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MEASUREMENTS OF THE THERMAL PROPERTIES OF METALS AT ELEVATED TEMPERATURES

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ABSTRACT

The thermal properties of tungsten have been measured from 1500°K to 2900°K using a resistance heated 10 mil wire suspended in a vacuum of 10^{-5} mm Hg. The temperature distribution along the wire was obtained with a two color photoelectric pyrometer utilizing a photomultiplier tube and two optical interference filters isolating two narrow wavelength bands in the visible region of the spectrum. The total hemispherical emittance was determined by measuring the electrical power dissipated at the center of the wire. The thermal conductivity was obtained from the slopes of the temperature distribution curve at selected points along the wire and from graphical integrations of the radiated power and generated power versus temperature curves. The ratio of the total hemispherical emittance and the heat capacity was found from the slope of a curve obtained by plotting the reciprocal of the temperature cubed versus time taken at the center of the wire after the electrical power was turned off.

The total hemispherical emittance was measured to vary from 0.27 at 1500°K to 0.36 at 2900°K while the range of heat capacity was from 0.030 cal/gm°K to 0.048 cal/gm°K in the same temperature interval. The thermal conductivity was linear over this temperature range, changing from 0.20 to 0.17 cal/cm sec°K. The product of the thermal conductivity and the electrical resistivity divided by the absolute temperature was nearly constant and was about 10% lower than the theoretical value of the Lorentz number.

SUMMARY

The Problem:

Materials used in the construction of rocket nozzles and combustion chambers and at the surfaces of missile nose cones and re-entry vehicles are required to operate at very high temperatures. The actual temperatures attained are determined in part by the total hemispherical emittance, the thermal conductivity, and the heat capacity. A knowledge of these thermal properties at elevated temperatures is essential in the design of structures to withstand the extremely high rates of heat transfer. Techniques need to be developed for obtaining reliable information on the thermal properties of metals and alloys in this temperature range.

The Findings:

A classical method for measuring thermal conductivity and total hemispherical emittance using electrically heated wires has been modified. A method for measuring the heat capacity of the same wire was devised. A two color radiation pyrometer was developed to measure the wire temperature. The validity of the system has been verified in a preliminary investigation. The work described in this report has incorporated the required experimental refinements indicated by the preliminary work, has introduced more reliable data handling techniques, and has provided better information on the high temperature properties of tungsten. In general, the experimental as well as the mathematical treatment has been refined. The validity of the method is verified by results obtained on tungsten from 1500°K to 2900°K.

LIST OF SYMBOLS

T	Temperature (degrees K)
λ	Wavelength
J_λ	Power radiated per unit surface area per unit wavelength band.
j_λ	Output voltage from the photoelectric pyrometer (volts).
C_1, C_2	First and second radiation constants.
φ_λ	Composite spectral sensitivity of the photoelectric pyrometer times C_1.
ϵ_λ	Spectral emittance of the radiating surface of the wire.
ϵ	Total hemispherical emittance.
σ	Stefan Boltzmann constant (5.67×10^{-12} watts cm^{-2} deg^{-4}).
K	Thermal conductivity (joule cm^{-1} sec^{-1} deg^{-1}).
C	Heat capacity at constant pressure (joule gm^{-1} deg^{-1}).
A	Cross sectional area of the wire (cm^2).
P	Radiating area per unit length (cm).
D	Density (gm cm^{-3}).
I	Current through the wire (amp).
E	Voltage per unit length (volt cm^{-1}).
R	Electrical resistance per unit length (ohm cm^{-1}).
ρ	Resistivity of the wire (ohm -cm).
t	Time (sec)
x	Distance along the wire (cm)
$\exp(n)$	e^n
m	Mechanical equivalent of heat (1 cal = 4.19 joules).
k	Boltzmann's Constant
e	Electronic charge

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INTRODUCTION

The extremely high speeds with which missiles travel through the earth's atmosphere lead to excessively high surface heating rates. The kinetic energy lost in slowing these vehicles down is consumed in heating the air, and temperatures near the surface of a nose cone may exceed 7000°K.[1] Heat is transferred from the high temperature air by conduction, convection, diffusion and radiation. High surface heating rates usually last for less than thirty seconds but the peak input rate may exceed one kilowatt per square centimeter.[2] Three mechanisms are always present which serve to accomodate at least a portion of this added burden of heat. Some of it will be re-radiated, some will be conducted into the interior, and some will be stored with an attendant increase in temperature. It is necessary to use refractory materials at the surface because of the high temperature that is attained there. The actual value of the temperature rise is determined by the total hemispherical emittance, the thermal conductivity, and the heat capacity as well as by other cooling techniques that might be applied in any given situation such as ablation, evaporation, or transpiration. The same thermal properties are important in controlling the temperature of the combustion chamber and the nozzle of a rocket where the heat fluxes are smaller but may persist for three or four minutes or longer.[2]

At the present time there are large gaps in the knowledge of these properties at high temperatures. In fact, there is a scarcity of practical methods of reliably determining these properties. This report describes a way of measuring the total hemispherical emittance, thermal conductivity, and heat capacity for the refractory metals and alloys and tests the validity of the technique by measurements on tungsten.

More is known concerning the high temperature behavior of tungsten than that of any other refractory metal because of its use in the incandescent lamp. The electrical resistivity and the total hemispherical emittance of a 10 mil tungsten wire between 1200°K and 2800°K have been measured by Forsythe and Watson.[3] The voltage at the center of the wire was obtained by them by attaching potential leads to the uniform temperature section. Their temperature was measured with a disappearing filament optical pyrometer corrected for spectral emittance by the values of Forsythe and Worthing.[4] The thermal conductivity of tungsten wire has been determined between 1200°K and 1900°K by Osborn[5] and between 1500°K and 2400°K by Worthing[6] by observing the temperature distribution along the non-uniform portion of the wire with a disappearing filament optical pyrometer mounted on a cathetometer. Whereas Worthing's work indicated a positive temperature coefficient of thermal conductivity, Osborn's experiments exhibited a negative one.

Preliminary experimentation has been conducted at the Naval Radiological Defense Laboratory[7] to determine the feasibility of measuring the total hemispherical emittance, the thermal conductivity, and the heat capacity of metals above 1000°K, using electrically heated wires with photoelectric methods of temperature determination. The work described in this report is a continuation of that study. Although the basic methods are the same, several modifications in the experimental set-up and in the data handling techniques have been introduced. Measurements were made on tungsten again to serve as a comparison and to give refinements to the preliminary results published in the earlier work. Supplements to this report will include results on the other refractory metals.

THEORY OF THE METHOD

The differential equation of heat flow in an electrically heated wire with no convective heat losses is given by

$$I^2R = IE = A\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \epsilon P\sigma T^4 + DAC\frac{\partial T}{\partial t} \tag{1}$$

if wall radiation and reflection can be neglected. The power terms on the left hand side of Equation (1) represent the rate of heat generation per unit length. They are equated to the rate of heat loss by conduction and radiation plus the rate of heat storage. The determination of the total hemispherical emittance, the heat capacity, and the thermal conductivity are achieved by isolating the various terms in Equation (1) experimentally.

Under static conditions at the center of a wire of sufficient length to establish a uniform temperature region in the central portion, the energy can be considered to be lost by radiation alone. Under these conditions Equation (1) reduces to

$$\epsilon = IE/P\sigma T^4 \tag{2}$$

which is the defining equation for the total hemispherical emittance.

When the electrical power is turned off the history of the temperature at the center of the wire obeys the following differential equation:

$$P\sigma\epsilon T^4 = -DAC\ dT/dt \tag{3}$$

Although the value of the ratio ϵ/C can be determined directly from Equation (3) as was done in the preliminary work, a more precise method is derived by integration. It is noted that ϵ and C are both mildly increasing functions of the temperature, and so their ratio is nearly constant over small temperature ranges. The integration of Equation (3) over the small temperature range between T_1 and T_2 leads to

$$\frac{1}{T_2{}^3} - \frac{1}{T_1{}^3} = \frac{3P\sigma\epsilon}{DAC}\ (t_2-t_1) \tag{4}$$

Thus, by plotting $\frac{1}{T^3}$ versus t, the slope at any temperature is a measure of ϵ/C. Using the measured values of emittance versus temperature, this relationship yields the heat capacity as a function of temperature. The virtue of using Equation (4) instead of Equation (3) is that slope measurements are much less difficult because of the linearity of the curve.

Under steady state conditions, Equation (1) reduced to

$$A\ \frac{d}{dx}\left(K\frac{dT}{dx}\right) = I^2R - P\epsilon\sigma T^4 \tag{5}$$

In order to evaluate the thermal conductivity, both sides are multiplied by KdT and integrated between T_c, the temperature at the center of the wire, and T_m, the temperature at which the thermal conductivity is to be determined.

$$\frac{A}{2}K_m^2\left(\frac{dT}{dx}\right)_m^2 - \frac{A}{2}K_c^2\left(\frac{dT}{dx}\right)_c^2 = \int_{T_c}^{T_m} K(I^2R - P\epsilon\sigma T^4)\ dT \tag{6}$$

The second term on the left is equal to zero since the wire is of sufficient length to establish a uniform temperature at its center. Since K is not very temperature sensitive, it can be represented by a linear function over a narrow temperature range, and thus

$$K \approx K_m + (T-T_m)\frac{dK}{dT} = K_m\left[1 + \frac{(T-T_m)}{K_m}\frac{dK}{dT}\right] \tag{7}$$

Substitution of Equation (7) into Equation (6) yields

$$K_m \approx \frac{2}{A}\left(\frac{dT}{dx}\right)_m^{-2}\left[1 + \frac{1}{K_m}\frac{dK}{dT}\,\frac{\int_{T_c}^{T_m}(T-T_m)(I^2R-P\epsilon\sigma T^4)\,dT}{\int_{T_c}^{T_m}(I^2R-P\epsilon\sigma T^4)\,dT}\right]\int_{T_c}^{T_m}(I^2R-P\epsilon\sigma T^4)\,dT \tag{8}$$

The ratio of the integrals within the brackets is the average value of $(T-T_m)$ weighted according to the function, $I^2R-P\epsilon\sigma T^4$, in the interval between T_m and T_c. Thus the expression within the brackets is given by

$$1 + \frac{\overline{T-T_m}}{K_m}\frac{dK}{dT} = \frac{K_a}{K_m} \tag{9}$$

where K_a is the thermal conductivity at $T_m + \overline{T-T_m}$. And finally, the expression for determining K from the experimental measured quantities is

$$K_m \approx \frac{2}{A}\left(\frac{K_A}{K_M}\right)\left(\frac{dT}{dx}\right)_m^{-2}\int_{T_c}^{T_m}(I^2R-P\epsilon\sigma T^4)\,dT \tag{10}$$

In practice the ratio $\frac{K_A}{K_M}$ is ignored in the initial plot of K versus T. From this curve the corrective factor is taken if it is significantly different from unity.

An alternate method of determining the thermal conductivity is obtained by multiplying both sides of Equation (5) by dx and integrating between the point at which T_m appears and the center of the wire

$$K_m A\left(\frac{dT}{dx}\right)_m^{-2} = \int_{x_m}^{x_c}(I^2R-P\epsilon\sigma T^4)\,dx \tag{11}$$

This is the technique used in the preliminary work and also by previous investigators.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Fig. 1. A spectrographically pure tungsten wire of 0.010 inch diameter was suspended vertically in a vacuum of better than 10^{-5} mm Hg and heated by passing an electrical current through it. The wire mount is constructed so that the metal arms which support the wire cannot rotate about the vertical axis, but are free to move in a vertical direction. This assures that the wire specimen is always vertical and it allows for variation of the wire length. The wire specimen is held in place by means of clamps built as a part of the supporting arms. The heating current from a variable d.c. supply is delivered through the wire mount to the wire. That portion of the wire specimen which extends beyond the clamps forms part of the potential leads of a high impedance (11 megohms) digital voltmeter from which voltage was determined with an estimated error of ±1%. In addition to measuring the voltage across the wire, this voltmeter is used to measure the current through a calibrated resistance in series with the wire, thereby giving an accurate determination of the wire current. An adjustable current which varies the length of the diagonal control wire shown in Fig. 1 serves to keep the specimen wire straight without strain as it expands with increasing temperatures.

The experimental arrangement is shown photographically in Fig. 2. The vacuum system is in the central portion of the photograph with the photoelectric pyrometer on the right and the optical pyrometer on the left. The wire mount cannot be seen but it is located directly behind the rectangular window on the right side of the vacuum chamber. Also not shown in the photograph are the d.c. supply for the wire, the digital voltmeter used to measure the wire current and voltage, and an oscilloscope.

The temperature along an electrically heated wire in a vacuum increases from the supporting structure to a point some distance from the end where it becomes constant and independent of wire length. This distance is a function of the ratio of the energy radiated from the surface to that conducted along the wire. The voltage gradient at the center of two wires of different lengths, both long enough to have a uniform temperature region in the center, will be equal to the difference in terminal voltage required to maintain the same current in each wire divided by the difference in length of the two wires. This is based upon the assumption that the temperature profile in the non-uniform temperature region of the wire is the same in both cases. This assumption was verified in the preliminary investigation and is confirmed by the present results.

TEMPERATURE DETERMINATION

The temperatures are measured with the photoelectric pyrometer shown schematically in Fig. 1. The optical system consists of a focusing lens, a slit, a collimating lens, an interference filter, and an end-on photomultiplier tube. The output of the photomultiplier is read on the digital voltmeter or displayed on an oscilloscope and photographed by a Polaroid Land Camera. The basis of the photoelectric pyrometer measurement is derived from Planck's radiation law,

$$J_\lambda = C_1 \lambda^{-5} \left[\exp\left(\frac{C2}{\lambda T}\right) - 1 \right]^{-1} \tag{12}$$

On the short wavelength side of the maximum of the spectral distribution curve, where $\left(\frac{C2}{\lambda T}\right) \gg 1$, Equation (12) reduces to the more convenient Wein's Law,

$$J_\lambda = C_1 \lambda^{-5} \exp\left(\frac{-C2}{\lambda T}\right) \tag{13}$$

For real surfaces the voltage measured by the pyrometer is

$$j_\lambda = \varphi_\lambda \epsilon_\lambda \lambda^{-5} \exp\left(\frac{-C_2}{\lambda T}\right) \tag{14}$$

Taking natural logarithms, this yields

$$\ln j_\lambda = \ln \varphi_\lambda + \ln \epsilon_\lambda - 5 \ln\lambda - \frac{C_2}{\lambda T} \tag{15}$$

which serves to determine the temperature if φ_λ and ϵ_λ are known.

The interference filters in the photoelectric pyrometer are mounted in a slide mechanism so that data can be taken at various wavelengths. The advantages of two color pyrometry can be used to determine temperatures with a minimum of reliance on spectral emittance data. For two interference filters with wavelengths of λ_1 and λ_2, according to Equation (15)

$$\ln j_2 = \ln\varphi_2 + \ln\epsilon_2 - 5 \ln\lambda_2 - \frac{C_2}{\lambda_2 T} \tag{16}$$

$$\ln j_1 = \ln\varphi_1 + \ln\epsilon_1 - 5\ln\lambda_1 - \frac{C_2}{\lambda_1 T} \quad (17)$$

and by subtracting (17) from (16),

$$\ln\frac{j_2}{j_1} = \ln\frac{\varphi_2}{\varphi_1} + \ln\frac{\epsilon_2}{\epsilon_1} - 5\ln\frac{\lambda_2}{\lambda_1} + \frac{C_2}{\lambda_2}\left(\frac{\lambda_2}{\lambda_1} - 1\right)\frac{1}{T} \quad (18)$$

Although the absolute spectral sensitivity, φ, of the photoelectric pyrometer is difficult to obtain accurately, the ratio φ_2/φ_1 is an easier determination. This is done by measuring the ratio of the output voltages of the pyrometer for both wavelengths from the tungsten ribbon filament of a lamp calibrated spectrally by the National Bureau of Standards. Although the spectral emissivities, ϵ_λ, are not, in general, well known, they do not vary greatly with wavelength for the materials to be studied. If the wavelengths are not too far apart, ϵ_2/ϵ_1 will be nearly unity and $\ln \epsilon_2/\epsilon_1$ will be a very small quantity. To insure this condition, λ_1 and λ_2 should be two wavelengths that are close together. However, the errors encountered experimentally in the determination of the term λ_2/λ_1-1 become greater as λ_2 and λ_1 approach each other. To determine which of these sources of error was dominant, data were collected at three wavelengths, 550, 537, and 463 millimicrons. The relationship of these wavelengths to the spectral response curve of the photomultiplier used with tungsten are shown in Fig. 3. The relationship between the band width and separations can also be seen from this figure. Results obtained with the 550/463 pair were far more consistent and reproducible than the results obtained with the 550/537 pair of filters. This indicates that two color bands should be used whose wavelength separation is relatively large compared to the band widths.

Temperature determination by the one color method (Equation 15) or by the two color method (Equation 18) is based on monochromatic pass bands. In the case of bands of finite width there is an uncertainty concerning the best value of λ to use. This is particularly critical in Equation (18) where the factor (λ_2/λ_1-1) appears, since the ratio of the wavelengths used will not be far from unity. It is assumed that two effective wavelengths, λ_2' and λ_1', not necessarily coincident with the peak transmissions of the filters, can be substituted into Equation (18) to give the true temperature throughout the range of interest. If these effective wavelengths are substituted into Equations (16) and (18) and the quantity $C_2/\lambda_2'T$ is eliminated, it is found that

$$\ln\frac{j_2}{j_1} = \frac{\lambda_2'}{\lambda_1'}\ln(\varphi_2\epsilon_2/\lambda_2'^5) - \ln(\varphi_1\epsilon_1/\lambda_1'^5) - \left(\frac{\lambda_2'}{\lambda_1'}\right)\ln j_2 \quad (19)$$

Since the first two members on the right hand side are not very temperature sensitive, a plot of $\ln(j_2/j_1)$, versus $\ln j_2$ for various wire currents produces a straight line with a negative slope of $(\lambda'_2/\lambda'_1-1)$. The value of λ_2 used in Equation (18) is not as critical as the wavelength ratio minus one, and it was determined from the peak of the curve formed by the product of the filter transmission and the relative spectral sensitivity of the pyrometer. Using the 550 and the 463 millimicron filters, the plot of $\ln(j_2/j_1)$ versus $\ln j_2$ yielded a negative slope of 0.1787 and using the value 550.4 millimicrons for λ_2 the expression for the temperature was found by rewriting Equation (18),

$$T = \frac{4672}{0.822 + \ln(\epsilon_{463}/\epsilon_{550}) + \ln(J_{550}/J_{463})} \qquad (20)$$

Equation (20) was used to determine the temperature distribution under static conditions by scanning the wire with the photoelectric pyrometer and using the values of DeVos[8] for spectral emittance. A graph of $\ln(J_{550}/J_{463})$ versus $1/T$ appears in Fig. 4. In establishing the ratio of ϵ/C by the rate of temperature decay, it is more convenient to determine $1/T$ by the one color method. Equation (15) is of the form

$$\frac{1}{T} = A - B \ln j_\lambda \qquad (21)$$

where A and B are best determined by calibration using Equation (20) under steady state conditions. The term A is very nearly constant since the variation of spectral emittance with temperature is quite small.

RESULTS

A plot of the temperature at the center of the wire as a function of the current through it is given in Fig. 5. For comparison purposes, the temperature was measured by three techniques, the photoelectric pyrometer, the optical pyrometer, and by resistance thermometry using the resistivity versus temperature data from the Smithsonian Physical Tables.[9] The spread of the values obtained by the optical pyrometer was due partly to the subjective nature of the brightness matching particularly when applied to fine wires, and to some extent by the spectral emittance variations caused by surface structure effects as seen in Fig. 6. The spread of the resistance temperature data was probably due to the errors in voltage measurements since the resistivity calculations require the difference between two voltages.

The resistivity versus temperature curve, as given by the Smithsonian Physical Tables[9], is shown in Fig. 7. The data points are the values of resistivity given by $\rho = EA/I$ plotted against the temperature as determined by the photoelectric pyrometer. The values of resistivity used in the calculation of thermal conductivity are taken from the curve in Fig. 7.

Figure 8 is a plot of the total hemispherical emittance as a function of temperature. The surface condition of the wire is a probable cause for the higher values of the emittance than those published in the Smithsonian Physical Tables.[9] Fig. 6 contains photomicrographs with 125 times magnification showing the wire before and after it had been raised to 2800°K for 10 hours. Both surface areas and cross sectional areas were photographed in reflected light.

A typical photograph of the oscilloscopic display of the pyrometer voltage versus time at 550 millimicrons when the electrical power is turned off is shown in Fig. 9. These pictures were obtained for steady state wire currents of 8, 7, 6, 5, 4, and 3 amperes. The reciprocal of the temperature versus time was found by substitution of the pyrometer voltage in Equation (21). In Fig. 10 $1/T^3$ is plotted against t for the print taken at 8 amperes. Data is plotted in this figure for the lower currents also, but the zero on the time scale is adjusted so that the steady state temperatures fall on the composite curve. It was found that a straight line could be drawn through all of these points. A constant slope in this temperature range implies a constant ratio of ϵ/C between 1600°K and 2400°K neglecting small area and density variations due to a total thermal expansion of about 1%. This ratio was determined to be 8.24. The total hemispherical emittance curve in Fig. 7 was divided by this ratio to yield the heat capacity versus temperature curve in Fig. 11. It is seen that the results agree quite well with those from the Handbook of Chemistry and Physics[10] between 2000°K and 3000°K.

The thermal conductivity was determined from Equation (10). The temperature gradients were found from the temperature distribution curves plotted for various wire currents in Fig. 12. The terms inside the integral sign in Equation (10) express the difference between the power generated and the power radiated per unit length as a function of temperature. These two terms are plotted in Fig. 13, and their difference is graphically integrated from T_M to T_C. The power generated per unit length is taken from the product of the current squared and the resistivity versus temperature curve shown in Fig. 7. The power radiated per unit length is equal to $P\sigma T^4$ times the emittance versus temperature curve in Fig. 8. Although the thermal conductivity was also measured with Equation (11), it was found the spread of data was much less with Equation (10).

The thermal conductivity versus temperature curve shown in Fig. 14 has a negative coefficient, as does that of Osborn[3], with values somewhat below those of the other investigators. Curve a is obtained by a high temperature extension of an empirical curve found by Ewing[11] to hold within 10% for a large number of metals and alloys below 900°C. Curve b is obtained by multiplying the ratio of the temperature and the electrical resistivity from Fig. 7 by the theoretical value of the Lorentz number, L, which is determined using Fermi Dirac statistics.[12]

$$L = K\rho/T = \frac{\pi^2}{3m}\left(\frac{k}{e}\right)^2 = 5.83 \times 10^{-9} \frac{\text{cal ohm}}{\text{sec deg}^2} \qquad (22)$$

where k is Boltzmann's constant, e is the electronic charge, and m is the mechanical equivalent of heat.

CONCLUSIONS

A method of measuring the total hemispherical emittance, heat capacity, and thermal conductivity of metals and alloys at high temperature using electrically heated wires in conjunction with photoelectric techniques for temperature determination has been investigated, and it appears that these measurements can be made fairly rapidly with an estimated accuracy of ±10%. Although this does not represent the ultimate accuracy that can be attained in this way, it is sufficient in most engineering applications since there has to be a substantial margin of safety to provide for changes in these properties due to variations in composition, physical treatment and surface effects.

Evaporation provides an upper temperature limit for the measurements made in the manner described. The thermal conductivity determination depends on the static temperature distribution along the wire. For temperatures near the melting point appreciable material loss will occur before thermal equilibrium can be established. It is possible to carry the measurement of the emittance-heat capacity ratio to higher temperatures because of its dynamic character. If the current and voltage across the wire are recorded as a function of time, the resistivity and heat capacity can be determined right up to the melting point by measuring the temperature and its rate of rise in an electrically heated wire as determined by the photoelectric pyrometer. By establishing the value of the quantity, $K\rho/T$, which is theoretically independent of temperature, it is possible to make a reliable estimation of the thermal conductivity up to the melting point using available resistivity data.

For example, the Handbook of Chemistry and Physics quotes the electrical resistivity of tungsten at 3600°K as 115 micro ohm-cm and the present results between 1600° and 2800°K indicate an average value of $K\rho/T$ of approximately 5.2×10^{-9}, which leads to an estimated value of 0.17 (cal/cm sec deg) for the thermal conductivity at 3600°K.

Except for the measurements by Worthing in 1914 and for some preliminary results at NRDL in 1959, the only published data on tungsten above 2000°K is contained in the present report. The present method differs from the other two in that the difference between the power generated and the power radiated per unit length is integrated with respect to temperature instead of distance along the wire. Both methods were tried and the integration with respect to temperature was easier to perform and gave rise to a smaller spread in data.

The fact that the plot of $1/T^3$ versus t for the tungsten wire is a straight line throughout the range between 1600°K and 2800°K for the tungsten wire was fortuitous. However, in most all cases this plot should exhibit only a slight curvature and thus provide a very sensitive method of measuring the ϵ/C ratio. Once the heat capacity of a wire is determined, this ratio provides a convenient method of investigating the change in emittance with surface conditions. The total hemispherical emittance is strongly effected by surface effects such as dye marks or thermal etching which changes a smooth surface to an irregular one when maintained at high temperatures for long periods, with an attendant increase in emittance due to the increased effective radiating area.

The choice of wavelength bands to be used in the photoelectric pyrometer is very important. In consideration of the greater stability of the ultraviolet sensitive photomultipliers over those required for the infrared, it is better to choose two wavelengths below 6000Å. Although the effect of variations in spectral emittance can be minimized by choosing two adjacent color bands, the pyrometer is much more sensitive to temperature variations if these bands are not too close together. In order to maintain a fixed effective wavelength which is independent of temperature, the band passes of the interference filters should not be too large. The choice of very narrow wavelength bands located in the short wavelength region must, however, be weighed against the problem of providing an adequate signal level to the detector. In the temperature range of this investigation the two filters chosen satisfied this compromise adequately.

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For the Scientific Director

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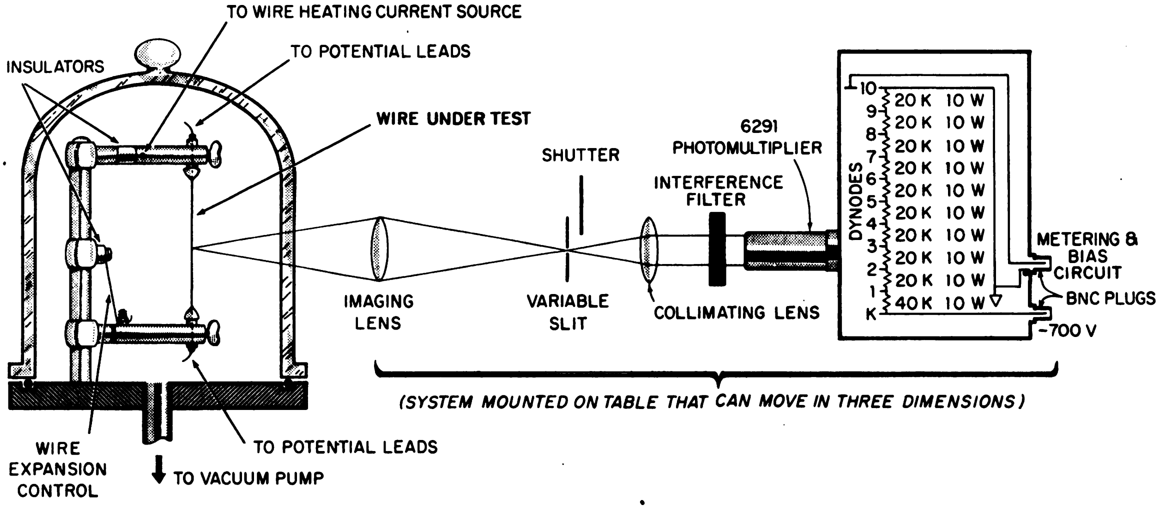


Fig. 1 Schematic diagram of experimental setup.

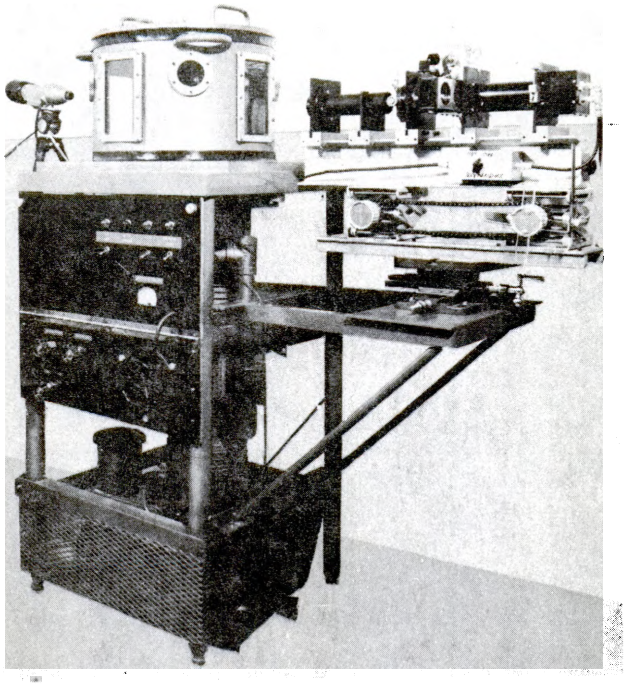


Fig. 2   Photograph of experimental setup.

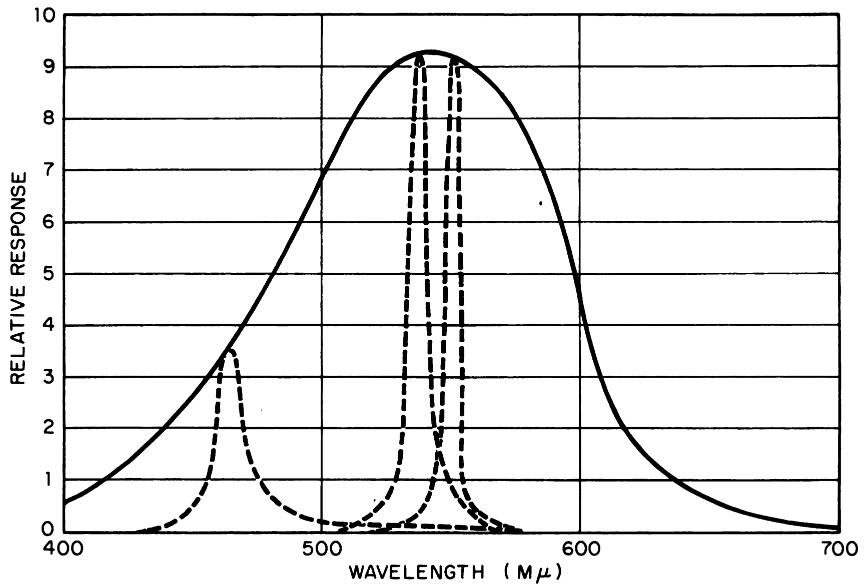


Fig. 3 Relative spectral response curve of the S-11 photomultiplier to the radiation from a 2800°K tungsten wire. The dashed curves indicate the modified spectral response due to the 463, 537, and the 550 mμ interference filters.

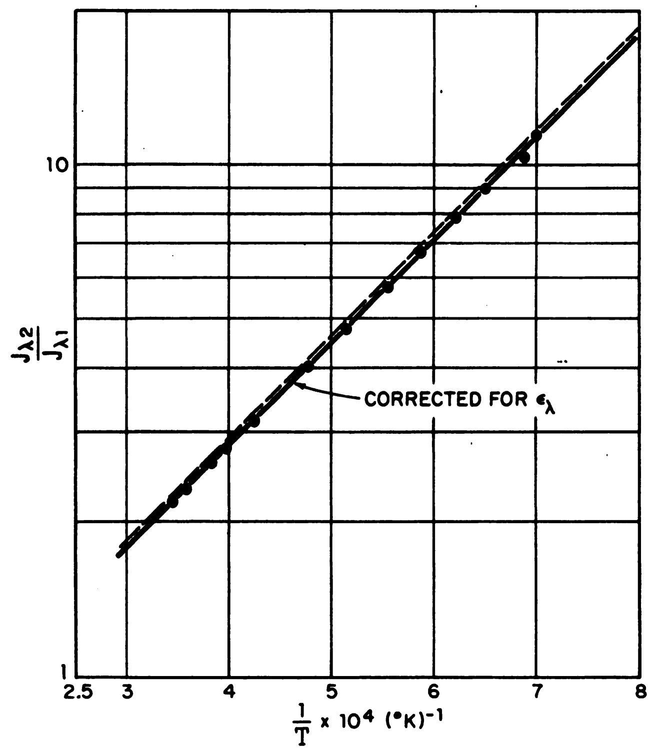


Fig. 4 Log J_2/J_1 versus $1/_T$.

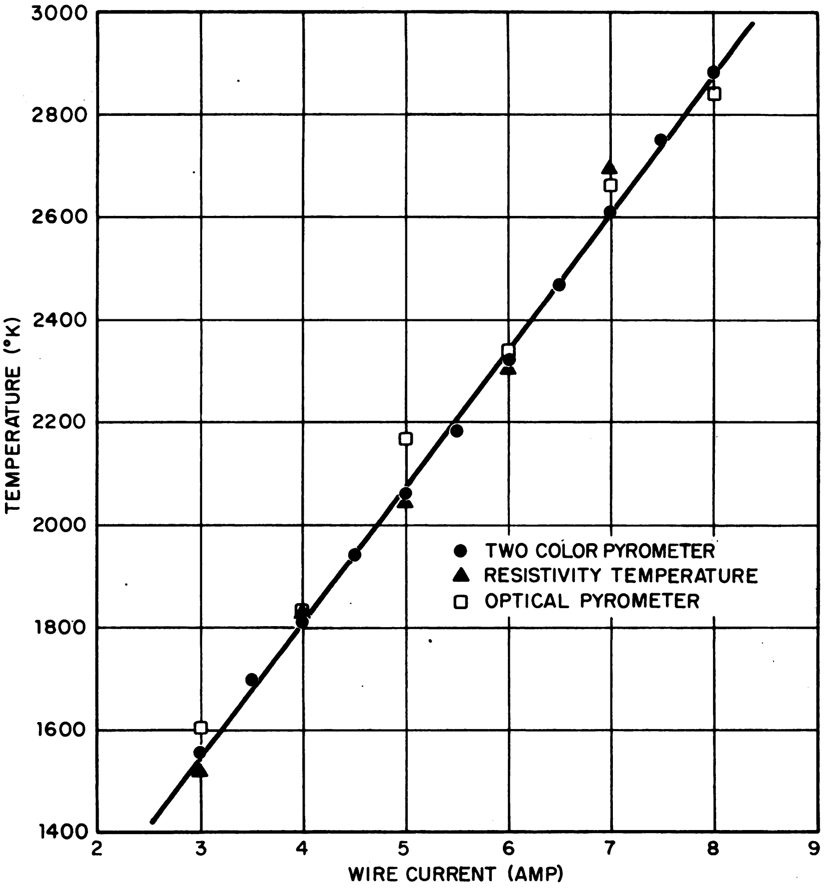
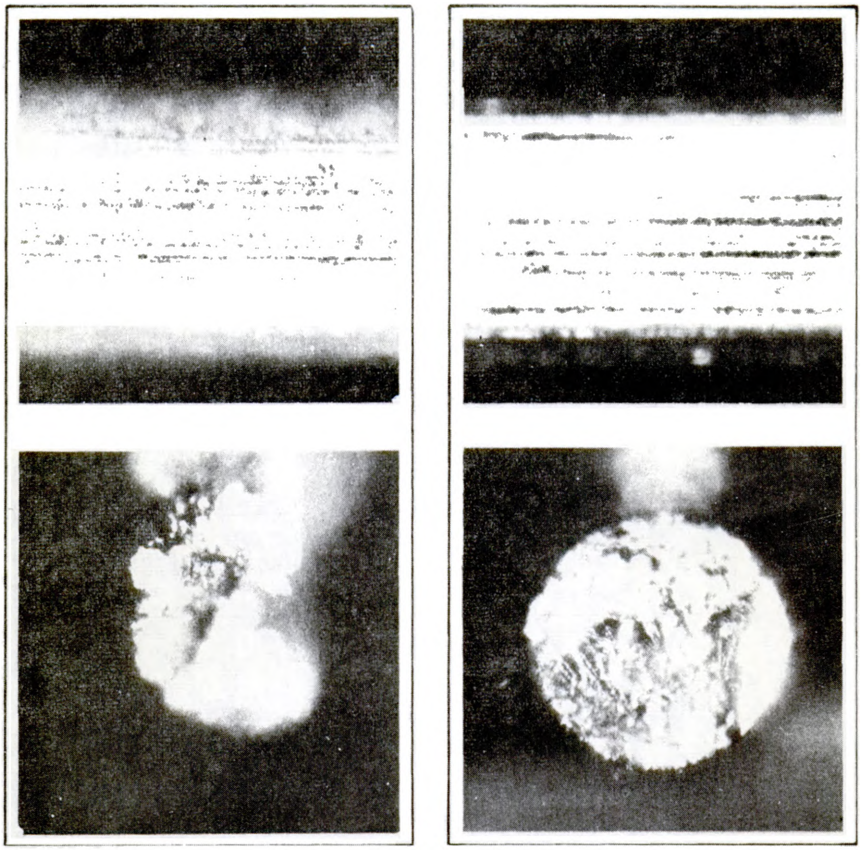


Fig. 5 Temperature versus current.



(a) (b)

Fig. 6 Photomicrographs of 10 mil tungsten wire.
Top: longitudinal view
Bottom: cross sectional view
(a) wire as received
(b) wire after use as a specimen

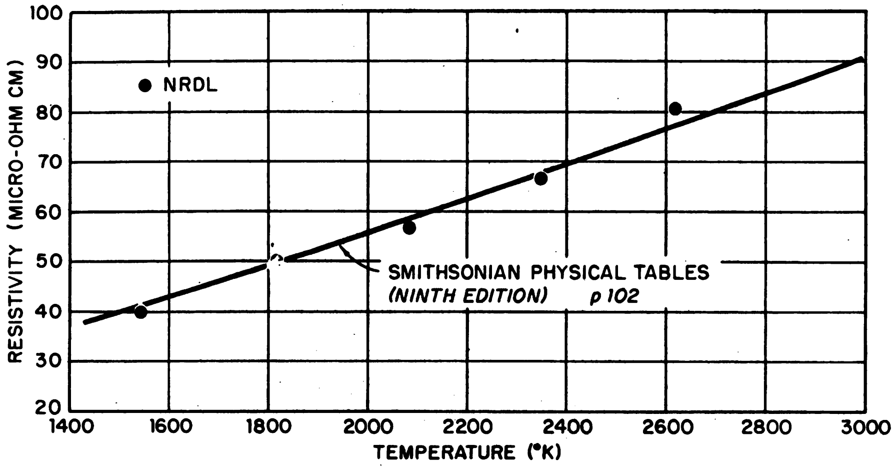


Fig. 7 Resistivity of tungsten versus temperature.

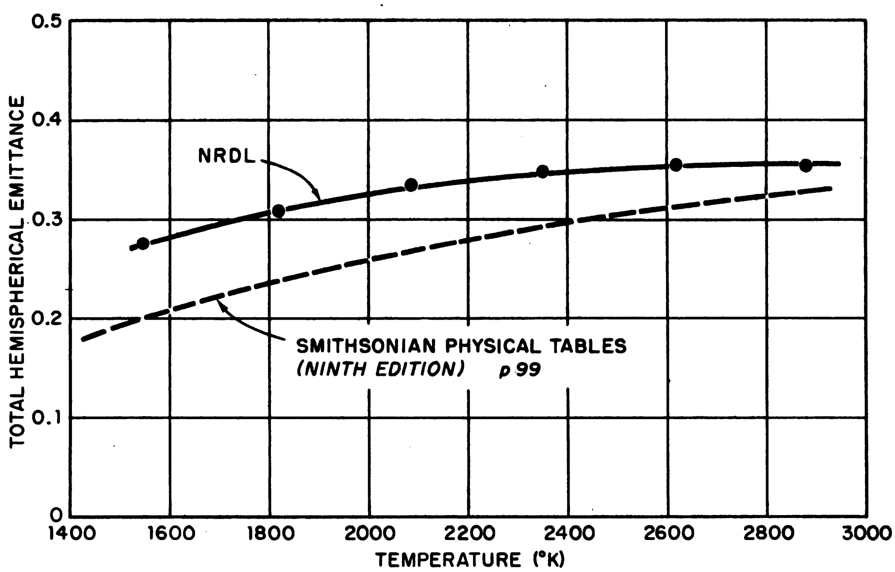


Fig. 8 Total hemispherical emittance versus temperature.

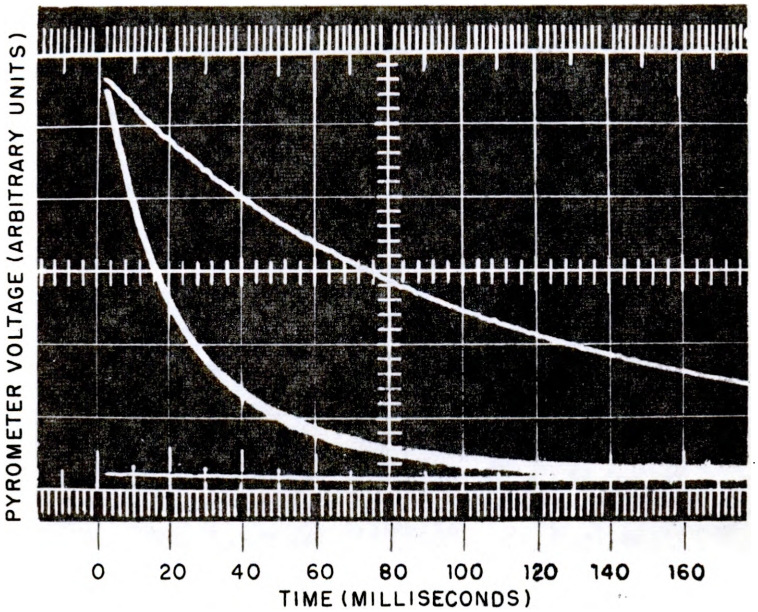


Fig. 9 Polaroid Land print showing the temperature decay in a 10 mil tungsten wire.

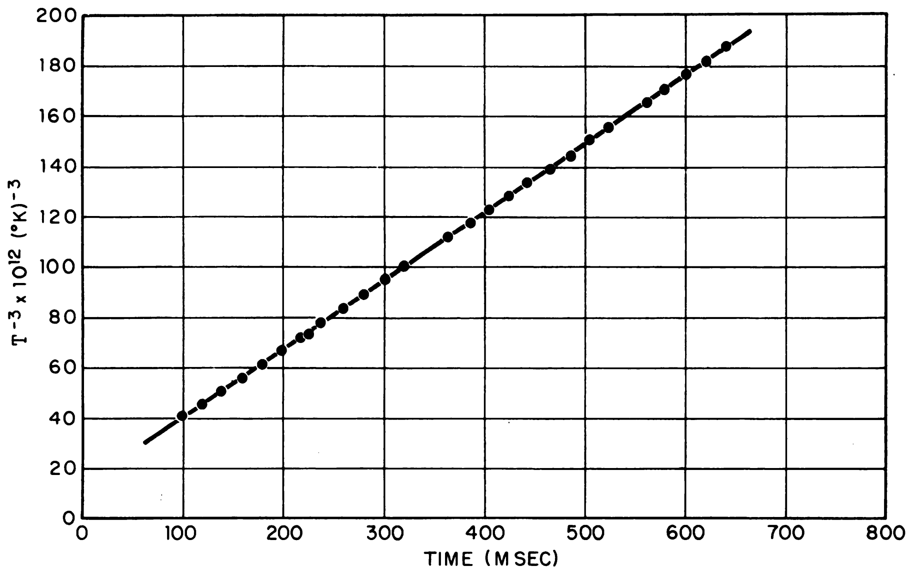


Fig. 10 $1/T^3$ versus t.

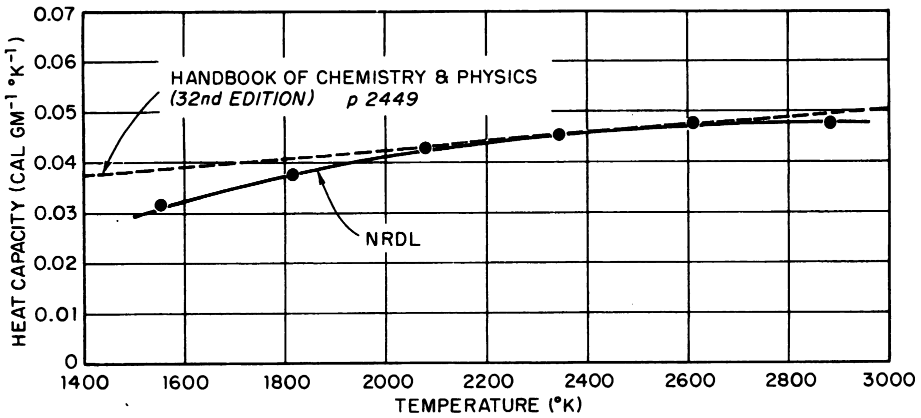


Fig. 11 Heat capacity of tungsten versus temperature.

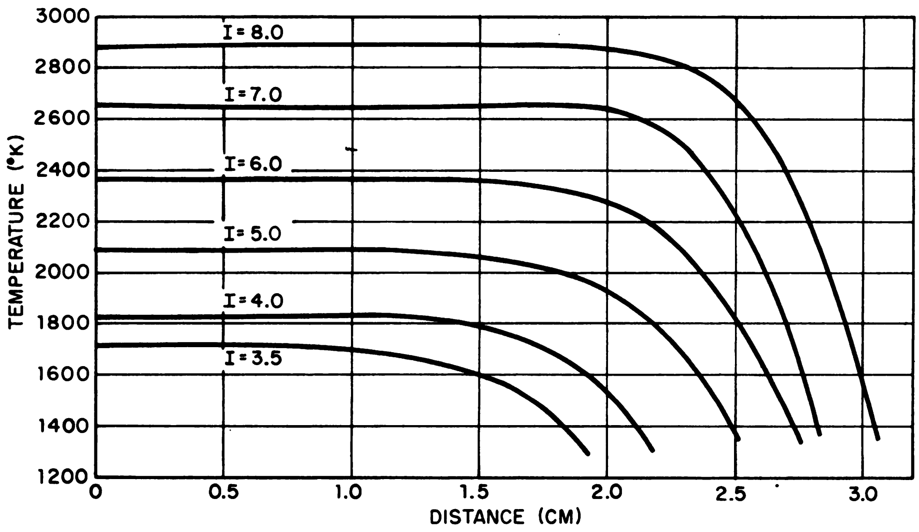


Fig. 12 Temperature profiles of 10 mil tungsten wire.

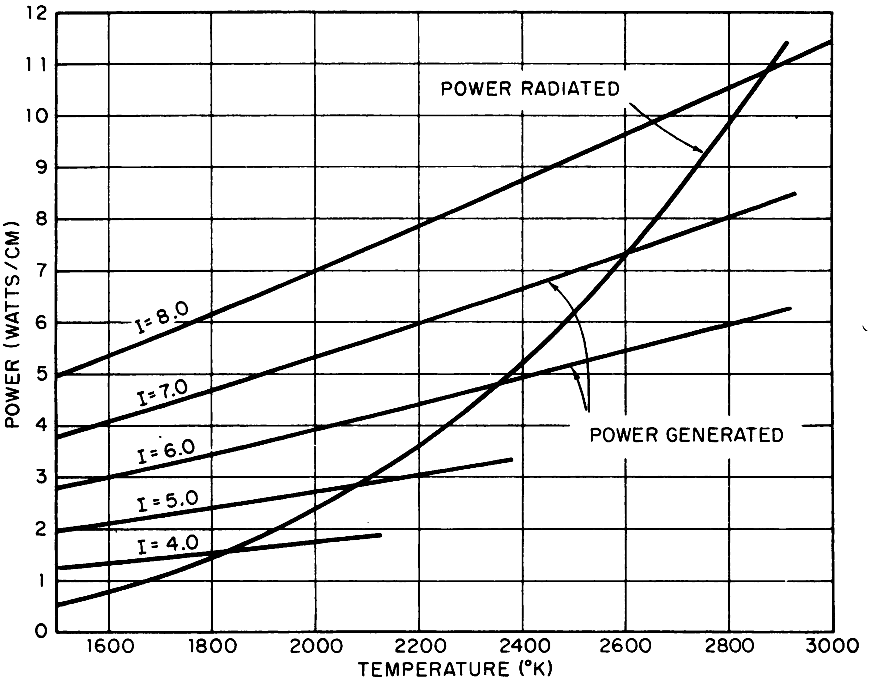


Fig. 13 Power versus temperature of 10 mil tungsten wire.

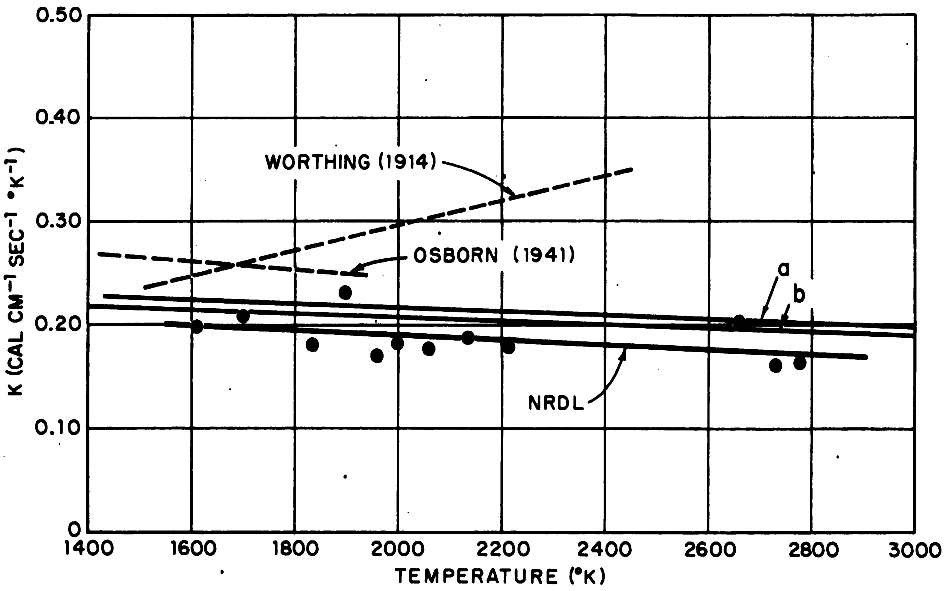


Fig. 14 Thermal conductivity of tungsten versus temperature.
(a) $K = 6.25x10^{-9}(T/\rho) - 5x10^{-18}(T/\rho)^2$ 1/DC
(b) $K = 5.83x10^{-9}(T/\rho)$