NASA CR 54151
BATT- 7096

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) $2.00

Microfiche (MF) .50

ff 653 July 65

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL FROM 0 TO 1800F

by

J. Matolich, Jr.

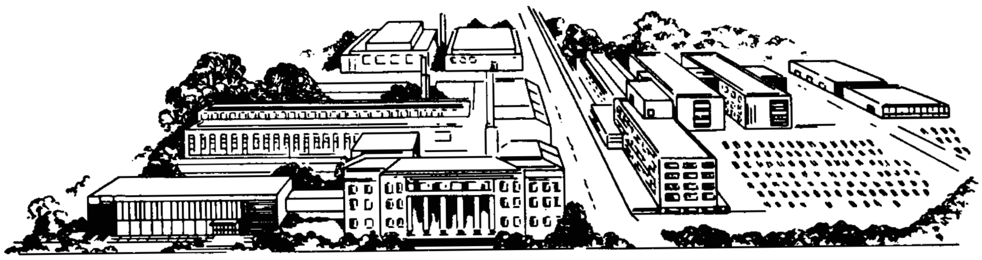
prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NASA PO NO. C 46539-A

FACILITY FORM 602

N65-34531	
(ACCESSION NUMBER)	(THRU)
32	1
(PAGES)	(CODE)
	17
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)



BATTELLE
MEMORIAL INSTITUTE

Requests for copies of this report
should be referred to:

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Washington 25, D.C.
Attention: AFSS-A

NASA CR-54151
BATT-7096

TOPICAL REPORT

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL FROM 0 TO 1800 F

by

J. Matolich, Jr.

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

September 15, 1965

CONTRACT NASA PO NO. C 46539-A

Technical Monitor
NASA-Lewis Research Center
Cleveland, Ohio
Fluid Systems Components Division
Marshall W. Dietrich

BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus, Ohio 43201

ABSTRACT

34431

Thermal-conductivity and electrical-resistivity measurements were made on two Type 316 stainless steel specimens from different heats. Within experimental error there is no significant difference between the two specimens except at 800 F, where the data suggest a solid-state reaction. Thermal-conductivity values range from 7.43 to 17.0 Btu hr^{-1}ft^{-2}ft ^{o}R^{-1} over the temperature range 0 to 1800 F. Over the same temperature range the electrical-resistivity values range from 74 to 120 microhm-cm.

Author

TABLE OF CONTENTS

Page

APPENDIX A

APPENDIX B

LIST OF TABLES

TABLE OF CONTENTS
(Continued)

Page

LIST OF FIGURES

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL FROM 0 TO 1800 F

by

J. Matolich, Jr.

SUMMARY

Results of laboratory determinations of the thermal conductivity and electrical resistivity of two samples of Type 316 stainless steel over the temperature range 0 to 1800 F are presented. There is no significant difference between the two specimens except at 800 F where the data suggest a solid-state reaction. A difference between the specimens occurs at this point, presumed to be caused by slight differences in chemical composition. Thermal-conductivity values range from 7.43 to 17.0 Btu hr^{-1} ft^{-2}ft ^{o}R^{-1} from 0 to 1800 F. At low temperatures the observed data are essentially in agreement with the literature. At elevated temperatures the observed values are about 11 per cent higher than previously reported data. Electrical-resistivity values, measured concurrently with the thermal conductivity, range from 74 to 120 microhm-cm over the same temperature range. Experimental values of thermal conductivity and electrical resistivity are correlated with the Wiedemann-Franz-Lorenz relationship.

INTRODUCTION

In many cases, when comparing experimental and theoretical heat-transfer results, it is necessary to know the specific thermal properties of the material under study. Since handbook property values for the general type of material used are not sufficiently accurate, it is necessary to determine the values of the properties of importance for a specimen of the actual material of interest. This report presents the results of the determination of the variation of thermal conductivity with temperature for two specimens of Type 316 stainless steel material used in a heat-transfer comparison study.

Since thermal conductivity is a structure-sensitive property, accurate measurements also give data on structural changes that occur. Also, two determinations on essentially the same alloy give a unique opportunity to examine the precision of the method used in making the thermal-conductivity measurements.

SPECIMEN DESCRIPTION

The two Type 316 stainless steel specimens studied were machined from materials submitted by NASA-Lewis. The first specimen, 3A, was labeled 38514-D3571 (2) and was received in a bar 1-1/2 inches square by 12 inches long. The second specimen, 4A, was labeled 18227-D3571 (4) and was 1-1/4 inches square by 12 inches long.

Data furnished by the material supplier and other specimen details are given in Table 1. Additional measurements of material density and electrical resistivity at room temperature were made by Battelle. The chemical composition of the two specimens fell within the allowable range specified for AISI-316 stainless steel. However, Specimen 3A contained amounts of copper and cobalt that were not reported in Specimen 4A. The differences in the chemical composition of the two specimens are further reflected in the significant variation of the mechanical properties appearing in Table 1.

TABLE 1. SPECIMEN DETAILS

	Specimen 3A	Specimen 4A
Material	Stainless Steel Type 316	
Condition	Hot rolled, annealed, and pickled	
Heat Number	38514	18227
Composition, wt %		
C	0.063	0.063
Mn	1.59	1.88
P	0.023	0.021
S	0.010	0.014
Si	0.60	0.54
Cr	17.45	17.45
Ni	12.60	12.62
Mo	2.55	2.70
Cu	0.09	N.R.(a)
Co	0.19	N.R.
Fe(b)	64.83	64.71
Yield Strength, psi	35,200	38,000
Tensile Strength, psi	80,800	88,000
Elongation, per cent	64	60
Reduction, per cent	75	74
Hardness, Rockwell B	78-79	77
Density(c) at 20 C, g cm^{-3}	7.95	7.95
Electrical Resistivity(c) at 20 C, microhm-cm	75.4	77.4

(a) None reported.

(b) Fe wt. % by differences.

(c) Battelle measurements; other data from supplier data sheet.

The machined specimens were 0.900 ± 0.001 inch in diameter by 5.715 ± 0.006 inches long in the measuring section and 1.125 ± 0.003 inches in diameter by 3.375 ± 0.006 inches long in the heater section. The specimens were about ideal in size for use in the thermal-conductivity apparatus. All thermal-property measurements were conducted on the specimens in the as-received condition.

METHOD AND APPARATUS

A longitudinal, steady-state comparison method was used in making the thermal-conductivity measurements. Figure 1 is a schematic drawing of the apparatus. The longitudinal, steady-state comparative method has been extensively used and is well suited to measure thermal conductivity of metals.(1, 2, 3)* This method yields the conductivity directly and is very reliable for metals from cryogenic temperatures to about 1200 C. However, the method requires complex apparatus and a long time to make measurements.

The method, in brief, consists of heating one end of a specimen, measuring the temperature gradients along the specimen, and determining the rate of heat flow through the specimen by means of a metal reference material of known thermal conductivity attached to the cold end of the specimen. Radial heat flow into, or away from, the specimen and reference-material assembly is minimized by thermal insulation and an encircling guard tube in which temperatures at corresponding levels are adjusted, as nearly as possible, to match those in the specimen and reference material. The thermal insulation used consists of bubbled alumina, which fills the annular space between the specimen reference-material assembly and the guard cylinder. The specimen is protected by a vacuum of approximately 2×10^{-5} Torr during the measurements.

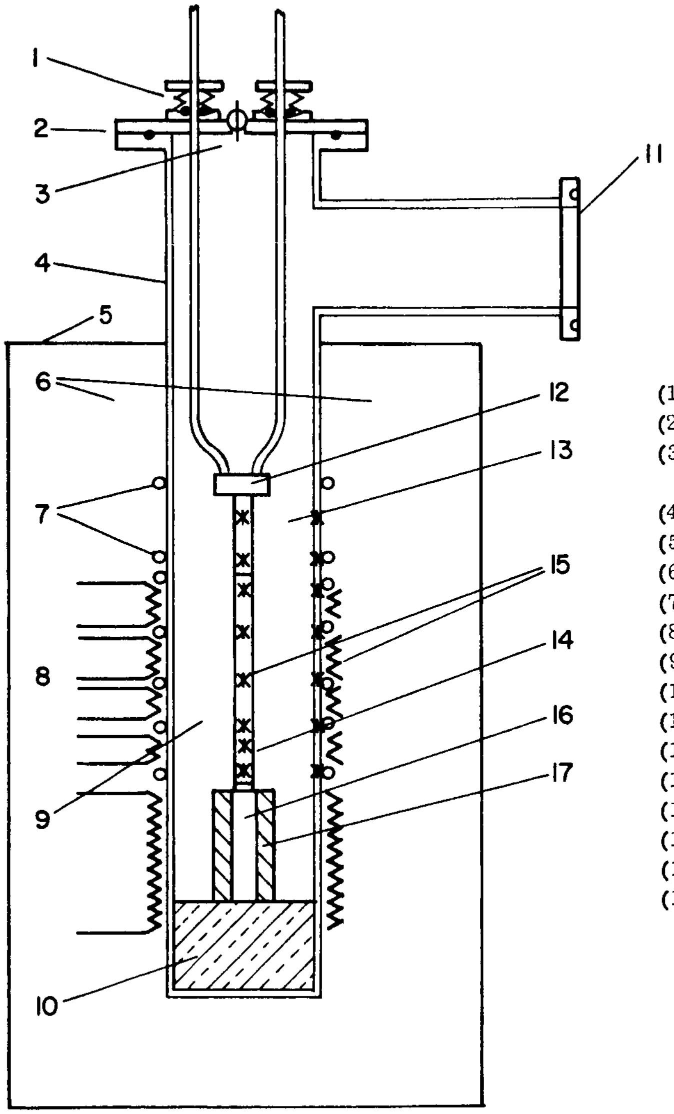
Six 32-gage Chromel-Alumel thermocouples of calibrated wire are wedged in holes spaced along the specimen, and three similar thermocouples are placed in the Armco iron used as the reference material. Each part of the specimen between thermocouples may be regarded as an independent small specimen. A thermal-conductivity value is calculated for each section of the specimen bounded by two thermocouples and is reported for the mean temperature of that particular section of specimen. The thermocouple placement used here permits the calculation of five thermal-conductivity values, each at a different mean temperature, for each thermal-equilibrium setting.

The Battelle thermal-conductivity apparatus is equipped to make electrical-resistivity measurements concurrently with the thermal-conductivity measurements. These data are often useful in interpreting thermal-conductivity results. Electrical-resistivity measurements are made by the comparative voltage-drop method. A direct current is passed through the specimen, and voltage drops are measured over sections of the specimen. Corresponding legs of the specimen thermocouples are used as potential probes. Current flowing through the specimen is determined by measuring the voltage drop across a standard resistor in series with the specimen. Measurements are taken with the current flowing in both directions, and the values are averaged to minimize thermal and induced potentials.

Generally, thermal-conductivity and electrical-resistivity measurements are made in steps from low to higher temperatures, after which one or more equilibria are obtained at lower temperatures. This duplication of measurements is used as a check on

---

*References are given on page 25.



(1) Vacuum seals
(2) Top plate
(3) Hermetic seals for thermocouples and power leads
(4) Vacuum chamber and guard
(5) Insulation enclosure
(6) Sil-O-Cel insulation
(7) Guard cooling coils
(8) Guard balancing heaters
(9) Insulation
(10) K-30 brick
(11) Connection to vacuum system
(12) Sink assembly
(13) Reference standard
(14) Specimen
(15) Thermocouples (*)
(16) Heater block
(17) Specimen heater

A-51812

FIGURE 1. SCHEMATIC DRAWING OF THE THERMAL-CONDUCTIVITY APPARATUS

thermocouple and specimen changes which may have taken place during the 5-day measuring period. (Sections of the specimen have been exposed to an individual heat treatment that could induce structural changes.)

Auxiliary apparatus required for the measurements, but not shown in Figure 1, is as follows:

(1) Voltage-regulated power supply for heaters
(2) Constant-temperature water supply for the heat sink
(3) Thermocouple emf-measuring system
(4) Regulated air supply for cooling coils.

Thermocouples are made from previously calibrated wire. A continuous program of establishing the values for the conductivity of the reference material(4) is maintained.

The heat-flux balance in the specimen-standard assembly may be written as

$$Q_o = \frac{kA(\Delta T)}{(\Delta x)} \pm f(s) \pm g'(m) \quad , \tag{1}$$

where

Q_o = true heat flow through the specimen, Btu hr^{-1}

k = thermal conductivity, Btu $\text{hr}^{-1}\ \text{ft}^{-2}\ \text{ft}^{o}\ \text{R}^{-1}$

A = area, ft^2

ΔT = temperature difference between adjacent thermocouples, ^{o}R

Δx = distance between thermocouples, ft

$f(s)$ = net radial heat exchanged resulting from guard-specimen temperature mismatch and possible radiant heat exchange, Btu hr^{-1}

$g'(m)$ = net heat evolved or absorbed resulting from non-steady state, Btu hr^{-1}.

At thermal equilibrium the thermal conductivity is defined by

$$k = \frac{Q\Delta x}{A\Delta T} \quad , \tag{2}$$

where

Q = measured value of heat flow (Btu/hr) = $Q_o \pm f(s) \pm g'(m)$.

The method has been constructively criticized in the literature. Bidwell's(5) early criticism is answered by proper guarding and the comparative standard method of measuring heat flows. More recently, Laubitz(6) examined the limits on the difference between the reference material and the unknown. The work of Watson and Robinson(3) shows that even for the much more difficult task of guarding an absolute specimen-input heater, circumvented by the comparative method, the radial heat exchange before corrections was of the order of only 5 per cent.

The apparatus employed in the measurements is a proven piece of equipment and has been in satisfactory use for several years. Experience has established that the relative error between different measurements performed in the apparatus does not exceed ± 2 per cent. This is considered to be the apparatus reproducibility when using the same reference material. The absolute error of the thermal-conductivity values is estimated not to exceed ± 5 per cent, the chief uncertainty being the absolute thermal conductivity of the reference material. A detailed error analysis is given in Appendix A.

The measuring method was designed for thermal-conductivity measurements and not electrical-resistivity measurements, and although components of the electrical measuring system are all of high accuracy, the total error in electrical-resistivity measurements is estimated not to exceed ± 2 per cent. This somewhat large error results from the temperature gradients in the apparatus and the small potential drops resulting from the relatively large cross section of the thermal-conductivity specimen.

RESULTS

Table 2 gives observed grouped thermal-conductivity and electrical-resistivity values. The standard deviation is included to illustrate the scatter in the data at each temperature. These data are a reduction of the individual observed points that are given in Appendix B. This reduction of data allows a direct comparison between specimen conductivity values at the selected temperatures. The reduction in the number of points was made by moving each observed point along the curve to a convenient nearby selected temperature. This was done using the slope of the data evaluated near that point and the difference in temperature between the selected point and the experimental point. The adjustment may be viewed as being based on the linear term of the Taylor series expansion of the conductivity data about the selected temperature. Since the adjustment is small, this first term is adequate. This adjustment brings all the experimental points to a reduced number of temperature points at which an average value can be calculated and an estimate made of the standard deviations, which is the measure of the scatter of the data about the average and a measure of internal consistency. The data for both specimens reproduced well at lower temperatures after the specimens had been to the highest temperatures, indicating that no irreversible property change had taken place. These data at lower temperatures are given as Equilibrium 6, in Tables B-1 and B-2 in Appendix B. The data at low temperatures, from 0 to about 800 F, are essentially the same for both specimens. Of a total of about 42 points, none are beyond ± 1.5 per cent from the average.

To analytically express the thermal-conductivity data, they were fitted with two curves. A curve of the form

$$k = AT^B \qquad 0 \leq T \leq 800 \text{ F} \tag{3}$$

was used below the inflection point.

TABLE 2. OBSERVED THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL

Temperature, F	Specimen 3A						Specimen 4A					
	k(a)	σ(b)	n(c)	ρ(d)	σ	n	k	σ	n	ρ	σ	n
70	7.77	- -	1	76.1	1.4	2	7.95	- -	1	77.6	0.5	3
200	8.62	0.08	6	82.3	0.1	6	8.75	0.23	5	82.7	0.4	5
400	9.77	0.13	8	90.0	1.0	8	9.77	0.16	8	90.3	0.4	8
600	10.85	0.10	3	95.7	0.7	3	10.57	0.15	3	96.9	0.5	3
750	11.37	0.11	3	99.9	0.3	3	11.04	0.10	3	99.8	2.1	3
850	11.76	0.12	2	105.6	1.2	2	11.50	- -	1	103.6	2.2	2
1000	12.84	0.09	2	105.8	1.2	2	12.44	0.32	3	107.9	0.8	3
1200	13.80	0.14	2	109.8	0.6	2	13.46	0.14	2	112.0	2.1	2
1400	14.73	- -	1	114.1	- -	1	14.76	- -	1	116.0	- -	1
1600	15.62	0.04	2	116.8	3.5	2	16.37	- -	1	115.3	- -	1
1800	- -	- -	- -	- -	- -	- -	17.19	- -	1	122.4	- -	1

(a) k, thermal conductivity, Btu $hr^{-1} ft^{-2} ft\ {}^{\circ}R^{-1}$.

(b) σ, standard deviation in conductivity or resistivity units.

(c) n, number of points.

(d) ρ, electrical resistivity, microhm -cm.

A straight line

$$k = C + DT \qquad 800 \leq T \leq 1800 \tag{4}$$

was used above the inflection point, where

k = thermal conductivity, Btu hr^{-1} ft^{-2} ft ^{o}R

T = absolute temperature, ^{o}R.

All the individual points from both specimens given in Appendix B were used to fit Equations (3) and (4).

In the temperature range from 0 to 800 F, least-squares fit yielded the following constants for Equation (3):

$$A = 0.52048 \pm 0.0188$$

$$B = 0.43367 \pm 0.0096$$

and with a standard error of the curve, which is the measure of the scatter of the observed data about the fitted curve, of 0.14 based on 38 degrees of freedom.

Based on these errors, the largest observed deviation from the curve, which is given in Table 3 at 750 F for Specimen 4A, occurs about 1 in 20 times and is considered significant.(7) None of the other deviations are significant.

For the temperature range from 800 to 1800 F, an analysis using Equation (4) yielded

$$C = 4.553 \pm 5.62(10^{-2})$$

$$D = 5.507(10^{-3}) \pm 1.88(10^{-5}) \quad ,$$

with a standard error of the curve of 0.25 based on 18 degrees of freedom.

The data for each specimen cross at about 950 F. Hence, both specimens have essentially the same absolute value of thermal conductivity over the temperature range. However, the slope of the best curve visually fitted through the two sets of data differs slightly, and the data were examined for the possibility that the two specimens might have different slopes. The difference found is expected 1 out of 10 times for the respective number of points and their standard errors, and it is not significant.

The individual points and the grouped observed points are plotted in Figures 2 and 3. The analytical variations between Equations (3) and (4) are also included in the figures. An inflection in the thermal conductivity-versus-temperature curve is clearly shown in the vicinity of 800 F for both specimens.

A plot of the electrical-resistivity data for both specimens is given in Figure 4. The data do not show the inflection that is readily observed in the thermal-conductivity data. This is not surprising in view of the small change expected. The method and

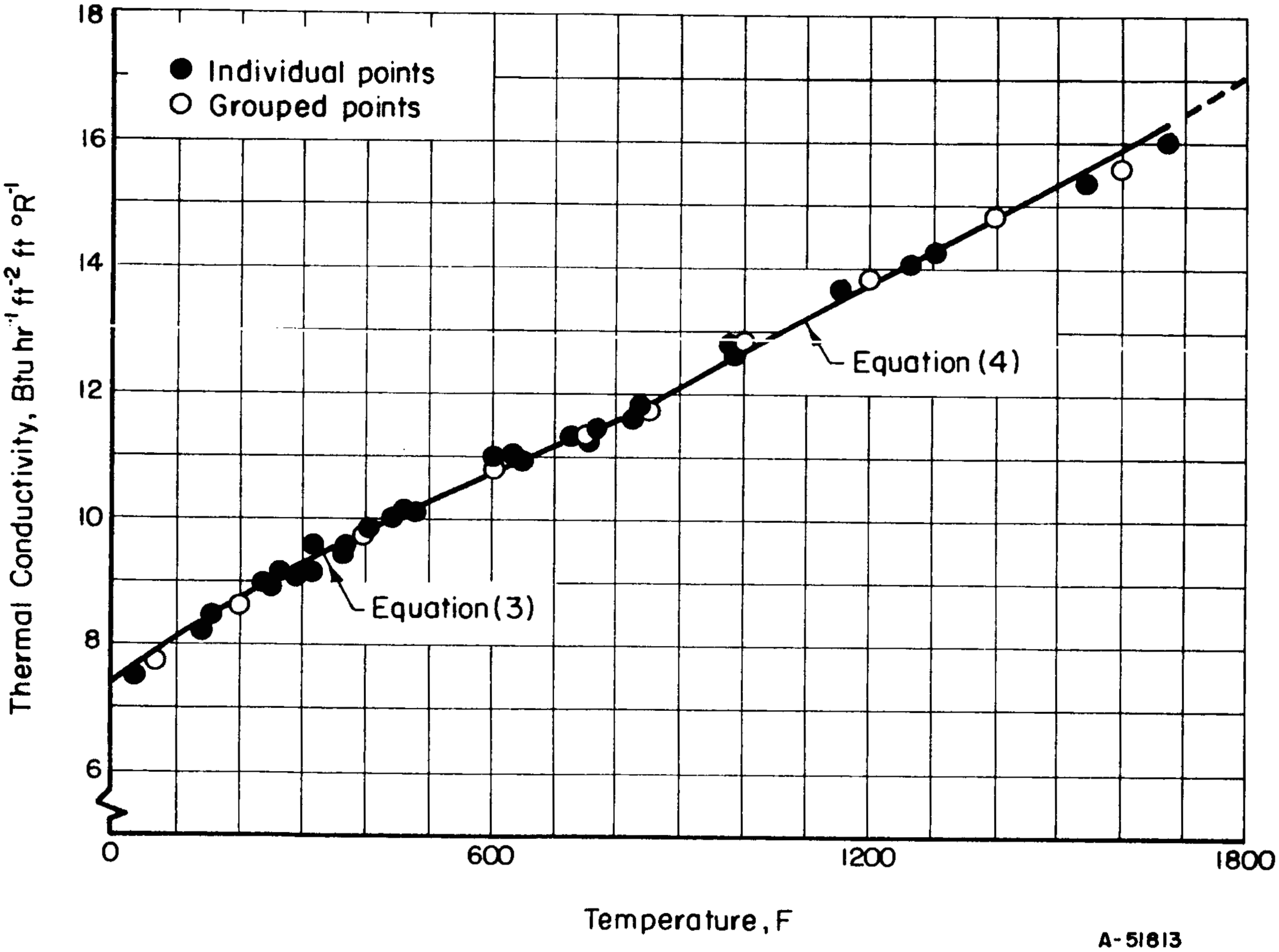


FIGURE 2. THERMAL CONDUCTIVITY OF TYPE 316 STAINLESS STEEL, SPECIMEN 3A

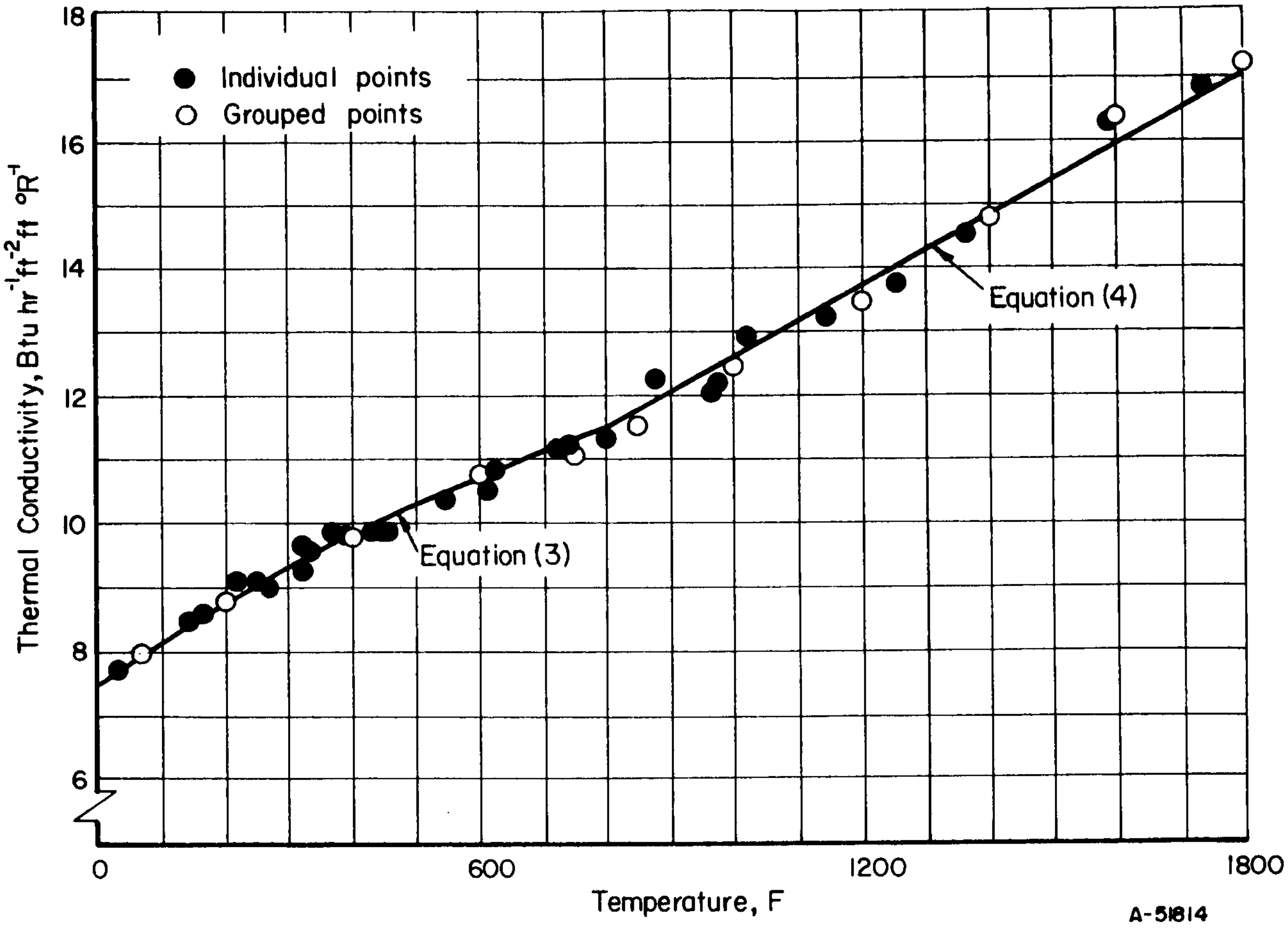


FIGURE 3. THERMAL CONDUCTIVITY OF TYPE 316 STAINLESS STEEL, SPECIMEN 4A

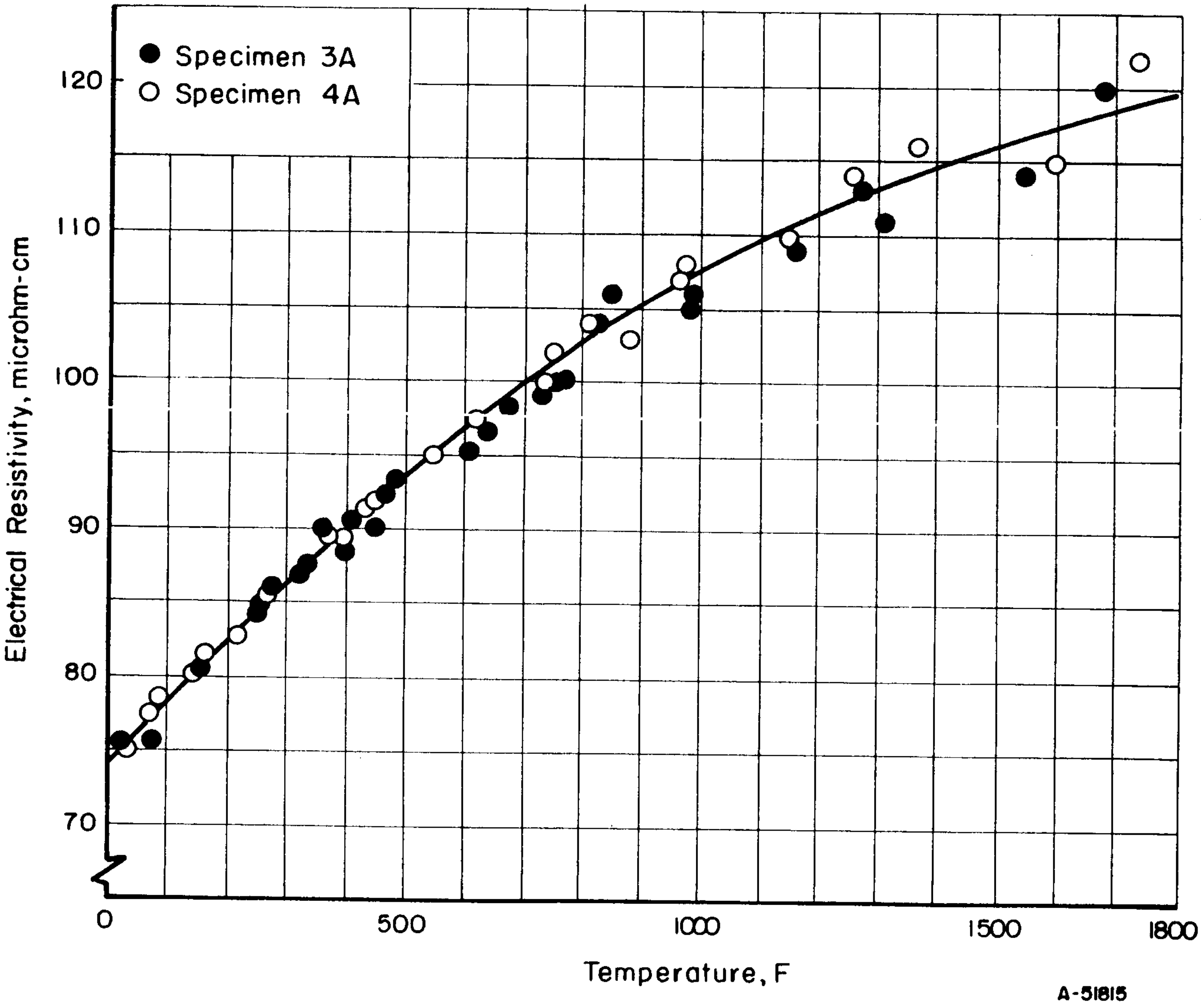


FIGURE 4. ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL, SPECIMENS 3A AND 4A

apparatus was designed for thermal-conductivity measurements, and the electrical measurements are valuable, incidental data, readily obtained. As a result, the precision of the electrical measurements is too low to contribute to the question of the inflection, but on the whole, they add information on the material.

Table 3 gives, at selected temperatures, interpolated thermal-conductivity values calculated from the above expressions and also gives comparative data from other investigators. Included in the table are electrical-resistivity values read from a smooth curve visually fitted to the observed resistivity data.

TABLE 3. INTERPOLATED THERMAL CONDUCTIVITY, LITERATURE VALUES, AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL

Temperature, F	Thermal Conductivity, Btu $hr^{-1}ft^{-2}ft\ ^{o}F^{-1}$ Present Work	Battelle[a]	Armour[b, c]	Electrical Resistivity, microhm-cm Present Work
0	7.4	--	--	74
200	8.7	8.3	8.3	82
400	9.8	9.2	9.3	90
600	10.7	10.0	9.9	97
750	11.3	--	--	102
800	11.5	11.0	10.2	103
850	11.8	--	--	104
1000	12.6	11.8	11.2	108
1200	13.7	12.6	12.2	112
1400	14.8	13.4	13.3	115
1600	15.9	14.3	14.3	117
1800	17.0	--	15.3	120

(a) Reference (8).

(b) Reference (9).

(c) Values read from a smooth curve drawn through data.

The thermal-conductivity values measured during the present work are 6 to 11 per cent higher than the values previously reported by Battelle.(8) This may reflect compositional differences or may result from structural differences, since thermal conductivity is a structure-dependent property, resulting from changes in the state of the art of producing this alloy. There is no explanation for this behavior on the basis of these data alone.

At about 800 F there is an inflection in the previous Battelle-observed thermal-conductivity(8) data. The same inflection can also be observed in the Armour(9) data.

Several subtle metallurgical changes take place in stainless steels beginning at about 800 F. They have been observed in several other measured properties, and are clearly illustrated in the enthalpy data of Douglas and Devers.(10) Several transition phases have been identified in some of these materials, as well as the "K" state in nickel-chromium materials.(11) These are in addition to regular metallurgical changes such as carbide formation and solution. Essentially pure iron shows a subtle change at about

820 F.(12, 13) Since all these elements are in the alloy, the inflection point in the thermal-conductivity values of the specimens at 800 F is thought to be real and to have resulted from any of the mechanisms listed above.

In view of the significant difference of the point at 750 F, which occurs only 1 time out of 20, and the inflection in the data at 800 F, with no significant difference elsewhere, it is concluded that the chemical differences between the specimens apparently affect the thermal conductivity only near 800 F.

DISCUSSION

Wiedemann-Franz-Lorenz Relationship

The Wiedemann-Franz-Lorenz relationship is a correlation that exists between thermal conductivity and electrical resistivity. It is recognized that carriers of electrical current also transport heat. This is theoretically sound(14) and has been experimentally verified for many metal systems.(15, 16, 17) In conformity with the usual practice in the literature, these data are presented in watt-°K units. The relationship is expressed as

$$L = \frac{k\rho}{T} \quad , \qquad (5)$$

where

L = Lorenz ratio, which has the theoretical value $2.45(10^{-8})$ watt-ohm $^{\circ}C^{-1}$ $^{\circ}K$

k = thermal conductivity, watt cm^{-2} $cm^{\circ}C^{-1}$

ρ = electrical resistivity, ohm-cm

T = absolute temperature, °K.

Figure 5 shows the observed thermal conductivity of Specimens 3A and 4A plotted against the ratio of the absolute temperature to the observed electrical resistivity. The data suggest that linear functions of the form

$$k = \frac{A(T)}{\rho} + B \quad , \qquad (6)$$

having the correlation variable T/ρ, be used to fit the points. These functions were fitted to both sections of the experimental data. Table 4 presents results of the computations and shows close agreement between L, above, and the constant A in Equation (6).

TABLE 4. CONSTANTS FOR EQUATION 6

Range of $\frac{T}{\rho} \times 10^{-6}$	Constant A, x 10^8	Constant B	Standard Deviation, thermal-conductivity units
3.60 to 7.16	2.056	0.0592	0.0024
7.16 to 10.02	2.660	0.0160	0.0044

Also included in Figure 5 is the theoretical relationship based on Equation (5) and values reported by Powell(20) for a number of austenitic alloys. The agreement with Powell's data is good and, on re-examination, a break can also be seen in his data at about the same region that the break occurs in Figure 5.

Composition Correlation

Another correlation can be made with the experimental data based on composition. Figure 6 shows the variation of thermal conductivity with alloy content in the iron system for temperatures of 1800 F, 800 F, and 200 F. As a rule, small additions to pure iron cause a rapid decrease of the conductivity with composition which soon saturates out, and the conductivity, at a high alloy content, becomes essentially independent of small variations. The data from the specimens tested herein (square symbols) tend to support this rule. On the basis of literature values this rule does not seem to hold for the 1800 F data. However, where both Armco and stainless steel have been measured at 1800 F by the same laboratory, with the same apparatus, the stainless steel is found to have a slightly lower thermal-conductivity value thus still conforming to the rule. Although the absolute values differ, Armour(9) found a difference of 9 per cent between Armco iron and Type 316 stainless steel, and Battelle(18) found a difference of 7 per cent.

Literature Comparison

Figure 7 gives a plot of thermal conductivity versus temperature for the Type 316 stainless steels and a few related alloys. The present work is in good agreement at lower temperatures with the more recent data on high-alloy steels.

Of considerable interest is the behavior of the austenitic alloy at the highest temperatures reached, particularly when contrasted with iron, which is also austenitic above 1670 F. Much work has been done on Armco iron, which is used as a thermal-conductivity standard. Figure 7 suggests that an extrapolation to higher temperatures of the best literature values given at lower temperatures for stainless steel would yield conductivity values that would be higher than some values reported for pure iron. The figure also shows that there is considerable disagreement on the slope of the thermal conductivity of austenite. Based on the values derived in the present study for the slope of austenitic stainless steel and the most recent determinations on Armco iron, the best value for the slope of austenitic iron appears to be about 4.0×10^{-3} Btu units/°F.

JM/sel

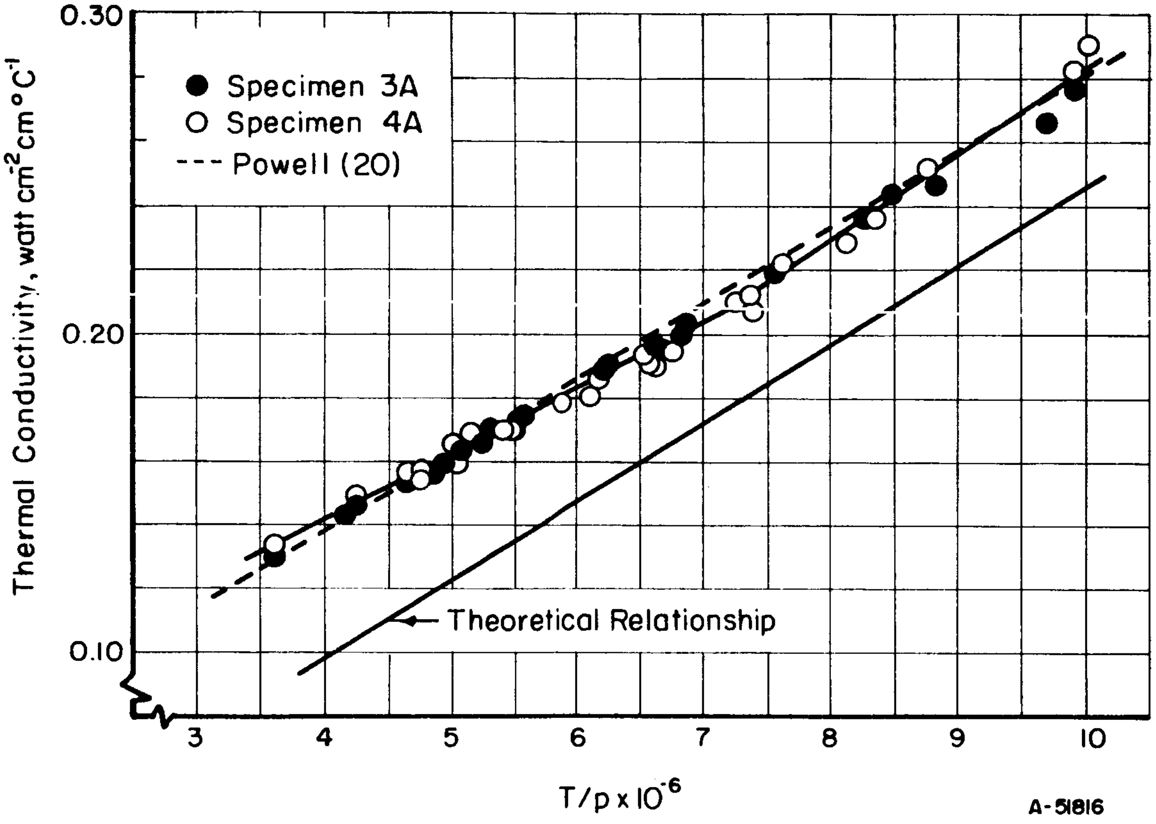


FIGURE 5. THERMAL CONDUCTIVITY VERSUS ABSOLUTE TEMPERATURE/ ELECTRICAL RESISTIVITY FOR TYPE 316 STAINLESS STEEL

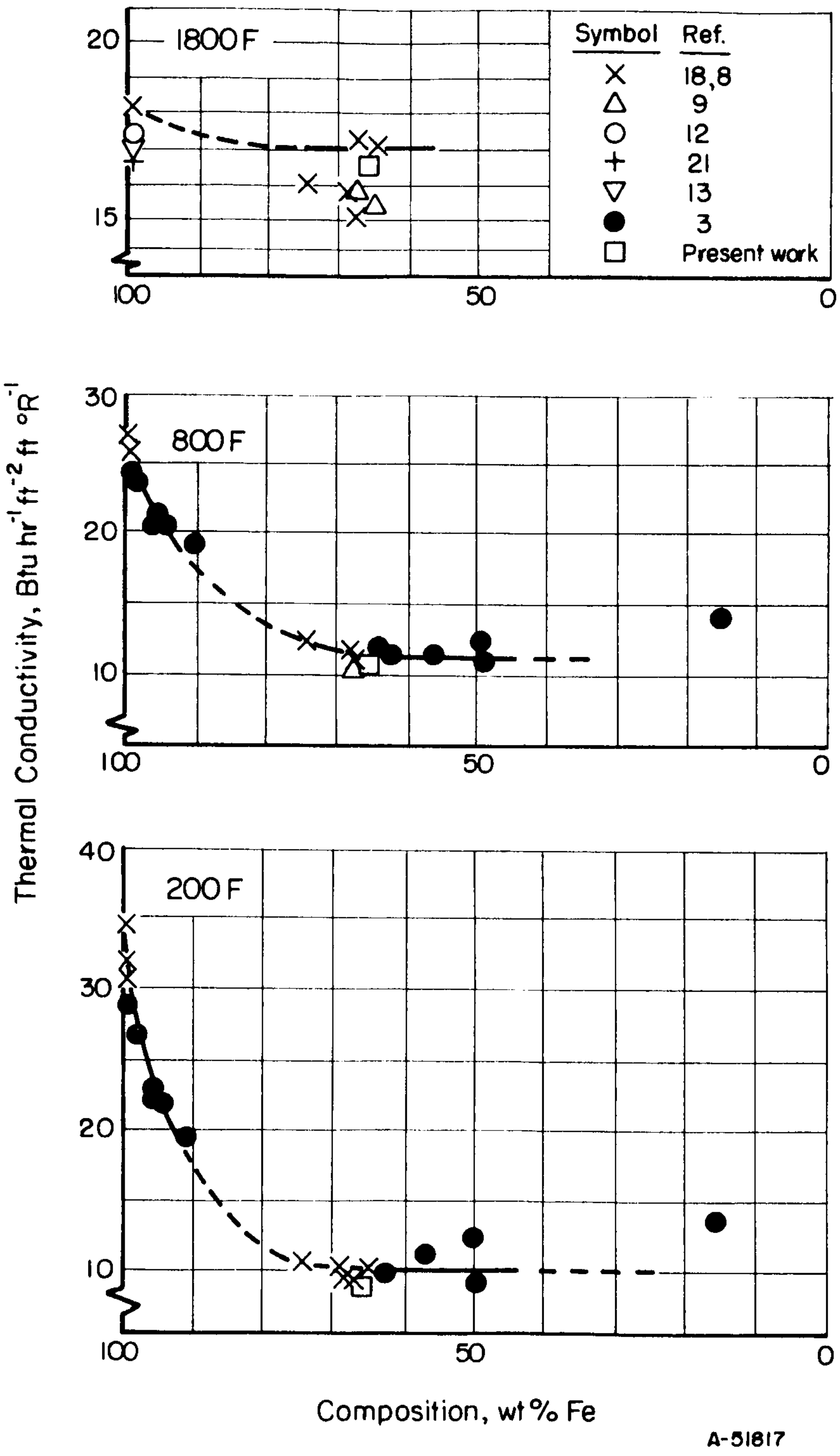


FIGURE 6. VARIATION OF THERMAL CONDUCTIVITY OF IRON WITH ALLOY CONTENT

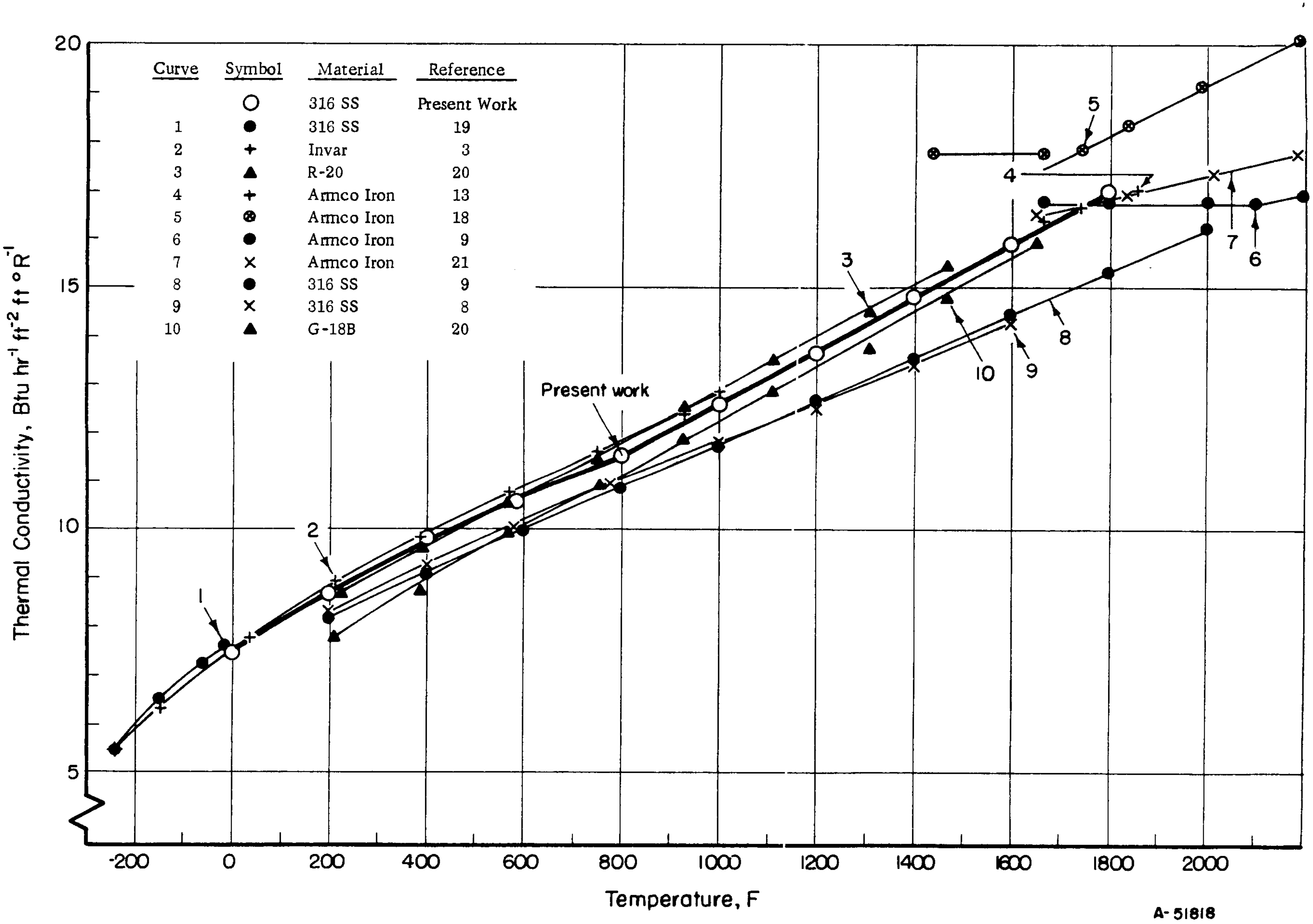


FIGURE 7. THERMAL CONDUCTIVITY OF TYPE 316 STAINLESS STEEL AND RELATED ALLOYS

APPENDIX A

ANALYSIS OF ERRORS

APPENDIX A

ANALYSIS OF ERRORS

The relative error in the thermal conductivity, k, due to fluctuations in the various factors in the method and apparatus, may be evaluated in two steps. First, the error in the heat flow through the specimen, Q, may be evaluated through use of Equation (1). The use of Equation (1) assumes realistically that the net radial-heat losses and the heat effect of the temperature drift are reflected entirely in the measurement of Q. Then, second, the total relative error in the thermal conductivity may be evaluated using the definitive Equation (2).

Equation (1) may be rewritten as

$$Q = Q_0 - f(s) - g'(m) = kA\frac{\Delta T}{\Delta x} \quad , \qquad \text{(A-1)}$$

where Q = the measured heat flow through the reference material, Q_0 = the true heat flow, and the remaining terms have meanings as defined for Equation (1).

Experience under various guarding conditions and with varying degrees of temperature drift has yielded estimates for the variation in Q_0 of 0.8 and 0.3 per cent resulting from f(s) and g'(m), respectively.

The determinable error in Q may be written(20) as

$$\epsilon_Q^2 = \left(\frac{\sigma Q}{Q}\right)^2 = \left(\frac{\sigma k}{k}\right)^2 + \left(\frac{\sigma A}{A}\right)^2 + \left(\frac{\sigma \Delta T}{\Delta T}\right)^2 + \left(\frac{\sigma \Delta x}{\Delta x}\right)^2 = \sum\left(\epsilon_i\right)^2 \quad , \qquad \text{(A-2)}$$

where ϵ_Q is the fractional uncertainty in Q, ϵ_i is the fractional uncertainty in the i^{th} term in the right-hand side of Equation A-1, and the remaining terms have meanings as defined for Equation (1). The equation says that the squares of the relative errors of the terms are additive.

The best estimate of the relative error is then given by

$$\epsilon = \left[\sum\left(\epsilon_i\right)^2\right]^{1/2} \quad , \qquad \text{(A-3)}$$

which is the root mean square error and ϵ_i is, again, the relative mean error of the various terms entering the definitive equations.

The relative errors, as given in the following tables, and indicated by the use of sigma for the various factors entering the equations, have a somewhat wider interpretation than the relative error, $\frac{(\Delta i)}{i}$. The values used are based on the average values of these errors observed in many conductivity measurements. They reflect the techniques used to measure the factors, and their magnitudes point out areas for improving the measurements. Table A-1 gives the relative errors for the various terms which affect the measured heat flow, Q, measured by the reference material.

TABLE A-1. RELATIVE ERRORS, FOR ESTIMATING ϵ_Q

Source of Error	k[(a)]	A	ΔT	Δx
Relative Error, ϵ_i, per cent	0	0.2	1.0	0.5

(a) Thermal conductivity of the reference material.

Equation (A-2) and the values given in Table A-1, coupled with the earlier estimates for the effects of unbalance and drift, through the use of Equation (A-3) lead to an estimate for the relative error of Q of ± 1.4 per cent.

Table A-2 gives the relative errors used to estimate the total error in the measured specimen thermal conductivity using the error of Q as evaluated above.

TABLE A-2. RELATIVE ERRORS, FOR ESTIMATING ϵ_k

Source of Error	Q	Δx	A	ΔT
Relative Error, ϵ_i, per cent	1.4	0.5	0.2	1.0

Equation (A-3) leads to the estimate $\epsilon_k = \pm 1.8$ per cent, which is the relative error using the same reference material. This assumes that the conductivity of the reference material is known with certainty; hence, it is the reproducibility of the apparatus and is considered to be ±1.8 per cent with a given reference material.

The absolute error of the measurements is estimated by allowing ±1.5 per cent for the possible error in conductivity of the Armco iron used as the reference material, a reasonable value for the low temperatures where it was employed. Then Equation (A-3) yields approximately, $\epsilon_k = \pm 2.4$ for the specimen, which is the root-mean-square error. If we take $\pm 1.96\ \epsilon_k$ as the error band for the absolute error, then 95 per cent of time the method would yield values within this band. That is to say only 5 times out of 100, on the average, would the method and apparatus yield a value, by chance, which deviates by more than ±5 per cent from the true value.

APPENDIX B

EXPERIMENTAL THERMAL-CONDUCTIVITY AND ELECTRICAL-RESISTIVITY DATA FOR TYPE 316 STAINLESS STEEL

APPENDIX B

EXPERIMENTAL THERMAL-CONDUCTIVITY AND ELECTRICAL-RESISTIVITY DATA FOR TYPE 316 STAINLESS STEEL

Table B-1 gives experimental thermal-conductivity and electrical-resistivity data for Type 316 stainless steel, Specimen 3A. Table B-2 gives data for Specimen 4A. The various thermal equilibria for each specimen are numbered in chronological order.

TABLE B-1. OBSERVED THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL, SPECIMEN 3A

Temperature, F	Thermal Conductivity, Btu $hr^{-1}ft^{-2}ft\ {}^{\circ}F^{-1}$	Electrical Resistivity, microhm-cm	Equilibrium Number	Temperature, F	Thermal Conductivity, Btu $hr^{-1}ft^{-2}ft\ {}^{\circ}F^{-1}$	Electrical Resistivity, microhm-cm	Equilibrium Number
73	--	75.4(a)		477	10.12	93.4	6
33	7.50	75.4	2	602	10.93	95.2	5
143	8.23	80.1	2	630	11.00	96.7	3
159	8.45	80.6	1	645	10.93	98.2	6
240	8.92	83.9	1	727	11.33	99.5	4
245	8.92	84.1	2	747	11.24	100	3
285	9.14	85.5	3	764	11.49	100	6
292	9.08	86.1	6	823	11.54	104	3
316	9.55	86.3	1	840	11.77	106	6
317	9.19	86.9	2	980	12.78	105	4
363	9.44	90.0	2	982	12.69	106	5
370	9.54	88.4	1	1155	13.63	109	4
407	9.88	90.8	1	1265	14.08	113	4
442	10.02	90.0	4	1309	14.23	111	5
466	10.11	92.3	3	1544	15.33	114	5
				1675	16.00	120	5

(a) Before thermal-conductivity measurements.

TABLE B-2. OBSERVED THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF TYPE 316 STAINLESS STEEL, SPECIMEN 4A

Temperature, F	Thermal Conductivity, Btu $hr^{-1}ft^{-2}ft\ {}^{\circ}F^{-1}$	Electrical Resistivity, microhm-cm	Equilibrium Number	Temperature, F	Thermal Conductivity, Btu $hr^{-1}ft^{-2}ft\ {}^{\circ}F^{-1}$	Electrical Resistivity, microhm-cm	Equilibrium Number
70	--	77.4(a)		616	10.5	97.8	3
31	7.66	75.7	1	622	10.8	97.2	5
144	8.43	80.3	1	724	11.1	99.0	4
164	8.58	81.6	2	733	11.1	100	3
216	9.08	82.7	1	742	11.2	102	6
250	9.07	84.7	2	807	11.3	104	3
276	8.92	86.0	3	879	12.2(b)	103	6
321	9.62	87.3	1	966	12.0	107	6
329	9.23	87.5	6	974	12.2	108	4
332	9.56	87.8	2	1020	12.9	108	5
367	9.82	89.7	1	1147	13.2	110	4
391	9.78	89.7	2	1255	13.7	114	4
430	9.84	91.5	2	1362	14.5	116	5
444	9.84	92.0	4	1594	16.3	115	5
453	9.83	92.1	3	1734	16.8	112	5
545	10.33	95.1	6	82	--	78.6(c)	

(a) Before thermal-conductivity measurements.
(b) Rejected, loss of precision.
(c) After thermal-conductivity measurements.

REFERENCES

(1) Van Dusen, M. S., and Shelton, S. M., "Apparatus for Measuring Thermal Conductivity of Metals up to 600 C", J. R. Natl. Bur. St., 12, No. 4 (April, 1934), RP 668.

(2) Powell, R. W., "The Thermal and Electrical Conductivities of Metals and Alloys, Part I, From 0° to 800°C", Proc. Phys. Soc., 46 (1934), pp 659-678.

(3) Watson, T. W., and Robinson, H. E., "Thermal Conductivity of Some Commercial Iron-Nickel Alloys", J. Heat Transfer, Trans. ASME (November, 1961), pp 403.

(4) Lucks, C. F., Battelle Memorial Institute, A Review of the Thermal Conductivity Values of Armco Iron as measured by Battelle is in publication.

(5) Bidwell, C. C., Phys. Rev., 56, 9 (1939), p 594.

(6) Laubitz, J. J., Can. J. Phys., 39 (1961), p 1029.

(7) Fisher, R. A., "Statistical Methods for Research Workers", Hafner Publishing Company, Inc. (New York), 1948, p 44 and 45.

(8) Lucks, C. F., and Deem, H. W., "Thermal Properties of Thirteen Metals", ASTM Special Tech. Pub. No. 227 (February, 1958).

(9) Fieldhouse, I. B., Hedge, J. C., and Lang, J. I., "Measurements of Thermal Properties", WADC Tech. Rept. 58-274 (November, 1958).

(10) Douglas, T. B., and Devers, J. L., Am. Chem. Cos., 76, 4824 (1954).

(11) Tomas, H., Z. Physik, 129, 219 (1951), Metall., 10 (1956), and Z. Metallk.,

(12) Laubitz, M. J., "Thermal and Electrical Properties of Armco Iron at High Temperatures", Can. J. Phys., 38 (7), 887 (1960).

(13) McElroy, D. L., et al., "Thermal Conductivity of Uranium Dioxide and Armco Iron by an Improved Radial Heat Flow Technique", ORNL - 3556 (June, 1964).

(14) Kittel, C., "Introduction to Solid State Physics", John Wiley and Sons, New York (1955), p 241.

(15) Kempf, L. W., Smith, C. S., and Taylor, C. S., "Thermal and Electrical Conductivities of Aluminum Alloys", Trans. AIME, Vol 124 (1937), pp 287-299.

(16) Powell, R. W., "The Thermal and Electrical Conductivities of Beryllium", Philosophical Magazine, Series 7, Vol 44, No. 353, 645-663 (June, 1953).

(17) Fine, M. E., "Correlation Between Electrical and Thermal Conductivity in Nickel and Nickel Alloys", Trans. AIME, 188, J. Metals (1950), pp 951-952.

(18) Unpublished Battelle data.

(19) Tyler, W. W., and Wilson, A. C., (1952) as reported in R. L. Powell and W. A. Blanpied, "Thermal Conductivity of Metals and Alloys at Low Temperatures", Natl. Bur. St. Circ. 556 (September, 1954).

(20) Powell, R. W., "Thermal Conductivities of Some Gas Turbine Materials", Iron and Steel Inst., Special Report No. 43, 351 (1952).

(21) Powell, R. W., et al., "Armco Iron as a Thermal Conductivity Standard, Review of Published Data", in Progress Transport Properties, edited by J. F. Masi and D. H. Tsai, The American Society of Mechanical Engineers and Academic Press, New York (1962), p 454.

(22) Paradine, C. G., and Rivett, B. H., "Statistics for Technologists", D. Van Nostrand Co., Inc. (New York), 1955, p 162.

DISTRIBUTION LIST

NASA Lewis Research Center (5)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: James H. Diedrich

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Norman Musial

NASA Scientific and Technical
Information Facility (6)
Box 5700
Bethesda, Maryland
Attention: NASA Representative

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Report Control Office

NASA Lewis Research Center (2)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Library

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: L. P. Kelley

National Aeronautics and
Space Administration (1)
Washington, D. C. 20546
Attention: R. M. Raring (RRM)

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: S. S. Manson

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: G. M. Ault

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: J. C. Freche

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: T. A. Moss

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: R. Dennington

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: R. Mather

Battelle Memorial Institute (1)
505 King Avenue (DMIC)
Columbus, Ohio 43201

Lockheed Missiles and Space Co. (1)
1111 Lockheed Way
Sunnyvale, California
Attention: Y. C. Lee

Lockheed Missiles and Space Co. (1)
1111 Lockheed Way
Sunnyvale, California
Attention: John Cox

Lockheed Missiles and Space Co. (1)
1111 Lockheed Way
Sunnyvale, California
Attention: J. Turner

Solar Aircraft Corporation (1)
2200 Pacific Highway
San Diego 12, California
Attention: W. A. Compton

Solar Aircraft Corporation (1)
2200 Pacific Highway
San Diego 12, California
Attention: Frank Hill

Solar Aircraft Corporation (1)
2200 Pacific Highway
San Diego 12, California
Attention: Sumner Alpert

North American Aviation, Inc. (1)
Los Angeles Division
International Airport
Los Angeles 9, California
Attention: Mr. Jannsen

North American Aviation, Inc. (1)
Los Angeles Division
International Airport
Los Angeles 9, California
Attention: N. Klimmek

DISTRIBUTION LIST
(Continued)

IIT Research Institute (1)
10 West 35 Street
Chicago 16, Illinois
Attention: H. Schwartzbart

IIT Research Institute (1)
10 West 35 Street
Chicago 16, Illinois
Attention: R. Van Thyne

Aeronautical Systems Division (1)
ASRCM-31
Wright-Patterson Air Force Base
Ohio
Attention: K. L. Kojola

AiResearch Manufacturing Co. (1)
9851 Sepulveda Blvd.
Los Angeles 45, California
Attention: K. O. Parker

AiResearch Manufacturing Co. (1)
9851 Sepulveda Blvd.
Los Angeles 45, California
Attention: Alec Anderson

The Garrett Corporation (2)
Cleveland Office
20545 Center Ridge Road
Cleveland 16, Ohio
Attention: W. K. Thorson

General Electric Company (1)
Space Sciences Laboratory
Valley Forge Space Technology
Center
King of Prussia, Pennsylvania
Attention: L. R. McCreight

General Electric Company (1)
Space Sciences Laboratory
Valley Forge Space Technology
Center
King of Prussia, Pennsylvania
Attention: E. Ray

General Electric Company (1)
Cincinnati, Ohio
Attention: W. Semmel

General Electric Company (1)
Cincinnati, Ohio
Attention: R. Brooks

Nuclear Metals, Inc. (1)
Box 125
West Concord, Mass.
Attention: J. J. Siergiej

Nuclear Metals, Inc. (1)
Box 125
West Concord, Mass.
Attention: S. Abkowitz

Oak Ridge National Laboratory (1)
P. O. Box X
Oak Ridge, Tennessee
Attention: A. P. Fraas

Oak Ridge National Laboratory (1)
Metals and Ceramics Division
P. O. Box X
Oak Ridge, Tennessee
Attention: G. M. Slaughter

Oak Ridge National Laboratory (1)
P. O. Box X
Oak Ridge, Tennessee
Attention: W. Thurber

Douglas Aircraft Company, Inc. (1)
333 W. First Street, Suite 620
Dayton 2, Ohio
Attention: J. J. Pakiz

Douglas Aircraft Company, Inc. (1)
Santa Monica, California
Attention: R. G. Monger

Douglas Aircraft Company, Inc. (1)
Missiles and Space Systems Div.
Space Propulsion A2-260
Santa Monica, California
Attention: Dr. R. J. Teitel
Dr. R. Holl

Pratt & Whitney Aircraft Corp. (1)
East Hartford, Connecticut
Attention: W. J. Lueckel

Pratt & Whitney Aircraft Corp. (1)
CANEL
East Hartford, Connecticut
Attention: R. Meyer

General Motors Defense Research
Laboratories (1)
Santa Barbara, California
Attention: J. W. Gehring

DISTRIBUTION LIST
(Continued)

Materials Advisory Board (1)
2101 Constitution Ave., N.W.
Washington 25, D. C.
Attention: Dr. J. S. Lane

NASA Ames Research Center (1)
Moffett Field, California 94035
Attention: Library

NASA Goddard Space Flight
Center (1)
Greenbelt, Maryland 20771
Attention: Library

NASA Flight Research Center (1)
P. O. Box 273
Edwards, California 93523
Attention: Library

Jet Propulsion Laboratory (1)
4800 Oak Grove Drive
Pasadena, California 91103
Attention: Library

NASA Langley Research Center (1)
Langley Station
Hampton, Virginia 23365

NASA Manned Spacecraft
Center (1)
Houston, Texas 77001
Attention: Library

NASA George C. Marshall
Space Flight Center (1)
Huntsville, Alabama 35812
Attention: Library

NASA Western Operations
Office (1)
150 Pico Blvd.
Santa Monica, California 90406
Attention: Library

Purdue University (1)
Thermophysical Properties
Research Center
2595 Yeager Rd.
West Lafayette, Indiana
Attention: Y. S. Touloukian,
Director