NATIONAL BUREAU OF STANDARDS REPORT

9869

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF A SAMPLE OF AISI TYPE 304 STAINLESS STEEL

Report to

National Aeronautics and Space Administration
Lewis Research Center

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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Environmental Engineering Section
Building Research Division
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1. Introduction

This report presents thermal conductivity and electrical resistivity values obtained on a sample of AISI Type 304 stainless steel over the temperature range -20 to +150 °C. The sample was supplied by the National Aeronautics and Space Administration, Lewis Research Center, in the form of a section of 3/4-inch plate. No chemical analysis of the sample was provided nor was the thermal history of the sample provided.

2. Method and Apparatus

The thermal conductivity and electrical resistivity were measured by an electrical method in which the sample was heated directly by passage of an electric current. The apparatus used for these measurements is shown in figure 1. The specimen, A, was machined to the form of a right circular cylinder 1/2-inch in diameter and 5-inch long. The specimen was surrounded by silica aerogel thermal insulation, B, which was contained within a borosilicate glass cylinder, C. The ends of the thermal insulation were capped with brass end pieces, D, which were

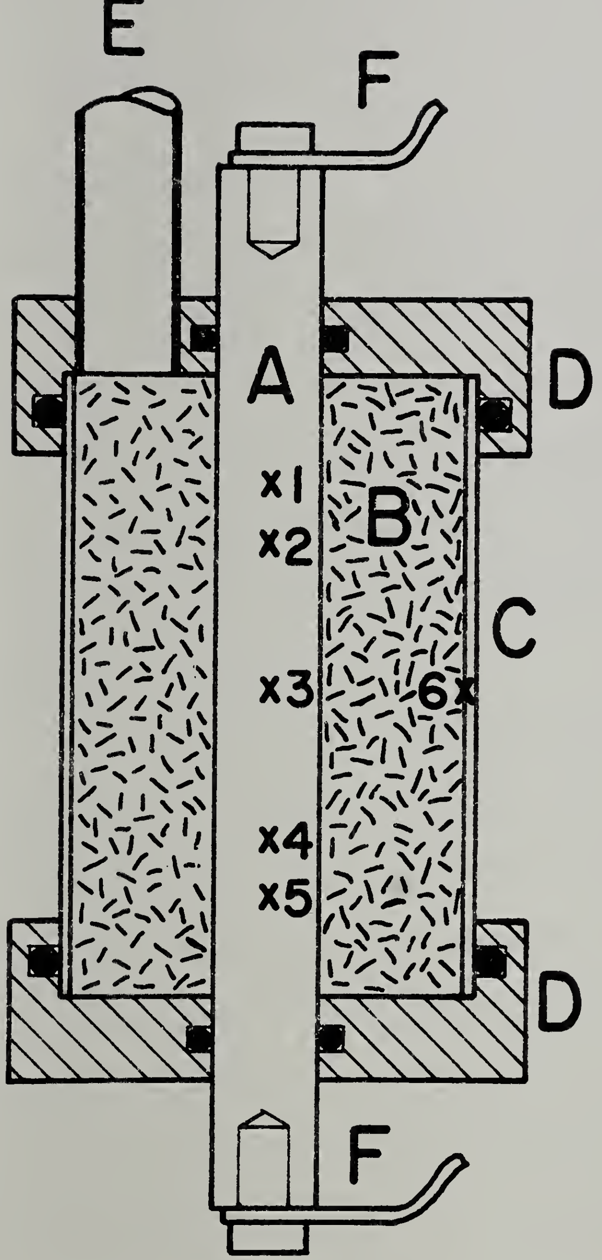

Figure 1. Apparatus used to measure the thermal conductivity and electrical resistivity. The components are identified in the text.

equipped with rubber O-rings to provide vacuum-tight seals to the specimen and to the glass cylinder. A stainless steel tube, E, attached to the upper end piece enabled the thermal insulation surrounding the specimen to be evacuated, thus reducing its thermal conductivity. The entire assembly shown in figure 1 was immersed in a constant temperature kerosene bath.

The specimen was heated by passage of a dc current of up to 100 A introduced via copper leads, F, at each end of the specimen. Temperatures along the specimen were measured using five thermocouples fabricated from 0.005 inch Chromel P and constantan wires. The two wires of each thermocouple were individually attached to the specimen by inserting each wire into a small hole (~.006 inch diam by ~.012 inch deep) in the convex surface of the sample and then peening the metal around the wire. The two holes for a given thermocouple were spaced 1/8-inch apart at the same longitudinal position. The insulated thermocouple wires were tempered by wrapping them around the specimen in the same longitudinal plane as the junction and cementing them in place with electrical varnish.

The specimen was placed in series with a calibrated standard resistor and a regulated dc power supply operating in a constant current mode. Thermocouple emfs, voltage drops in the sample, and the voltage drop across the standard resistor were measured using a calibrated precision potentiometer and standard cell in conjunction with an electronic null detector. A representative thermocouple, fabricated from the same lot of wire, had been calibrated by the NBS Temperature Section.

Data were taken at a number of bath temperatures with currents of nominally 10, 70, and 100 A flowing through the specimen. The data taken in each test were:

1. Emf of the five specimen thermocouples and the thermocouple on the inner wall of the glass cylinder (C).
2. Current flowing through the specimen.
3. The voltage drop between the Chromel P leads of thermocouples 1 and 5 and between those of thermocouples 2 and 4.

All of these data were taken with the current flowing normally and reversed in order to separate thermoelectric emfs and voltages due to the current flow in the specimen.

3. Theory and Calculation Procedure

Consider an isotropic, homogeneous conductor as represented in figure 2. Electricity and heat can enter or leave the conductor only at the ends, as the boundary of the conductor is assumed to be perfectly insulated against the flow of heat and electricity. Passage of an electric current will generate heat within the conductor resulting in a maximum temperature, T_m, at some surface, S_m, in the conductor. If V is the voltage drop between two surfaces, S_0, both of which are at some lower temperature, T_0, on either side of S_m, then it can be shown [1][1] that:

$$V^2 = 8\int_{T_0}^{T_m} \lambda\rho \, dT \quad , \tag{1}$$

where λ and ρ are the thermal conductivity and electrical resistivity, respectively, of the conductor. Equation (1) is rigorous for any arbitrary temperature dependences of λ and ρ and for any arbitrary geometry, provided the boundary of the conductor is perfectly insulated. In deriving eq. (1), the Thomson effect cancels out to first order only. For metals, the Thomson coefficient is small so that higher order corrections to eq. (1) are negligibly small.

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[1] Figures in brackets indicate the literature references at the end of this report.

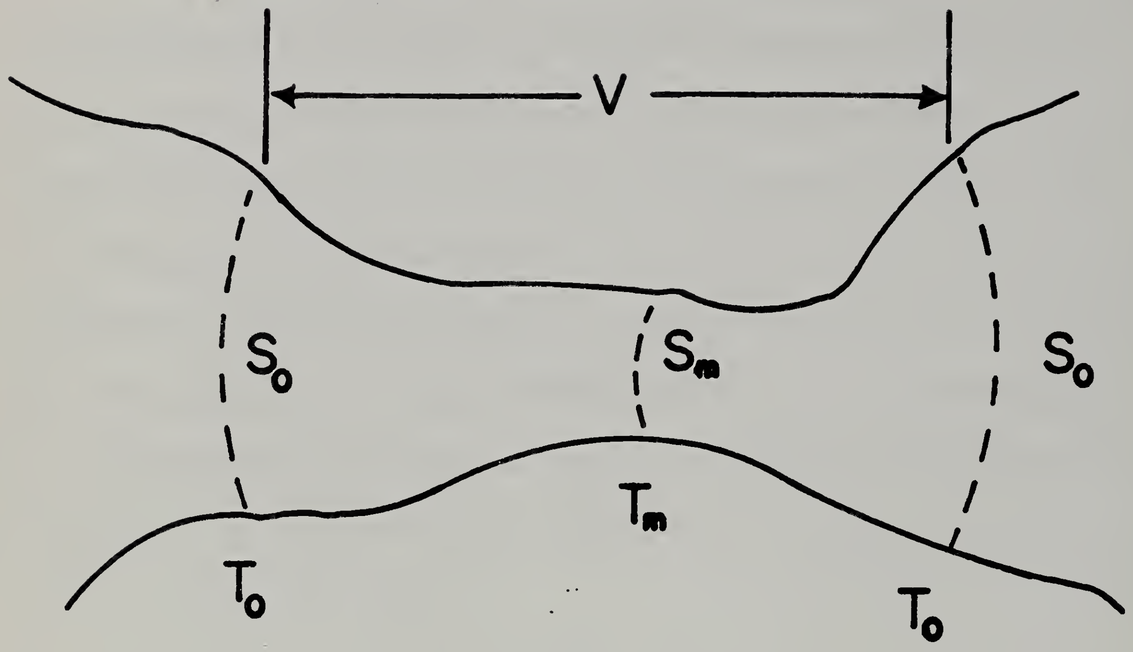

Figure 2. A conductor of arbitrary geometry having a lateral surface that is perfectly insulated both thermally and electrically.

The electrical resistance, R, between the two surfaces S_o is related to the resistance, R_e, that would exist if the conductor were isothermal at a reference temperature, T_e, by the expression [1]:

$$\frac{R_e}{R} = \frac{1}{F(T_m,T_o)} \int_{T_o}^{T_m} \frac{\lambda\rho_e \, dT}{F(T_m,T)} \; , \tag{2}$$

where

$$F_m(T_m,T) = + \left\{ 2\int_{T}^{T_m} \lambda\rho \, dT \right\}^{1/2} \; . \tag{3}$$

Over the temperature intervals, $T_m - T_o$, used in these measurements, both the electrical resistivity and the thermal conductivity may be assumed to have a linear temperature dependence:

$$\rho = \rho_e[1 + \alpha_e(T - T_e)] \; , \tag{4}$$

$$\lambda = \lambda_e[1 + \beta_e(T - T_e)] \; , \tag{5}$$

$$\lambda\rho = \lambda_e\rho_e[1 + \eta_e(T - T_e)], \tag{6}$$

where the higher order term in $\alpha_e\beta_e$ has been neglected in eq. (6). If we define our reference temperature as $T_e = (T_m + T_o)/2$, eqs. (4), (5), and (6) can be substituted into eqs. (1) and (2) to yield

$$\lambda_e = \frac{V^2}{8\rho_e(T_m - T_o)} \tag{7}$$

and

$$R_e = R\left[1 - \frac{\alpha_e}{6}(T_m - T_o)\right] , \tag{8}$$

where higher order terms in α_e and β_e have been neglected in eq. (8).

For a conductor of uniform cross-sectional area, the electrical resistivity ρ_e, at a temperature T_e, can be computed from R_e and the geometry. The relation used to compute ρ_e in this work was

$$\rho_e = \frac{VA}{IL}\left[1 - \frac{\alpha_e}{6}(T_m - T_o)\right], \tag{9}$$

where A is area, I is current, and L is the separation between the two outer surfaces, S_o, at which the temperature T_o is measured. As stated above, λ_e, R_e, and ρ_e correspond to a reference temperature

$$T_e = \frac{T_m + T_o}{2} \tag{10}$$

For a given test we computed ρ_e using eq. (9) and then computed λ_e using eq. (7). The correction term in eq. (9) involving α_e was quite small for the present measurements so that the use of an approximate value of α_e was sufficient.

In measuring thermal conductivity using relatively small temperature differences, significant errors can occur if there are even rather small differences among the calibrations of the several thermocouples. These errors can be eliminated to first order by taking data at two different current levels and treating the data as follows. For each test, ρ_e, λ_e, and T_e are computed using equations (9), (7), and (10), respectively. Then two sets of results, corresponding to approximately the same mean temperature but to different current levels, are used in the following equations:

$$\rho_e = \frac{\rho_e'\Delta T' - \rho_e''\Delta T''}{\Delta T' - \Delta T''} , \quad (11)$$

$$\lambda_e = \frac{\lambda_e'\Delta T' - \lambda_e''\Delta T''}{\Delta T' - \Delta T''} , \quad (12)$$

$$T_e = \frac{T_e'\Delta T' - T_e''\Delta T''}{\Delta T' - \Delta T''} , \quad (13)$$

where the single- and double-primed quantities correspond to the tests at two different current levels, $\Delta T' = T_m' - T_o'$, and $\Delta T'' = T_m'' - T_o''$.

These calculations were carried out

a) for the outer taps in which V was measured between the Chromel P legs of thermocouples 1 and 5 (see figure 1), $T_o = (T_1 + T_5)/2$, and $T_m = T_3$ and

b) for the inner taps in which V was measured between the Chromel P legs of thermocouples 2 and 4, $T_o = (T_2 + T_4)/2$, and $T_m = T_3$.

4. Results

The results obtained for electrical resistivity and thermal conductivity are shown in figures 3 and 4. The lower portion of each of these figures represents the smoothed data which are also tabulated below. The upper portion of figures 3 and 4 shows the scatter in the experimental data; the symbols are identified in the figure captions.

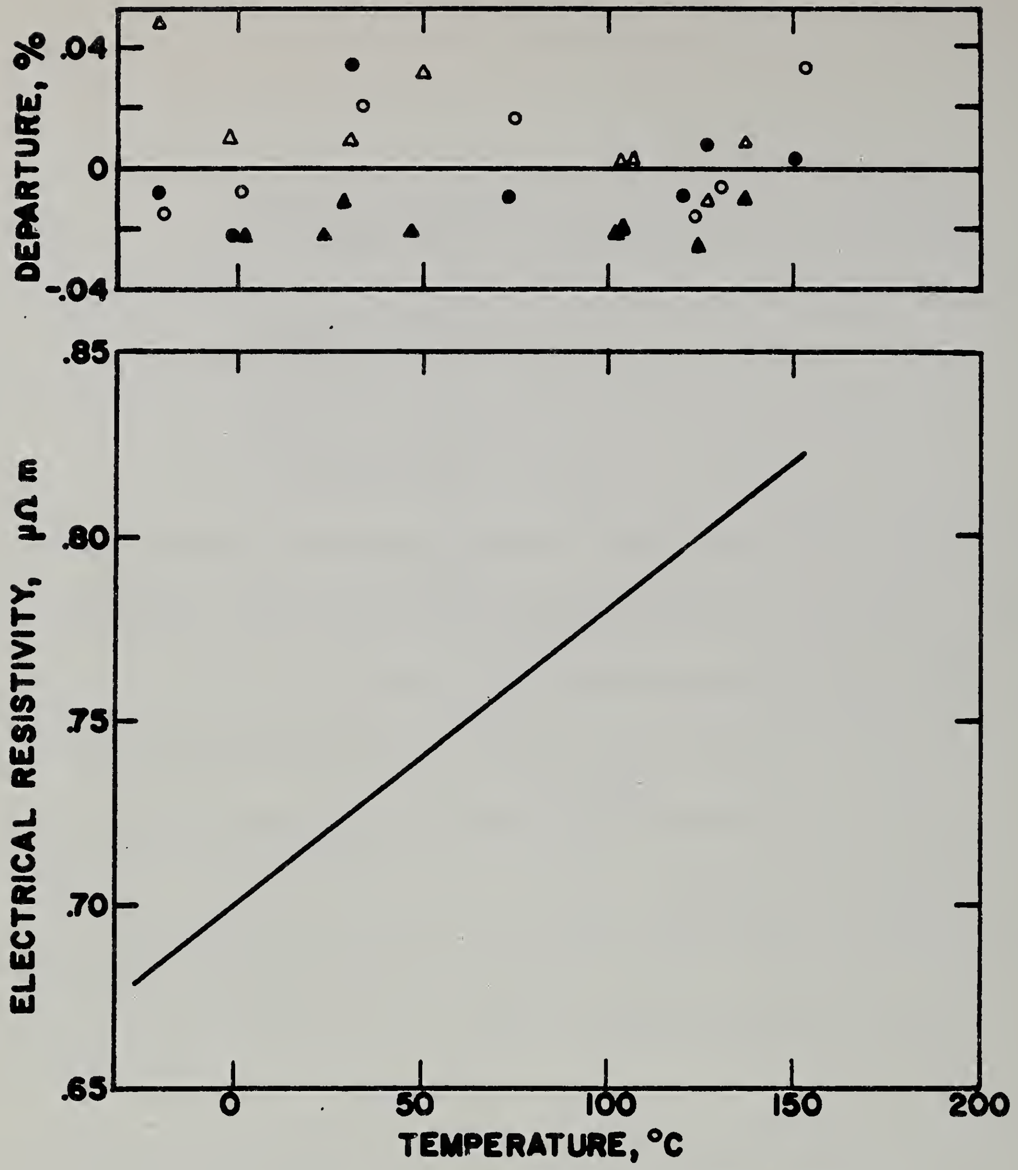

Figure 3. Electrical resistivity of the AISI Type 304 stainless steel sample. The curve in the lower portion of the figure represents the quadratic equation of least-squares-fit to all of the data obtained. The upper portion of the figure shows the scatter of the data from the curve in the lower portion of the figure. The different symbols correspond to different spans and current levels as follows:

Symbol	Span	Current Levels	Weight
●	Outer	100/10	4
▲	Outer	70/10	2
○	Inner	100/10	2
△	Inner	70/10	1

The notation for the current levels is such that 100/10 means a test of 100 A was solved simultaneously with a test of 10 A, etc. The weights are those which were assigned to the data points in deriving the least-squares equation.

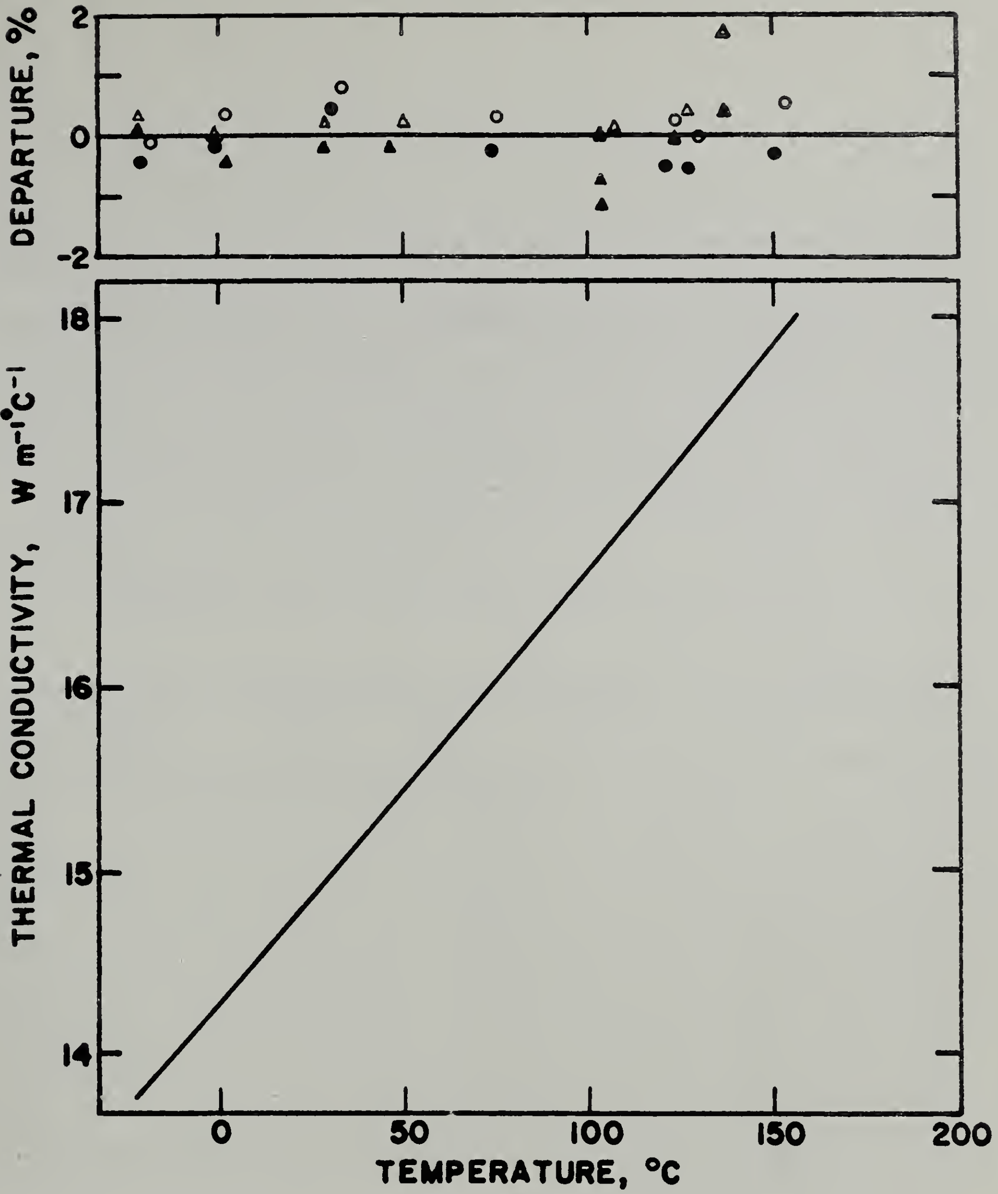

Figure 4. Thermal conductivity of the AISI Type 304 stainless steel sample. The curve represents the straight line of least squares fit to all of the data obtained. The upper portion shows the scatter in the data; the symbol notation is the same as in figure 3.

The tabulated values for electrical resistivity are believed to be in error by not more than ±0.5 percent. The tabulated thermal conductivity values are estimated to be uncertain by not more than two to three percent. The largest portion of the uncertainty in thermal conductivity is due to the uncorrected-for effects of small heat losses through the thermal insulation surrounding the specimen.

Temperature °C	Electrical Resistivity Ωm	Thermal Conductivity $W\ m^{-1}\ °C^{-1}$
-20	6.82×10^{-7}	13.9
0	7.00	14.3
20	7.17	14.8
40	7.33	15.2
60	7.50	15.7
80	7.66	16.2
100	7.81	16.7
120	7.97	17.1
140	8.12	17.7
150	8.19	17.9

5. References

[1] D. R. Flynn, Measurement of thermal conductivity by steady-state methods in which the sample is heated directly by passage of an electric current, in Thermal Conductivity, edited by R. P. Tye (Academic Press, in press).

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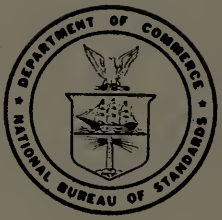

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