NATIONAL BUREAU OF STANDARDS REPORT

10 126

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOELECTRIC POWER OF A SPECIMEN OF CONSTANTAN

Report to
Rocketdyne Corporation
Canoga Park, California

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards [1] was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in four broad program areas. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Measurement Services and the following technical divisions:

Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic and Molecular Physics—Radio Physics [2]—Radio Engineering [2]—Time and Frequency [2]—Astrophysics [2]—Cryogenics.[2]

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; develops, produces, and distributes standard reference materials; relates the physical and chemical properties of materials to their behavior and their interaction with their environments; and provides advisory and research services to other Government agencies. The Institute consists of an Office of Standard Reference Materials and the following divisions:

Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations in the development of technological standards, and test methodologies; and provides advisory and research services for Federal, state, and local government agencies. The Institute consists of the following technical divisions and offices:

Engineering Standards—Weights and Measures — Invention and Innovation — Vehicle Systems Research—Product Evaluation—Building Research—Instrument Shops—Measurement Engineering—Electronic Technology—Technical Analysis.

THE CENTER FOR RADIATION RESEARCH engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center consists of the following divisions:

Reactor Radiation—Linac Radiation—Nuclear Radiation—Applied Radiation.

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in the selection, acquisition, and effective use of automatic data processing equipment; and serves as the principal focus for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

Information Processing Standards—Computer Information — Computer Services — Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System, and provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

Office of Standard Reference Data—Clearinghouse for Federal Scientific and Technical Information [3]—Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT 4213633

December 2, 1969

NBS REPORT 10 126

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOELECTRIC POWER OF A SPECIMEN OF CONSTANTAN

by

T. W. Watson, W. L. Carroll, and D. R. Flynn
Environmental Engineering Section
Building Research Division
Institute for Applied Technology

Report to
Rocketdyne Corporation
Canoga Park, California

IMPORTANT NOTICE

NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THERMAL CONDUCTIVITY, ELECTRICAL RESISTIVITY, AND THERMOELECTRIC POWER OF A SPECIMEN OF CONSTANTAN

by

T. W. Watson, W. L. Carroll, and D. R. Flynn

1. Introduction

This report presents values of thermal conductivity, electrical resistivity, and thermoelectric power (versus thermoelectric grade copper) determined on a sample of constantan alloy purchased for the Rocketdyne Division of North American Rockwell Corporation. The thermal conductivity and electrical resistivity were measured over the temperature range from -150 to 550 °C while the thermoelectric power versus copper was determined over the more limited temperature range from -150 to 400 °C.

2. Sample

The sample tested was a bar of constantan about 2.54 cm in diameter and 37.0 cm long which was cut and machined from a hot rolled 2 1/4 inch square bar 14 ft. in length. The material was purchased by the National Bureau of Standards from Driver-Harris Company, Harrison, New Jersey and was labeled "Advance Thermocouple Bar Def 100". It was identified as Heat No. 3296, composition given as 45 weight percent nickel and the balance being copper. No analysis of impurities present was supplied.

3. Thermal Conductivity Test Apparatus and Method

The thermal conductivity of the sample was determined by means of a steady-state flow of heat longitudinally in the bar specimen, with measurements of the temperatures existing at the ends of six consecutive, approximately 3.51 cm, spans along the central length of the bar. Each determination required a pair of tests at moderately different temperature conditions, and yielded values of thermal conductivity at six different mean temperatures [1][1].

The test apparatus is shown schematically in figure 1.

---

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

The specimen, a bar approximately 37 cm long and of uniform outside diameter, was supported at the top (coolant) end coaxially within a stainless steel guard tube of 0.8 cm wall thickness, which in turn was held coaxially within a cylindrical outer container. The specimen was drilled at each end with a 1.35 cm hole 5.5 cm deep. An electrical heater was inserted and secured in the hole at the bottom (hot) end by a completely enclosing metal cap (in lieu of the strap shown in figure 1). The supporting fixture at the top end provided a liquid-tight connection for circulating a coolant through the top drill hole.

Temperatures along the specimen were indicated by seven thermocouples located symmetrically about the longitudinal center of the specimen, spaced approximately 3.51 cm apart, with one additional thermocouple near the bottom end of the specimen. Thermocouples were located in corresponding longitudinal positions on the guard tube.

The guard tube was equipped near its lower end with two external circumferential electric heaters, as shown. The guard tube was cooled at the top by means of a copper-tube coil soldered circumferentially at a position corresponding in effect to that of the specimen coolant well. Coolant (liquid nitrogen at -196 °C or water at 40 °C) was pumped through the guard coil and specimen well in series connection, as shown.

The electrical heater for the specimen consisted of 24-gage nichrome heater wire threaded back and forth through longitudinal holes in a porcelain cylinder, 1.25 cm in diameter and 5.2 cm long. Its resistance at 25 °C was approximately 14 ohms. Current was brought to the heater through relatively large heater leads, to which separate potential leads were connected at the point where they entered the porcelain core. The heater was energized by an adjustable constant-voltage d-c source. Heater current and voltage drop measurements were made using standard resistors and the high-precision manual potentiometer used for thermocouple observations. The guard was heated with alternating current governed by a sensitive temperature controller actuated by the guard temperature at a selected position.

The thermocouples for the test specimen were made from calibrated Chromel P* and constantan 30-gage wires (0.025 cm), electrically welded to form a spherical junction about 0.05 cm in diameter.

---

[*] Chromel P is a registered trademark of Hoskins Manufacturing Company.

The thermocouple wires were pressed into transverse grooves 0.025 cm wide by 0.03 cm deep and 0.6 cm in length in the convex surface of the bar with the spherical junction pressed into radially-drilled holes 0.05 cm in diameter, centrally located in the grooves. The fiberglass covered thermocouple leads were individually brought out in the powder insulation in the same transverse plane as the junction (one wire in each direction around the bar) forming a 4 cm circle. The wires were then additionally insulated with alumina tubing in the hotter regions, and brought out through the powder insulation near the guard tube. The thermocouples in the guard tube were made from calibrated Platinel II* wires and were welded to form a spherical junction about 0.10 cm in diameter. The junctions in the guard were inserted into radially-drilled holes 0.11 cm in diameter and 0.17 cm deep, and tightly secured by punch-pricking the metal around the hole. The wires were similarly brought out through the powder insulation. The longitudinal positions of the thermocouple junctions were taken as those of the centers of the grooves, or of the drilled holes, measured to the nearest 0.01 cm with a laboratory cathetometer.

---

* Platinel II is a registered trademark of Engelhard Industries, Inc.

Current leads (0.1-cm Pt) were attached to the two ends of the bar specimen for passing a direct current of about 10 amperes along the bar for making electrical resistivity measurements. The lead at the hot end was led in a flat spiral in the powder insulation, in a plane transverse to the bar axis, to near the inner radius of the guard tube, from which point it was electrically insulated with broken ceramic tubing and brought upwards through the powder insulation near the guard tube.

After installation of the specimen, the space between it and the guard tube was filled with fine alumina powder, which also was used to insulate the space surrounding the guard tube. The tests were conducted with the insulation exposed to atmospheric air.

In principle, if there were no heat exchange between the specimen and its surroundings, the conductivity could be determined from the measured power input to the specimen and the average temperature gradient for each of the six spans along the specimen, all of uniform known cross-sectional area. In practice, a perfect balance of temperatures between the bar and guard all along their lengths is not possible, because of differences in their temperature coefficients of conductivity, and the effect of the outward heat losses of the guard. In addition to heat exchanges between the bar and guard from this cause, a relatively smaller longitudinal flow of heat occurs in the powder insulation surrounding the specimen, and the contribution of the specimen to this heat flow must depend somewhat on the bar-to-guard temperature unbalance.

In order to evaluate the heat flow in the bar at the center points of each of the six spans, a partly empirical procedure was used. Two steady-state test runs were made with slightly different bar and guard temperatures and power inputs. In the two tests, the heat flow and the observed temperature drop from end to end of a given span differed, as did also the approximate integral with respect to length of the observed temperature differences between bar and guard, summed from the hot end of the bar to the span center point. It is thus possible to write for each span two equations (one for each test run) of the form

$$\frac{Ak\Delta t}{\Delta x} + fS = Q$$

where A is the cross-sectional area of the specimen,

k is the specimen conductivity at the mean temperature of the span,

Δt is the temperature drop from end to end of the span,

Δx is the length of the span,

fS represents the total net heat loss from the bar from it bottom end at the heater to the midpoint, x, of the given span, expressed as the product of S, which is the integral $\int_o^x (t_{bar} - t_{guard})\,dx$, and an average heat transfer coefficient f for the thermal path from bar to guard.

Q is the measured power input to the specimen heater.

The two equations written for each of the six spans of the bar can be solved simultaneously to determine k and f. For this to be strictly valid, k and f must have equal values in the two equations. Since the mean temperatures of the span in the two tests will in general differ slightly, and the conductivity of the bar may vary with temperature, a slight adjustment is made to the observed values of ΔT so that k corresponds to the mean of the span mean temperatures in the two tests. Compensation is made for the temperature dependence of f by using an appropriate value for the temperature dependence of the thermal conductivity of the powder insulation.

Electrical resistivity measurements for each span were made, at the temperature conditions existing at the end of each pair of runs for determining the thermal conductivity, by passing a d-c current of about 10 amperes along the bar and observing the potential differences between adjacent positive leads of the span thermocouples, with the current direction forward and reversed. The average of the two potential drops between two adjacent leads indicated the net potential drop due to the current flowing in the span, and thus enabled calculation of its resistivity. Additional sets of data were taken with the specimen isothermal at room temperature before and after the tests described above.

The thermoelectric power of the constantan specimen versus the constantan thermocouple wire was determined for each span by observing the potential differences between adjacent negative constantan leads of the span thermocouples at steady-state temperature with zero electric current flow along the bar. These zero current values ranged from about 4 to 42 x 10^{-8} V/deg over the temperature range -150 to 400 °C, and are used, as described in the next section, in the determination of the thermoelectric power of the constantan specimen relative to thermoelectric grade copper.

The computation of results directly from the observed data was effected by digital computer suitably programmed to compute the thermal conductivity, the electrical resistivity, and the corresponding mean temperatures, for each of the six spans.

4. Results and Discussion

The results of the thermal conductivity and electrical resistivity determinations, obtained by the methods described above, are shown in figure 2. The thirty individual thermal conductivity data points represent five sets of tests, each with values for the six spans. Electrical resistivity and thermal conductivity data obtained from the constantan specimen are shown as solid circles. Smoothed values are given at 50 deg C intervals in table 1, and are represented by the solid curves in figure 2.

To obtain the smoothed values of thermal conductivity and electrical resistivity, least squares fits of cubic polynomials in temperature were made to the test data. The respective equations for the thermal conductivity and electrical resistivity are:

$$\lambda = 21.77 + 2.971 \times 10^{-2}T + 3.397 \times 10^{-5}T^2 - 3.325 \times 10^{-8}T^3 \qquad (1)$$

$$\rho = 49.41 \times 10^{-8} + 1.846 \times 10^{-11}T - 2.801 \times 10^{-13}T^2 + 5.246 \times 10^{-16}T^3 \qquad (2)$$

where T is in °C, λ is in units of $\mathrm{Wm}^{-1}\ {}^{\circ}\mathrm{C}^{-1}$, and ρ is in units of Ω m. These equations should be considered valid only in the temperature range -150 °C to 550 °C.

An indication of the precision of the experimental results is given by the estimated standard deviation obtained from the residuals of a set of data points with respect to the curve which is fitted to the set. In this case, the thermal conductivity standard deviation was about 1 percent, while that for the electrical resistivity was about 0.6 percent. The absolute reliability of results obtained from this apparatus has been established by comparison of results on the round-robin specimens by NBS and other reputable laboratories around the world, and is estimated to be about ± 2 percent [2 - 5].

Values for the thermoelectric power of the constantan specimen relative to thermoelectric grade copper are presented in table 1. These values were obtained by the following method. A thermocouple was fabricated from a length of 0.05 cm diameter thermoelectric grade copper wire and a 0.025 cm diameter constantan wire from the same lot as was used for the Chromel P: constantan specimen thermocouples. This copper: constantan thermocouple was calibrated in the temperature range from -180 °C to 400 °C by the NBS Temperature Measurements Section. A quartic polynomial in temperature was fitted to the calibration data, and this polynomial was then analytically differentiated to obtain the thermoelectric power of the constantan wire relative to the thermoelectric grade copper. Data were obtained on the thermoelectric power of the constantan specimen relative to the constantan wire by the method described in the preceding section, and a least squares fit of a cubic polynomial in temperature was made to these data. Finally, the thermoelectric power of the constantan specimen relative to the copper wire as a function of temperature was obtained by the proper algebraic addition of the two polynomials. The equation determined in this manner is

$$S = -\,38.349 \times 10^{-6} - 9.2023 \times 10^{-8} T + 1.0638 \times 10^{-10} T^2 - 5.4866 \times 10^{-14} T^3 \tag{3}$$

where T is in °C and the relative thermoelectric power S is in units of V/°C. This equation should be considered valid only in the temperature range -150 °C to 400 °C.

Table 1. Results for a specimen of constantan:

thermal conductivity, electrical resistivity, and

thermoelectric power versus thermoelectric grade copper

Temperature °C	Electrical Resistivity Ω m	Thermal Conductivity W m^{-1} deg^{-1}	Thermoelectric Power versus Thermoelectric Grade Copper V/°C
-150	48.33×10^{-8}	18.2	-22.0×10^{-6}
-100	48.89	19.2	-28.0
- 50	49.24	20.4	-33.5
0	49.41	21.8	-38.3
50	49.44	23.3	-42.7
100	49.37	25.1	-46.5
150	49.23	26.9	-49.9
200	49.08	28.8	-52.9
250	48.94	30.8	-55.6
300	48.86	32.8	-57.9
350	48.88	34.9	-59.9
400	49.03	37.0	-61.6
450	49.35	39.0	---
500	49.89	41.0	---
550	50.68	42.9	---

5. References

[1] T. W. Watson and H. E. Robinson, Thermal conductivity of some commercial iron-nickel alloys, Trans. ASME J. Heat Transfer 83C, 402 (1961).

[2] T. W. Watson, D. R. Flynn, and H. E. Robinson, Thermal conductivity and electrical resistivity of Armco Iron, J. Res. NBS 71C, 285 (1967).

[3] T. W. Watson and D. R. Flynn, Thermal conductivity of four heat-resistant alloys, Trans. Met. Soc. AIME 242, 844 (1968).

[4] M. J. Laubitz and K. D. Cotnam, Thermal and electrical properties of Inconel 702 at high temperatures, Canad. J. Phys. 42, 131 (1964).

[5] R. W. Powell and R. P. Tye, New measurements on thermal conductivity reference materials, Int. J. Heat Mass Transfer 10, 581 (1967).

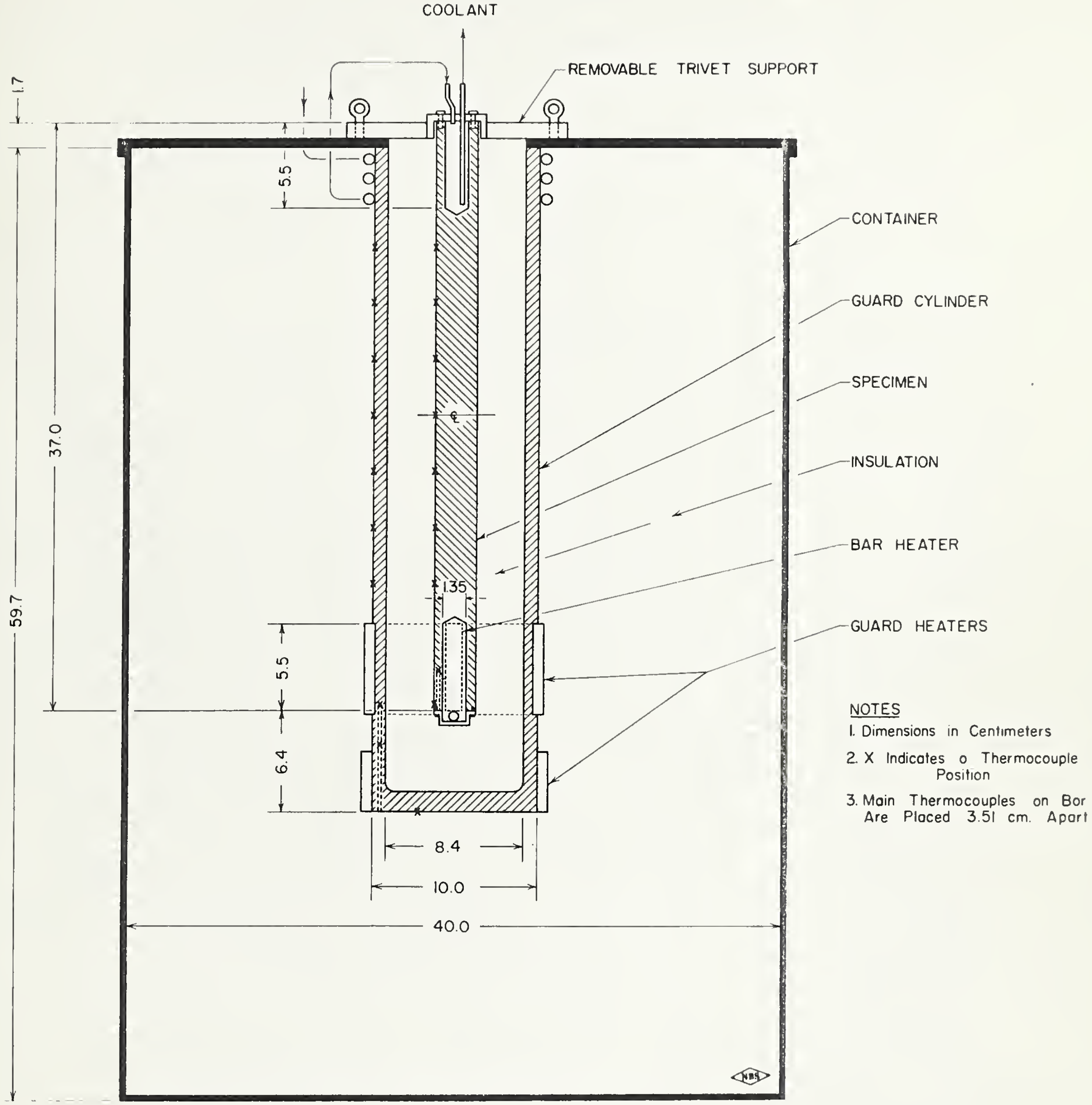

Figure 1. Apparatus used for measuring thermal conductivity of metal specimens.

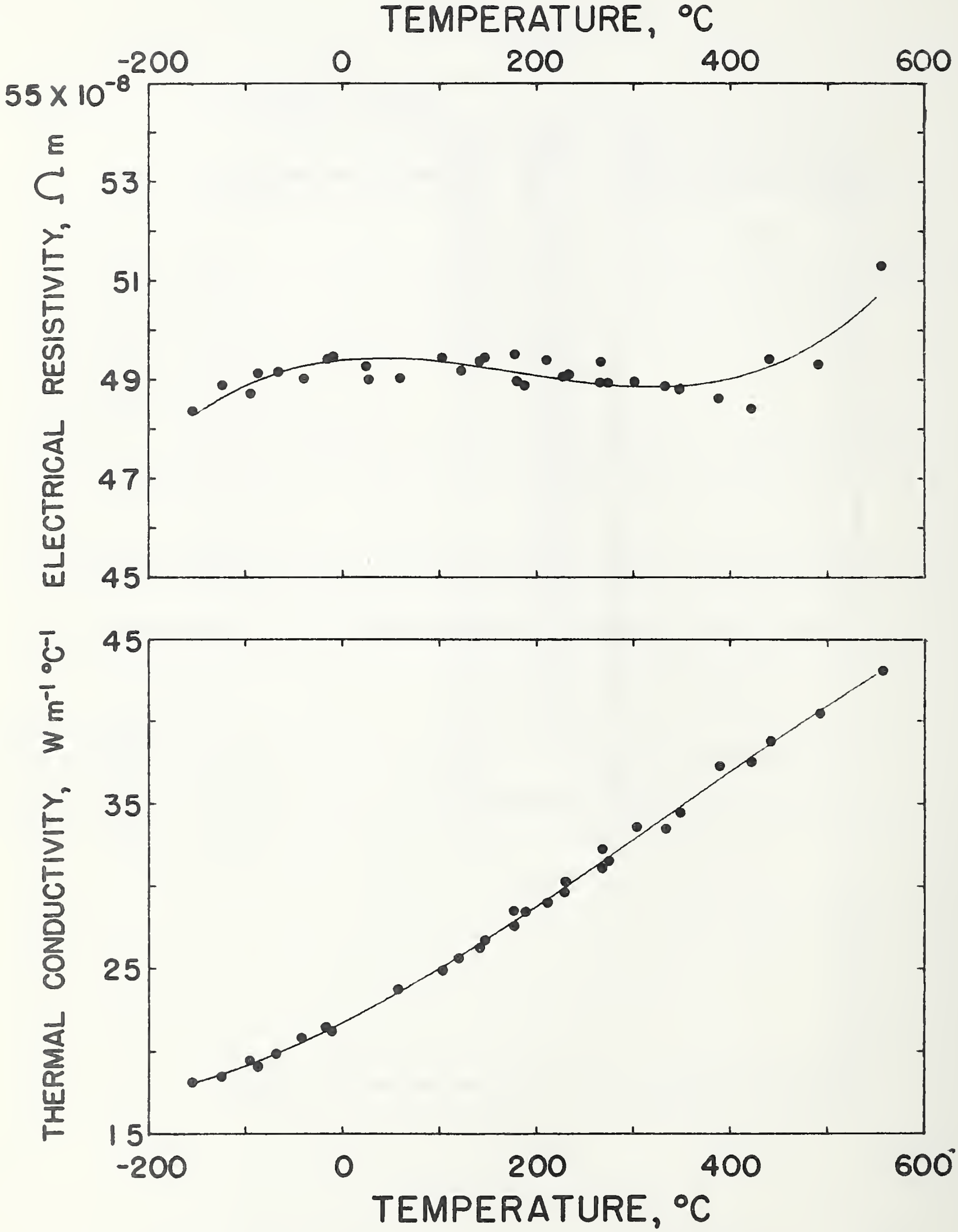

Figure 2. Thermal conductivity and electrical resistivity of a sample of constantan. The symbols are described in the text.


DEPARTMENT OF COMMERCE ★ NATIONAL BUREAU OF STANDARDS ★