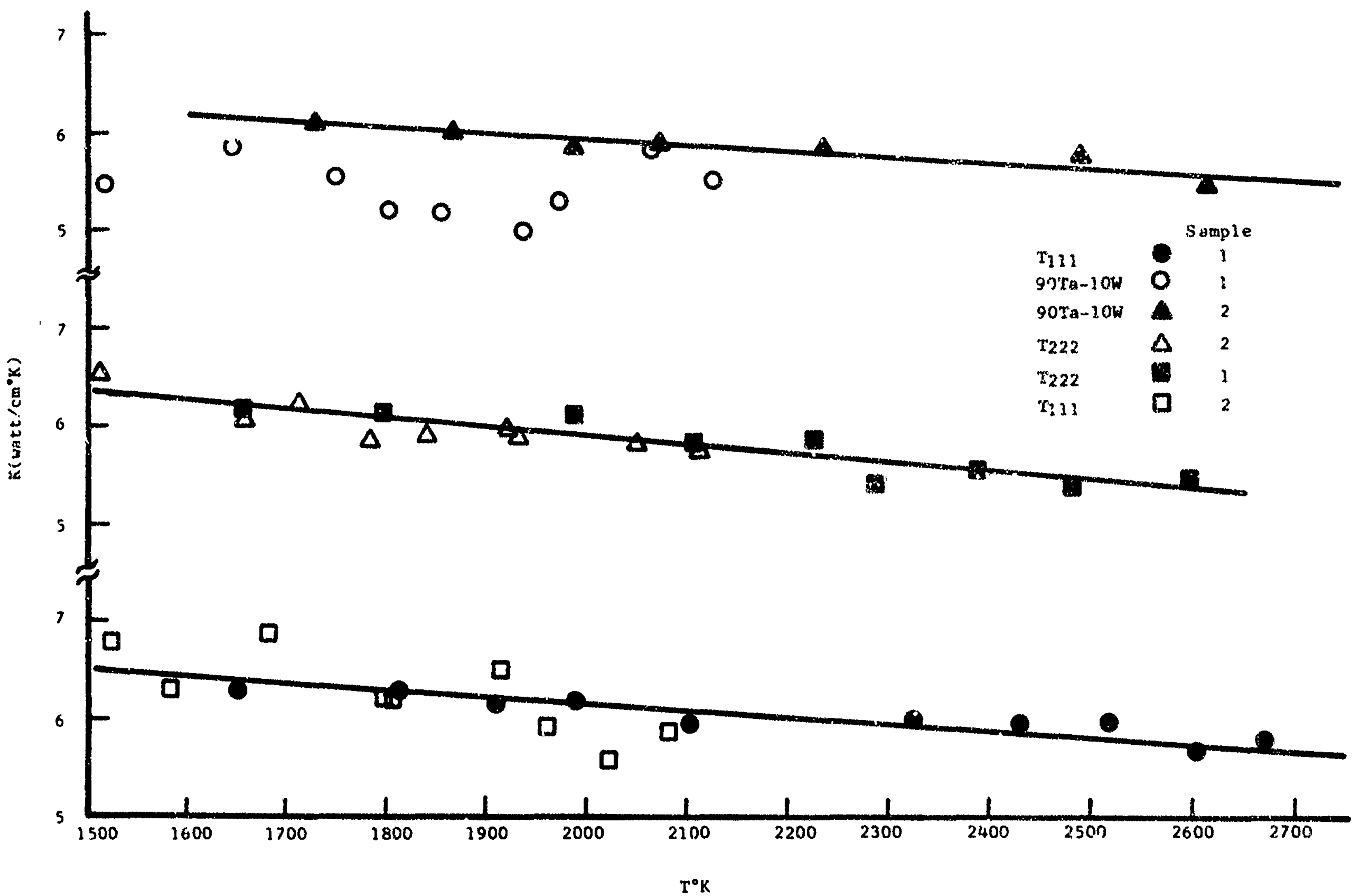

FIGURE 2 THERMAL CONDUCTIVITY OF TANTALUM ALLOYS

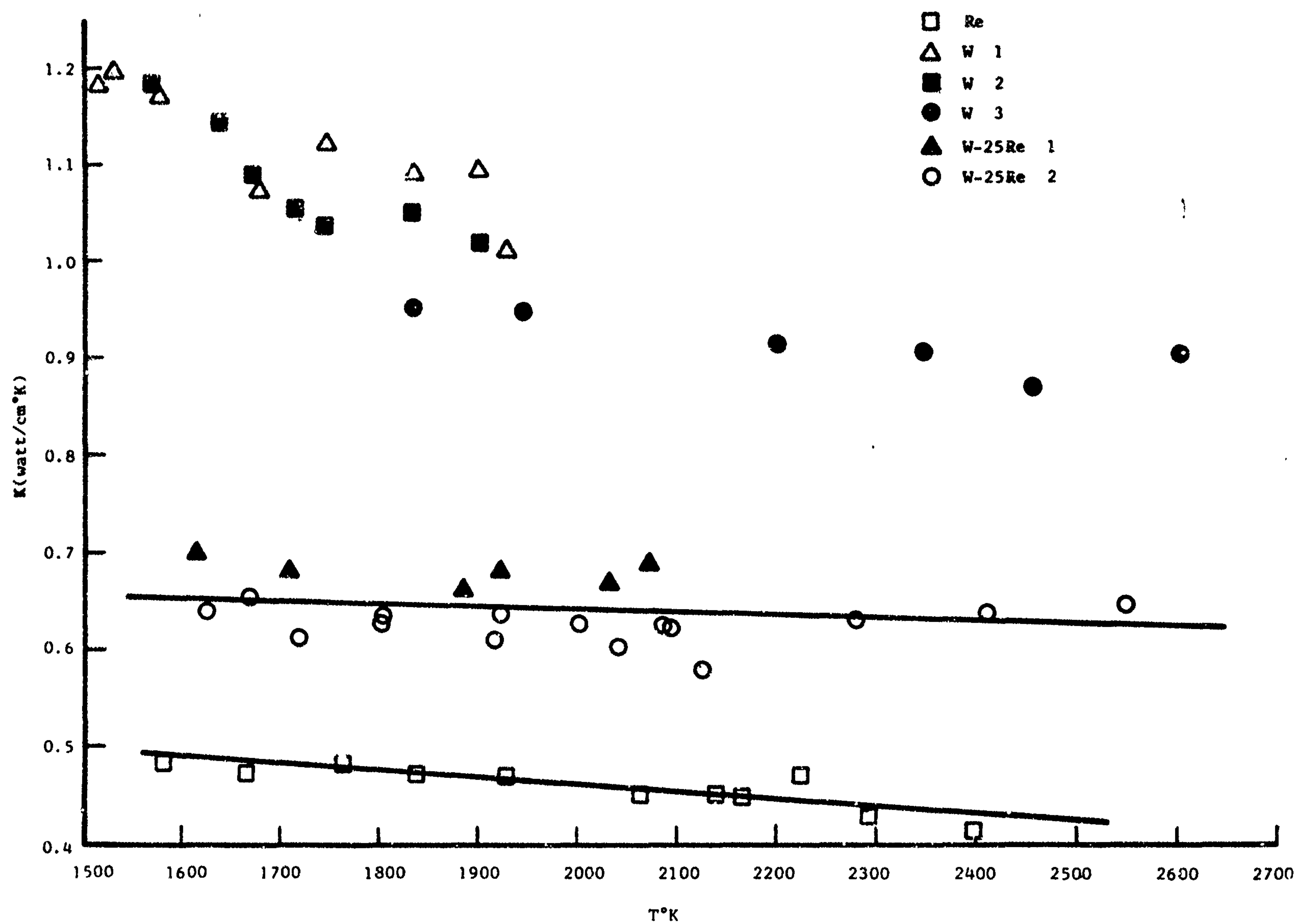

FIGURE 3 THERMAL CONDUCTIVITY OF TUNGSTEN, RHENIUM AND W-25Re

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13. ABSTRACT

The thermal conductivity K of tantalum, tungsten, rhenium, Ta-10W, T_{111}, T_{222}, and W-25Re alloys was measured in the temperature range 1500-2800°K. The data are consistent and in agreement with theoretical considerations.

For Ta,

$K=(.718\pm .006)-(.435\pm .208)\times 10^{-4}T$ watt/cm°K $1500<T<2700$°K.

For Ta-10W,

$K=(.720\pm .004)-(.655\pm .082)\times 10^{-4}T$ watt/cm°K $1500<T<2700$°K.

For T_{111},

$K=(.749\pm .005)-(.675\pm .141)\times 10^{-4}T$ watt/cm°K $1500<T<2800$°K

For T_{222},

$K=(.770\pm .003)-(.910\pm .103)\times 10^{-4}T$ watt/cm°K $1500<T<2000$°K.

For Re,

$K=(.601\pm .005)-(.712\pm .154)\times 10^{-4}T$ watt/cm°K $1500<T<2400$°K.

For W-25Re,

$K=(.701\pm .007)-(.304\pm .270)\times 10^{-4}T$ watt/cm°K $1500<T<2600$°K.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Thermal conductivity						
Total emittance						
Tantalum						
Tungsten						
T111, T222, Ta-10W						
Rhenium						
W-25Re						
Refractory metals						

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