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ELECTRICAL RESISTIVITY AND THERMAL CONDUCTIVITY OF NINE SELECTED AISI STAINLESS STEELS

By

C. Y. Ho and T. K. Chu

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This technical report reviews the available experimental data and information on the electrical resistivity and thermal conductivity of nine selected AISI stainless steels and presents the recommended values from near absolute zero (1 K) to above the melting point of the stainless steels (into the molten state). The nine selected stainless steels are AISI 303, 304, 304L, 316, 317, 321, 347, 410, and 430. The recommended values are generated as a result of critical evaluation, analysis, and synthesis of the available data and information. Data are synthesized

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PREFACE

This technical report was prepared by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, for the American Iron and Steel Institute (AISI), Washington, D.C., under AISI Project Number 67-371 entitled "Thermal and Electrical Properties of Steels". This project has been under the technical direction of AISI Panel on Physical, Electrical and Magnetic Properties with Dr. C. A. Beiser as Chairman of the Panel and with Dr. G. L. Houze, Member of the Panel, being the designated point of contact on technical matters.

The initial scope of the project is to establish the best values of the electrical resistivity, thermal conductivity, and thermal expansion of nine selected AISI stainless steels over a wide range of temperatures. This report presents the results on the first two properties. The results on the thermal expansion of the nine selected AISI stainless steels will be presented in a second technical report.

It is hoped that this work will prove useful not only to engineers and scientists specializing in the field but also to other engineering research and development programs and for industrial applications, as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is thought that the critical evaluation, analysis and synthesis of data, and reference data generation constitute a unique aspect of this work.

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September 1977

ABSTRACT

This technical report reviews the available experimental data and information on the electrical resistivity and thermal conductivity of nine selected AISI stainless steels and presents the recommended values from near absolute zero (1 K) to above the melting point of the stainless steels (into the molten state). The nine selected stainless steels are AISI 303, 304, 304L, 316, 317, 321, 347, 410, and 430. The recommended values are generated as a result of critical evaluation, analysis, and synthesis of the available data and information. Data are synthesized for those stainless steels and temperature ranges for which no data are available. General background information on the electrical resistivity and thermal conductivity of stainless steels is given. In particular, the effects of chemical composition, metallurgical structure, heat treatment, cold working, nuclear irradiation, and porosity on these two properties of stainless steels are briefly discussed. The methodology of data evaluation, analysis, and synthesis used in the generation of recommended values is outlined.

CONTENTS

I. INTRODUCTION

The primary objective of this study was to generate recommended values for the electrical resistivity and the thermal conductivity of seven of the 300 series and two of the 400 series of AISI stainless steels, which were selected primarily because of their current technological and commercial importance.

The nine selected AISI stainless steels and their chemical composition ranges and limits are given in the following table.

Chemical Composition Ranges and Limits of
Nine Selected AISI Stainless Steels

AISI No.	Chemical Composition Ranges and Limits, percent								
	C	Mn Max.	P Max.	S Max.	Si Max.	Cr	Ni	Mo	Other Elements
303	0.15 Max.	2.00	0.20	0.15 Min.	1.00	17.00/ 19.00	8.00/ 10.00	0.60* Max.	
304	0.08 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	8.00/ 10.50		
304L	0.030 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	8.00/ 12.00		
316	0.08 Max.	2.00	0.045	0.030	1.00	16.00/ 18.00	10.00/ 14.00	2.00/ 3.00	
317	0.08 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	11.00/ 15.00	3.00/ 4.00	
321	0.08 Max.	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 12.00		Ti 5 x C Min.
347	0.08 Max.	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 13.00		Nb-Ta 10 x C Min.
410	0.15 Max.	1.00	0.040	0.030	1.00	11.50/ 18.50			
430	0.12 Max.	1.00	0.040	0.030	1.00	16.00/ 18.00			

* Optional.

General background information on the electrical resistivity and thermal conductivity of stainless steels is given in Section II. In particular, the effects of chemical composition, metallurgical structure, heat treatment, cold working, nuclear irradiation, and porosity on these two properties of stainless steels are discussed. Besides imparting a general knowledge of these properties of stainless steels to the reader, such information will assist the reader to properly interpret and fully utilize the recommended values presented in this report and also enhance the usefulness of the recommended values.

The recommended values are generated through a process in which available data are exhaustively searched, systematically compiled, critically evaluated, and then analyzed and synthesized. The methodology of data evaluation, analysis, and synthesis used in the generation of recommended values is outlined in Section III.

In Section IV the recommended values for the electrical resistivity and the thermal conductivity of each of the nine selected stainless steels are presented in both tabular and graphical forms. The values given for eight of the nine stainless steels cover the temperature range from 1 K to above the melting point into the molten state and for one steel cover from 1 K to the melting point. The recommended values are for the quench-annealed state in the cases of the austenitic 300-series stainless steels. For stainless steel 410, the values are for the oil-quenched state. In the case of stainless steel 430, they are for the air-cooled, annealed state. It is noted that values above 1500 K are extrapolated, since the majority of the measurements are below this temperature. Unless stated otherwise, the uncertainty in the values are of the order of ±5%. In the majority of cases the recommended values in the tables are given beyond the physically significant figures, which is merely for retaining the smoothness of the tabulated values and should not be interpreted as indicative of the degree of accuracy of the values.

There is a discussion text for each stainless steel, in which the particular feature of the said steel is discussed, the available data and information on the electrical resistivity and the thermal conductivity are reviewed, and the considerations involved in arriving at the recommendations are discussed. Whenever appropriate, the effects of heat treatment and cold working on the recommended values are discussed individually in the text.

Conclusions of the present study are given in Section V. The complete bibliographic citations for the 54 references, which include all the major references on which the recommended values are based, are given in Section VI.

II. GENERAL BACKGROUND

In practical applications stainless steels are chosen mainly for their most important property - corrosion resistance. Other service requirements and properties may then become important after a stainless steel with the desired corrosion resistance has been chosen. In general, the chemical composition, the heat treatment, and the cold-work state are the major factors that determine the various properties of the steels. These will be discussed briefly below, with emphasis on their effects on the electrical resistivity and thermal conductivity.

The corrosion-resistant property of stainless steels is achieved by the addition of chromium, in excess of 12%, to iron. Thus chromium is the major alloying element in all stainless steels. In the 300 series stainless steels, the chromium content is about 18%. Nickel, which is usually present at about 8-12% in the 300 series stainless steels, serves to stabilize the austenite. The element next in abundance is manganese ($\leq 2\%$), which also tends to stabilize the austenite. Manganese in the sulfide form also improves the hot workability and the machinability. Silicon usually appears as trace impurity ($\leq 1\%$), though it might improve the corrosion resistance to a limited extent. Other elements are added to acquire certain desired properties for special service requirements. The 400 series stainless steels differ from the 300 series by the complete absence of nickel. Their structures also differ from that of the austenite, and may be ferritic or martensitic depending on the chromium concentration.

In an alloy significant contribution to the electrical resistivity comes from the solute atoms. In dilute binary alloys the electrical resistivity is directly proportional to the solute concentration. In concentrated binary alloys and in complicated multiple alloys such as stainless steels, this direct proportionality no longer holds. However, estimates can still be made by considering their relative abundance and their proximity to the host (i.e., iron in ferrous alloys such as steels) in the periodic table. In the 300 series stainless steels at room temperature, chromium contributes the most to the electrical resistivity. Measurements on chromium steels [1] show this contribution to be about 50%. Contribution from nickel is about 18%, as estimated from binary Fe + Ni alloys [2]. About 15% is due to the host iron matrix.

The remainder of the electrical resistivity can then be attributed to the other impurities, probably equally divided between silicon and manganese. Even though manganese is usually more abundant than silicon in stainless steels, its effect on the electrical resistivity is relatively smaller because of its closeness to iron in the periodic table. For the 400 series stainless steel, the major contribution (~65%) comes again from the chromium atoms. The host iron matrix contributes about 20% and the other alloying elements the rest of the resistivity. These relative contributions are temperature dependent. At elevated temperatures 90% of the electrical resistivity comes from the host iron matrix.

In metals and alloys, thermal energy is transported by electrons and by lattice wares (atomic vibrations). In the 400 series stainless steels at room temperature, for example, each of these carries about equal amount of thermal energy. At higher temperatures electrons are more effective in transporting thermal energy. As the temperature lowers, lattice waves become more and more effective, and usually gave the largest relative contribution to the total thermal conductivity of about 50 K. At liquid helium temperatues (< 4 K), these two contributions are again about equal.

To a first approximation, the electronic thermal conductivity is inversely proportional to the electrical resistivity. The relative effects of the various alloying elements on the electronic thermal conductivity can therefore be estimated from their relative contributions to the electrical resistivity. The behavior of the lattice component is more duplicated. In general, the lattice thermal conductivity decreases with increasing amount of alloying elements and with the dissimilarity between the alloying element atom and the host iron atom.

Impurity effect on the lattice thermal conductivity is more prominent at low temperatures (< 250 K). At elevated temperatures the lattice thermal conductivity is severely limited by the interaction between the lattice waves, and impurity effect is relatively unimportant. In principle, the lattice thermal conductivity can be calculated given the impurity content and the crystal structure. However the calculation is often not exact because the manner in which the host matrix is altered by an impurity is not known.

The electrical resistivity and thermal conductivity are also affected by different heat treatments. In the 300 series stainless steels, heat treatments are very limited. In order to maintain these steels in the metastable austenitic condition, they are invariably quench-annealed from about 1300 K (1900 °F) and perhaps stress-relieved by heating up to ~700 K (800 °F). Stainless steel 430 is ferritic at all temperatures and its properties are therefore also not changed by heat treatment.

Only stainless steel 410 among those studied is subject to different heat treatments. This steel is martensitic when oil-quenched or air-cooled from ≥ 1300 K (1850 °F) and is ferritic when in the annealed condition after slow cooling from 1050 K (1450 °F). Results on chromium steels [1] indicate that the annealed state should have a higher electrical resistivity (by about 12%) at room temperature and correspondingly a lower thermal conductivity.

Cold-worked metals contain dislocations, which affects both the thermal conductivity and the electrical resistivity. The effect on the latter, however, is quite negligible since these steels have high electrical resistivities (~70 x 10^{-8} Ω m at room temperature). Even if assuming a saturation density of 1 x 10^{16} m^{-2}, the electrical resistivity due to dislocations is estimated to be of the order of 2 x 10^{-8} Ω m. Dislocations have a much larger effect on the lattice component of the thermal conductivity. This will be discussed later individually for each of the stainless steels.

Cold-working may also produce metallurgical transformations in steels. In the austenitic stainless steels there is a tendency to form martensite. The degree of transformation depends on the deformation and on the type of steel. Measurements on low Ni-Cr alloy steel and on Mn steels [3] indicates that the martensitic state is lower in electrical resistivity (and hence higher in thermal conductivity) than the austenitic state by approximately a factor of 1.5. Reduction in electrical resistivity upon cold drawing has been observed in 302 and 304 stainless steels [4]. To a first approximation, a 50/50 martensite/austenite would have a decrease in electrical resistivity of about 20% from that of the austenitic.

Special service conditions may also change the electrical resistivity and the thermal conductivity. One notable instance is the nuclear reactor application. Experimental investigation on a 347 stainless steel [5] has shown that there is an increase in electrical resistivity and a decrease in thermal conductivity after being irradiated by a neutron fluence of 3.3 x 10^{17} cm^{-2} (neutron energy ≥ 1 Mev). The increase in electrical resistivity is 0.7% and 0.3% at 77 K and 297 K respectively, and the decrease in thermal conductivity is 0.9% and 0.1% at the same temperatures. These changes are, however, completely recovered after annealing at 463 K. Thus, it appears that neutron irradiation would not change significantly the electrical and thermal transport properties of bulk material, especially at elevated temperatures. Prolonged nuclear reactor service may produce another problem. The bulk material may become porous. In that case, the electrical resistivity and thermal conductivity can be estimated from values for the bulk material and the porosity.

The effect of porosity has been investigated for 304L stainless steel sintered from powders [6]. The results indicate that both the thermal conductivity and the electrical conductivity (reciprocal of the resistivity) decrease with porosity. The exact manner in which these properties vary with porosity is complicated and may depend on other factors such as the kind of material and the process by which the material is fabricated. For practical purposes, one can estimate properties for the porous material for porosity less than 10% by the equation [7]

$$k = k_b \frac{1 - P}{1 + 0.5\,P}$$

where k and k_b are the conductivities (thermal or electrical) of the porous material and of the bulk material, respectively, and P is the fractional porosity.

III. DATA EVALUATION AND GENERATION OF RECOMMENDED VALUES

Due to the difficulties of accurately measuring the properties of materials and of adequately characterizing the test specimens, especially solids, the property data available from the scientific and technical literature are often conflicting, divergent widely, and subject to large uncertainty. Indiscriminate use of literature data for engineering design calculations without knowing their reliability is dangerous and may cause inefficiency or product failure, which at times can be disastrous. Therefore, it is imperative to evaluate critically the validity, reliability, and accuracy of the literature data and related information, to resolve and reconcile the disagreements in conflicting data, and to synthesize often fragmentary data in order to generate a full range of internally consistent recommended values.

Considering the thermal conductivity, for example, in the critical evaluation of the validity and reliability of a particular set of experimental data, the temperature dependence of the data is examined and any unusual dependence or anomaly is carefully investigated. The experimental technique is reviewed to see whether the actual boundary conditions in the measurement agreed with those assumed in the theory and whether all the stray heat flows and losses were prevented or minimized and accounted for. The reduction of data is examined to see whether all the necessary corrections were appropriately applied. The estimation of experimental inaccuracies is checked to ensure that all the possible sources of error, particularly systematic error, were considered by the author(s). Experimental data could be judged to be reliable only if all sources of systematic error were eliminated or minimized and accounted for. Major sources of systematic error include unsuitable experimental method, poor experimental technique, poor instrumentation and poor sensitivity of measuring devices, sensors, or circuits, specimen and/or thermocouple contamination, unaccounted for stray heat flows, incorrect form factor, and, perhaps most important, the mismatch between actual experimental boundary conditions and those assumed in the theoretical model used to define and derive the value of the property. These and other possible sources of errors are carefully considered in critical evaluation and analysis of experimental data. The uncertainty of a set of data depends, however, not only on the estimated inaccuracy of the data, but also on the inadequacy of characterization of the material for which the data are reported.

In many cases, however, research papers do not contain adequate information for a data evaluator to perform a truly critical evaluation. In these cases, some other considerations may have to be used for data evaluation. For instance, if several authors' data agree with one another and, more importantly, these were obtained by using different experimental methods, these data are likely to be reliable. However, if the data were observed by using the same experimental method, even though they all agree, the reliability of the data is still subject to questioning, because they may all suffer from a common, but unknown source of error. Secondly, if the same apparatus has been used for measurements of other materials and the results are reliable, and if the result of measurement on the new material is in the same range, the result for the new material is likely to be reliable. However, if the information given by the author is entirely inadequate to make any value judgment, the data assessment becomes subjective. At times judgments may be based upon factors and considerations such as the purpose and motivation for the measurement, general knowledge of the experimenter, his past performance, the reputation of his laboratory, etc.

In the process of critical evaluation of experimental data outlined above, unreliable and erroneous data are uncovered and eliminated from further consideration. The remaining evaluated data are then subjected to further analysis and correlation in regard to the various factors that affect the property under study. In the cases where available data are scarce, estimated values can be synthesized by theoretical calculations such as calculating the electronic thermal conductivity from the electrical resistivity and by semiempirical techniques such as intercomparing the property values of various stainless steels (both domestic and foreign) of similar chemical compositions and metallurgical structures accounting for the various affecting factors. By using theoretical relationships, several properties of the same material can be cross-correlated for checking the consistency of data or for data estimation. For example, the thermal conductivity and specific heat can be correlated with the thermal diffusivity.

IV. ELECTRICAL RESISTIVITY AND THERMAL CONDUCTIVITY OF SELECTED AISI STAINLESS STEELS

1. AISI 303 Stainless Steel

This variation of the basic 18-8 austenitic stainless steel contains additional amounts of sulfur and phosphorous. The high sulfur content makes it more machinable. Another variation, 303 Se, contains some additional selenium for the same purpose. The sulfur may also improve the doctility of the steel. These elements are present in such small amounts (≤0.15%), that the electrical and thermal properties of these steels are almost identical to those of the more common type, AISI 304, though their mechanical properties are different.

There are four sets of experimental data available for the electrical resistivity [8, 9, 10, 11], but only one is for room temperature and above [8]. These results indicate that, to within measurement errors, the electrical resistivity of AISI 303 is the same as that of AISI 304. Measurements at high temperatures on foreign steels of compositions similar to AISI 303 [12, 13] also substantiate this conclusion. Therefore the recommended values for the electrical resistivity of AISI 303 are taken to be the same as those for AISI 304.

Nine sets of experimental data are available for the thermal conductivity of AISI 303, covering a wide temperature range [8, 9, 14, 15, 16, 17]. These results show that the thermal conductivity of AISI 303 is also not significantly differed from that of AISI 304, and the recommended values are taken to be the same as those for AISI 304.

The recommended values for both the electrical resistivity and the thermal conductivity are tabulated in Table 1 and shown in Figure 1. For the effects of cold working on these properties, see the discussion on AISI 304 stainless steel.

Table 1. Electrical Resistivity and Thermal Conductivity of AISI 303 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	48.5	0.069
4	48.5	0.305
10	48.5	0.875
20	48.3	1.99
30	48.2	3.27
40	48.3	4.65
50	48.5	6.02
60	48.9	7.11
70	49.5	7.98
80	50.3	8.69
90	51.2	9.26
100	52.2	9.75
150	57.5	11.55
200	62.7	12.89
250	67.5	13.90
273	69.6	14.39
293	71.3	14.76
300	71.9	14.89
350	76.0	15.79
400	79.8	16.61
500	86.8	18.28
600	93.3	19.77
700	99.2	21.21
800	104.3	22.59
900	108.6	23.99
1000	112.5	25.33
1100	115.8	26.58
1200	118.7	27.81
1300	121.4	29.18
1400	124.0	30.34
1500	126.4	31.55
1600	128.7	32.70
1672*	130.4	33.53
1727*	150.0	28.15
1800	151.7	28.99

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

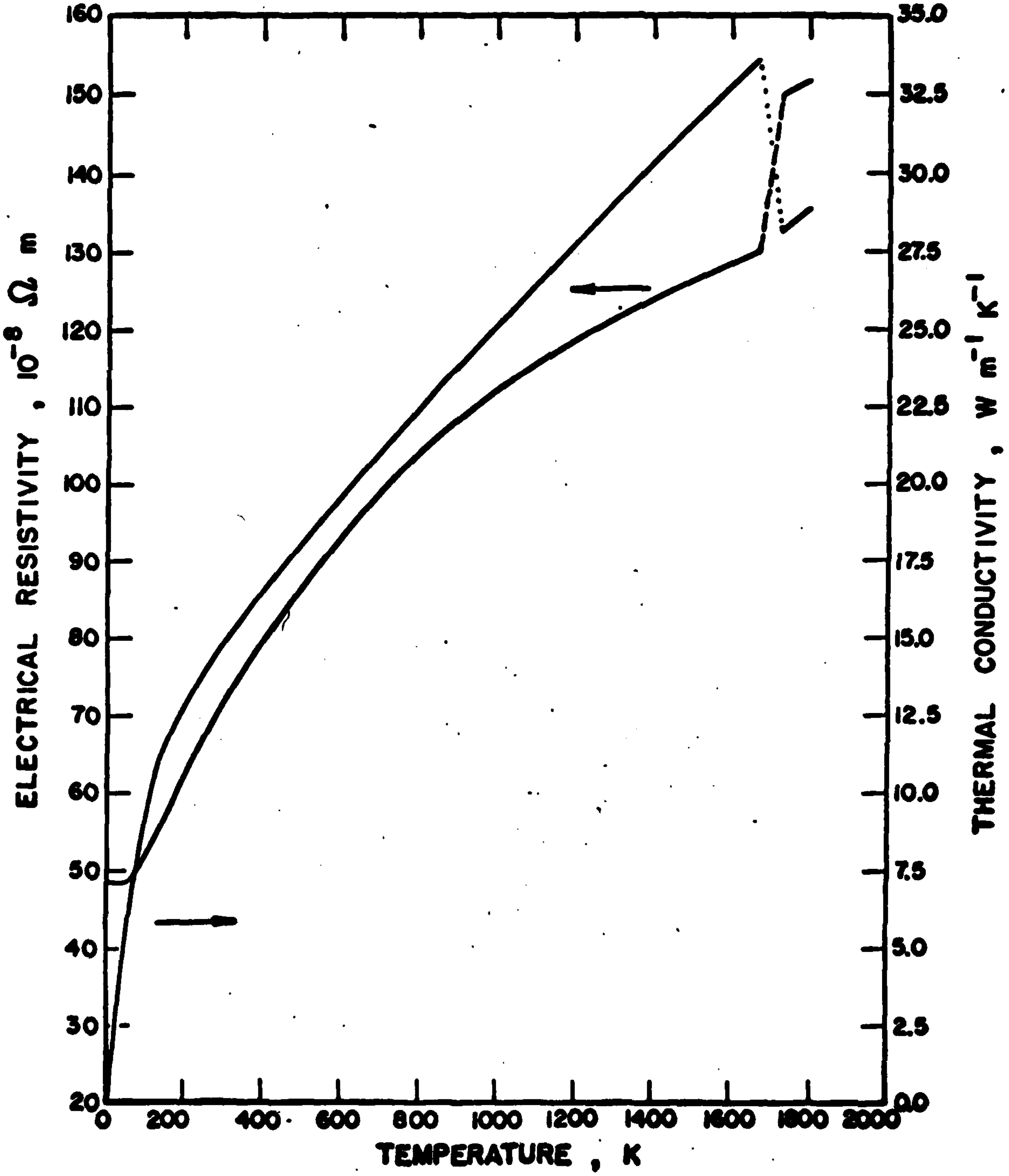

Figure 1. Electrical Resistivity and Thermal Conductivity of AISI 303 Stainless Steel.

2. AISI 304 Stainless Steel

This is a low-carbon member of the 18-8 type austenitic stainless steel, with a slightly higher chromium content for improved corrosion resistance. This steel is susceptible to intergranular corrosion in the temperature range 700-1150 K (800-1600 °F) due to carbide precipitation.

There are twenty-six sets of data available for the electrical resistivity of AISI 304, eighteen of which deal with the change of resistivity upon drawing [4]. In addition, there are ten sets of data on the lower carbon version, AISI 304L. Evaluation of these measurements leads to the conclusion that the small difference in carbon content between these two versions of AISI 304 is not significant enough to warrant separate recommendations. The recommended values therefore are based on measurements on both, such as those of Tye, et al. [18, 19], Tye [6], Clark, et al. [10], Feith, et al. [20], and of Stutius and Dillinger [21].

Twenty sets of data are available for the thermal conductivity of AISI 304 and seven sets for AISI 304L. Again, these results show that the thermal conductivity of these two steels are virtually the same. The recommended values are based on the results of Feith, et al. [20], Tye, et al. [18, 19], Powell [22], Taylor, et al. [23], Ewing, et al. [24], Deverall [25], Powers [26], Brown and Bergles [27], Tye [6], and Stutius and Dillinger [21].

The recommended electrical resistivity and thermal conductivity values for AISI 304 are tabulated in Table 2 and shown in Figure 2.

Stainless steel 304 has a tendency to undergo martensitic transformation upon cold working: the amount of martensite is probably less than 20% at 80% reduction. The existence of martensite decreases the electrical resistivity and thus increases the electronic component of the thermal conductivity. At 20% transformation to martensite, the electrical resistivity may decrease by about 7%. The martensitic transformation temperature of austenitic stainless steels is believed to be slightly lower than room temperature. Hence this change may diminish as the temperature is raised, since the martensite may partially revert back to the austenitic phase.

Severe cold working also produce dislocations which decrease the lattice component of the thermal conductivity at low temperatures. The percentage decrease depends on the temperature: for a saturation dislocation density of 10^{16} m^{-2}, the decrease is about 20% at 10 K; about 17% at 50 K, and about 7% at 100 K. The decrease in the lattice component of the thermal conductivity is compensated partially by the increase in the electronic component. The overall effect, including that of martensite and of dislocation, is such that at 10 K the total thermal conductivity would decrease by about 10%, at 50 K the decrease is again about 10%, at 100 K the thermal conductivity would remain unchanged, and it probably would increase by about 3% around room temperature. For materials that are not as severely cold worked, these changes would be somewhat smaller.

Table 2. Electrical Resistivity and Thermal Conductivity of AISI 304 Stainless Steel †

Temperature (K)	Electrical Resistivity ($10^{-8}\ \Omega$-m)	Thermal Conductivity ($W.m^{-1}\ K^{-1}$)
1	48.5	0.069
4	48.5	0.305
10	48.5	0.875
20	48.3	1.99
30	48.2	3.27
40	48.3	4.65
50	48.5	6.02
60	48.9	7.11
70	49.5	7.98
80	50.3	8.69
90	51.2	9.26
100	52.2	9.75
150	57.5	11.55
200	62.7	12.89
250	67.5	13.90
273	69.6	14.39
293	71.3	14.76
300	71.9	14.89
350	76.0	15.79
400	79.8	16.61
500	86.8	18.28
600	93.3	19.77
700	99.2	21.21
800	104.3	22.59
900	108.6	23.99
1000	112.5	25.33
1100	115.8	26.58
1200	118.7	27.81
1300	121.4	29.18
1400	124.0	30.34
1500	126.4	31.55
1600	128.7	32.70
1672*	130.4	33.53
1727*	150.0	28.15
1800	151.7	28.99

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

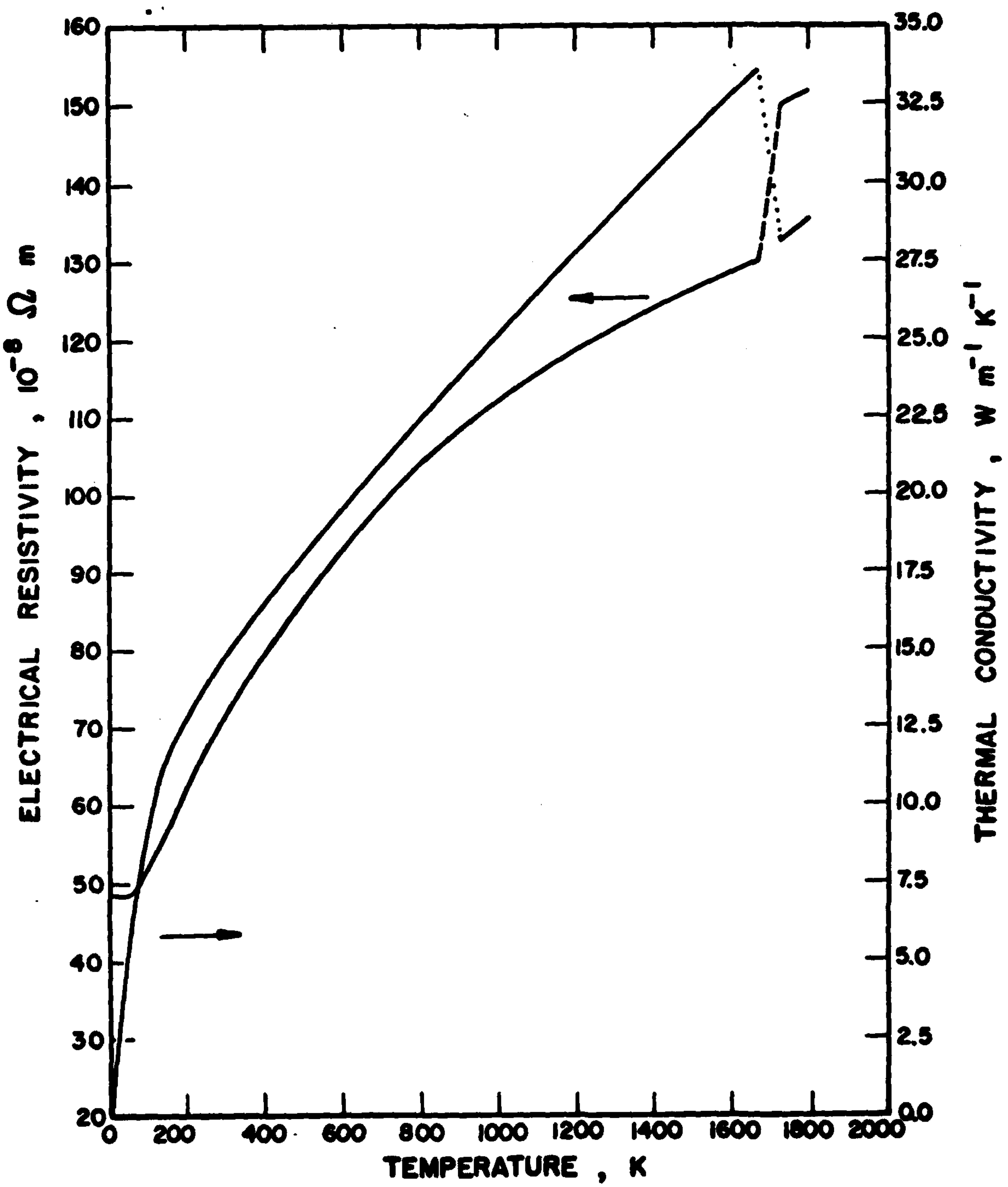

Figure 2. Electrical Resistivity and Thermal Conductivity of AISI 304 Stainless Steel.

3. AISI 304L Stainless Steel

This is a still lower carbon version of the basic 18-8 austenitic steel. The reduced carbon content improved the resistance to intergranular corrosion. The small difference of carbon content between this steel and AISI 304 is judged to be insignificant in altering the electrical and thermal properties. The recommended electrical resistivity and thermal conductivity values are arrived at by evaluating the information on both of these stainless steels. For the sake of completeness, the recommended values are tabulated also in Table 3 and shown in Figure 3.

Table 3. Electrical Resistivity and Thermal Conductivity of AISI 304L Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	48.5	0.069
4	48.5	0.305
10	48.5	0.875
20	48.3	1.99
30	48.2	3.27
40	48.3	4.65
50	48.5	6.02
60	48.9	7.11
70	49.5	7.98
80	50.3	8.69
90	51.2	9.26
100	52.2	9.75
150	57.5	11.55
200	62.7	12.89
250	67.5	13.90
273	69.6	14.39
293	71.3	14.76
300	71.9	14.89
350	76.0	15.79
400	79.8	16.61
500	86.8	18.28
600	93.3	19.77
700	99.2	21.21
800	104.3	22.59
900	108.6	23.99
1000	112.5	25.33
1100	115.8	26.58
1200	118.7	27.81
1300	121.4	29.18
1400	124.0	30.34
1500	126.4	31.55
1600	128.7	32.70
1672*	130.4	33.53
1727*	150.0	28.15
1800	151.7	28.99

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

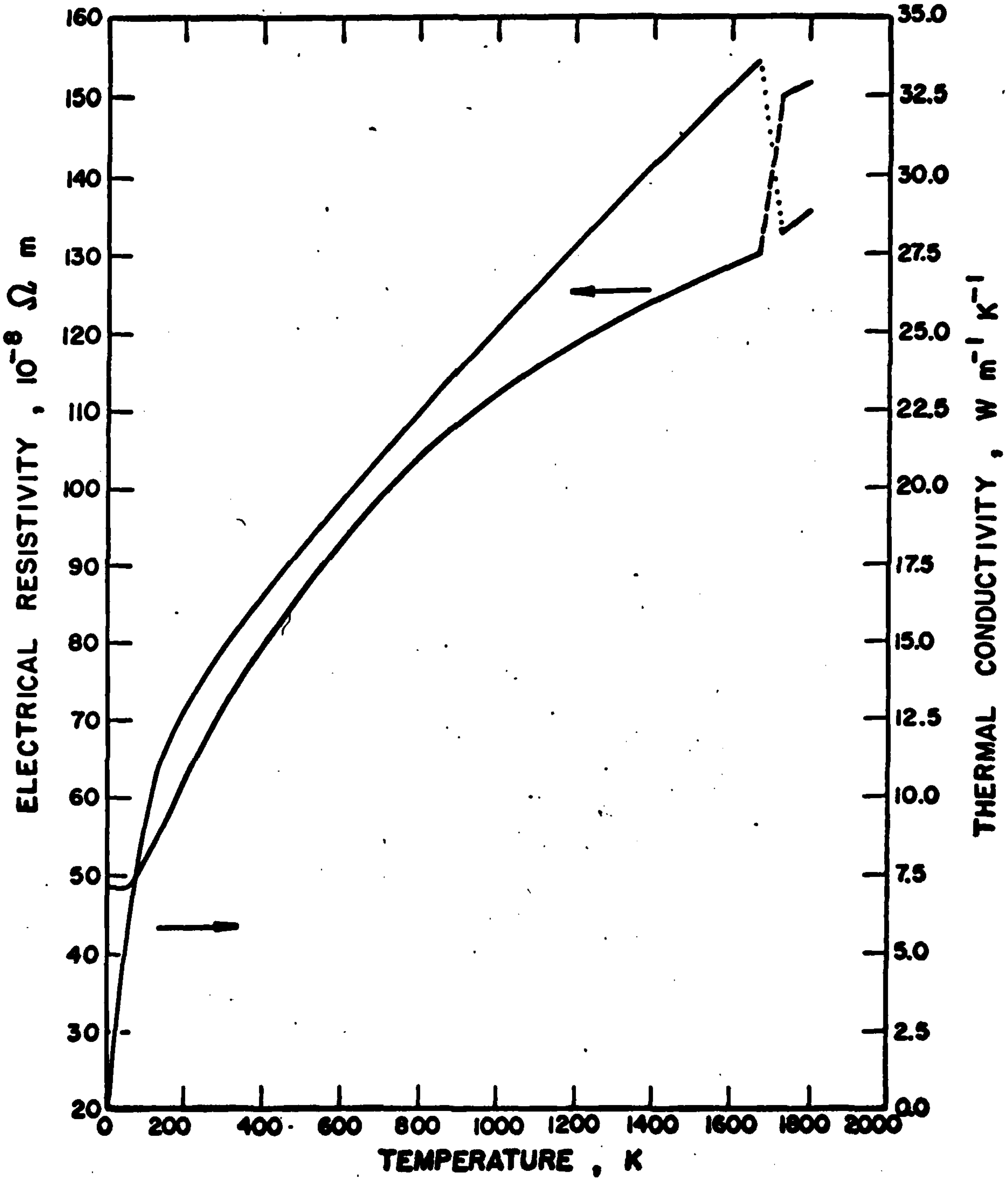

Figure 3. Electrical Resistivity and Thermal Conductivity of AISI 304L Stainless Steel.

4. AISI 316 Stainless Steel

Stainless steel 316 is one of the two* most stable of all austenitic stainless steels because of its higher molybdenum and nickel content. It contains 2-3% molybdenum for greater corrosion resistance and improved mechanical strength at elevated temperatures. It is, however, also susceptible to intergranular corrosion at 750-1150 K (900-1600 °F). Because of the molybdenum content, prolonged service at elevated temperatures may cause the formation of the brittle sigma phase at grain boundaries in stainless steel 316.

There are eight sets of experimental data available for the electrical resistivity covering a wide temperature range. The recommended values are based on the results of measurements of Matolich [28], Evangelisti, et al. [29], and Clark, et al. [10].

Twenty-three sets of experimental data are available for the thermal conductivity, most of which are for room temperature and above. The recommended values are based on the results of Lucks et al. [30], Matolich [28], Watson and Flynn [31], Feith et al. [32], Fieldhouse et al. [33], Williams and Blum [15], Iacobelli et al. [34], Evangelisti et al. [29], and Foster et al. [35]. Since there are no data on the thermal conductivity at low temperatures, the recommended values at those temperatues are obtained by comparison with other 300 series stainless steels, taking into account variations in composition.

The recommended values for the electrical resistivity and thermal conductivity of AISI 316 are tabulated in Table 4 and shown in Figure 4.

Upon cold-working, this steel displays very little tendency for martensitic transformation. Thus, the electrical resistivity is not expected to change by cold working. The thermal conductivity may be decreased by about 10% at temperatures below 50 K and by about 5% at 100 K at a saturation dislocation density of 10^{16} m^{-2}. This decrease is probably negligible at room temperature and above.

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* The other is AISI 317.

Table 4. Electrical Resistivity and Thermal Conductivity of AISI 316 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	54.4	0.056
4	54.4	0.248
10	54.4	0.713
20	54.4	1.63
30	54.4	2.69
40	54.6	3.87
50	55.1	5.01
60	55.8	6.03
70	56.7	6.88
80	57.5	7.55
90	58.5	8.10
100	59.5	8.54
150	64.5	10.29
200	69.1	11.49
250	73.6	12.51
273	75.4	12.97
293	77.1	13.31
300	77.7	13.44
350	81.5	14.32
400	85.2	15.16
500	91.7	16.80
600	97.7	18.36
700	103.1	19.87
800	108.0	21.39
900	112.1	22.79
1000	115.7	24.16
1100	118.9	25.46
1200	121.7	26.74
1300	124.3	28.02
1400	126.8	29.32
1500	129.2	30.61
1600	131.3	31.86
1644*	132.2	32.41
1672*	152.0	26.90
1700	152.6	27.24

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

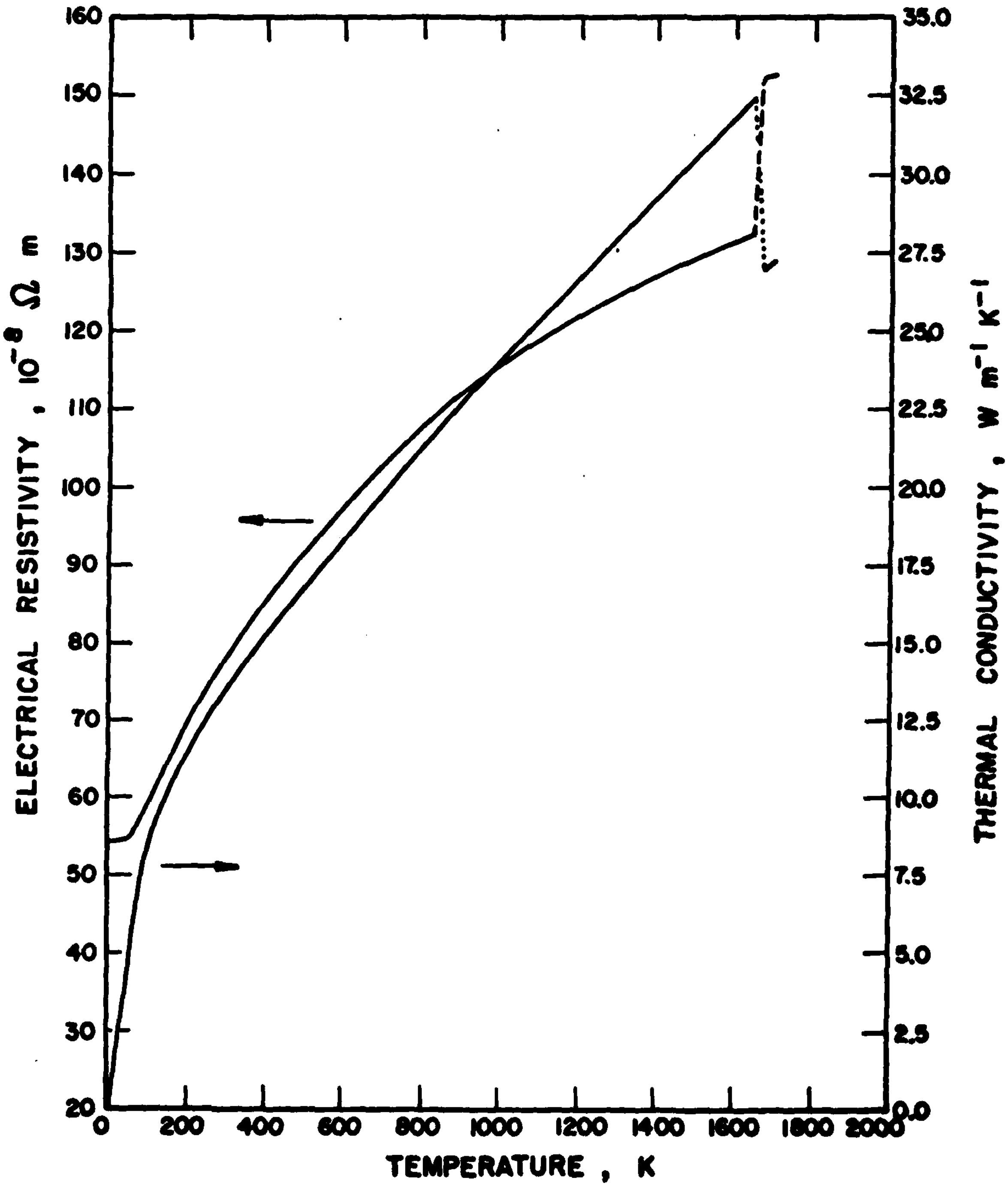

Figure 4. Electrical Resistivity and Thermal Conductivity of AISI 316 Stainless Steel.

5. AISI 317 Stainless Steel

Stainless steel 317, because of its high molybdenum and nickel contents is probably the most stable of all austenitic stainless steels. Its properties are almost identical with those of stainless steel 316.

No experimental data are available for the electrical resistivity and the thermal conductivity of this steel. The recommended values are derived from those for stainless steel 316 with adjustments according to the variation in composition. These are tabulated in Table 5 and shown in Figure 5.

The effects of cold work on these properties of this steel are most likely to be the same as those for stainless steel 316.

Table 5. Electrical Resistivity and Thermal Conductivity of AISI 317 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)
1	56.8	0.051
4	56.8	0.226
10	56.8	0.645
20	56.8	1.47
30	56.8	2.43
40	57.0	3.49
50	57.5	4.60
60	58.3	5.61
70	59.2	6.42
80	60.2	7.10
90	61.1	7.67
100	62.1	8.19
150	66.8	9.80
200	71.5	10.96
250	75.8	11.97
273	77.7	12.41
293	79.3	12.78
300	79.9	12.91
350	83.6	13.81
400	87.1	14.66
500	93.6	16.31
600	99.4	17.90
700	104.8	19.45
800	109.4	20.98
900	113.5	22.48
1000	116.9	23.86
1100	120.0	25.19
1200	122.8	26.50
1300	125.4	27.84
1400	128.9	29.15
1500	130.2	30.45
1600	132.5	31.72
1644*	133.5	32.28
1672*	153.5	26.63
1700	154.1	26.97

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

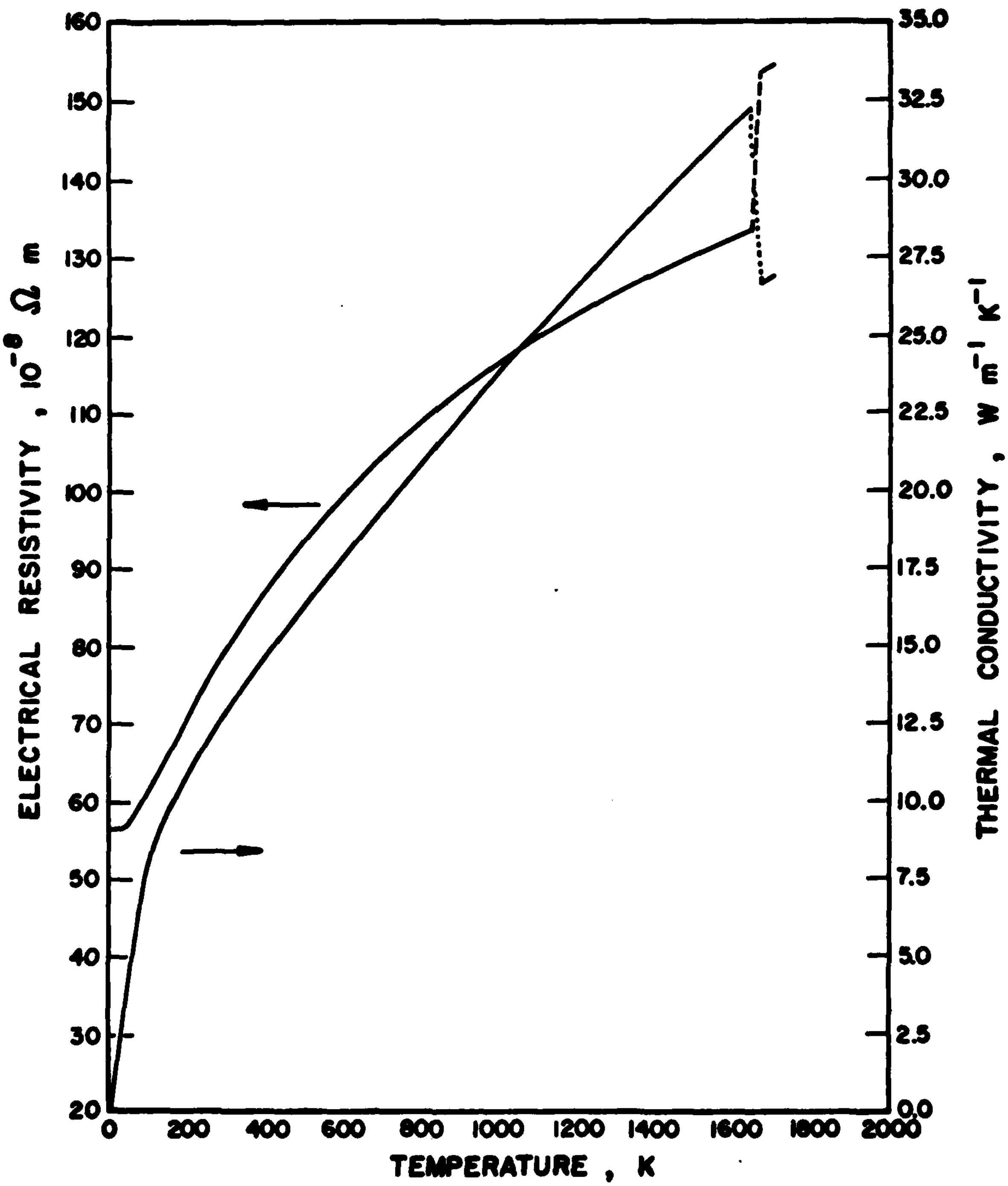

Figure 5. Electrical Resistivity and Thermal Conductivity of AISI 317 Stainless Steel.

6. AISI 321 Stainless Steel

Stainless steel 321 is a titanium-stabilized version of the 18-8 austenitic stainless steel. It is mostly used in welding applications where post-welding annealing is impractical and where intergranular corrosion in the temperature range 700-1150 K (800-1600 °F) would be high for the other austenitic steels.

There are two sets of experimental data available for the electrical resistivity of this steel, both of which are for low temperatures [10, 36]. However, there are a number of data sets available for foreign stainless steels of similar compositions, covering temperatures up to about 600 K [37, 38]. The recommended values below 600 K are based on the data for the above references. Above 600 K they are derived from the electrical resistivity of other austenitic stainless steels with adjustments according to variations in composition.

Two sets of experimental data are available for the thermal conductivity, both for temperatures below 159 K [14, 21]. For low temperatures the recommended values are based on these results. For room temperature and above, results on other austenitic steels are well as on foreign steels of similar compositions [39, 40, 41, 42] are used as basis for deriving values for stainless steel 321.

Because the titanium in stainless steel 321 is readily oxidizable upon melting, recommended values are given only for temperatures below the melting point. These are tabulated in Table 6 and shown in Figure 6.

Stainless steel 321 is less stable than other austenitic stainless steels upon cold working: at 75% reduction as much as 50% of austenite may be transformed into martensite. Thus effects of cold working on this steel are larger than those on most of the other 300 series stainless steels. Under severe cold working, the electrical resistivity may decrease by as much as 15%, with an equal percentage increase in the electronic component of the thermal conductivity. The lattice component of the thermal conductivity is estimated to decrease by about 30% at 10 K, about 17% at 50 K, about 6% at 100 K, and less than 1% at 200 K. The overall change in the thermal conductivity is a decrease of about 5% at 10 K, a decrease of about 3% at 50 K, an increase of about 2% at 100 K, and an increase of about 7% at 200 K.

At room temperature and above, it is not certain that changes in the electrical resistivity and thermal conductivity are, due to the lack of information on the austenitic-martensitic transition. It is estimated that these changes would be smaller than 10%.

Table 6. Electrical Resistivity and Thermal Conductivity of AISI 321 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	52.4	0.062
4	52.4	0.275
10	52.4	0.796
20	52.3	1.83
30	52.2	3.01
40	52.3	4.14
50	52.6	5.60
60	53.1	6.67
70	53.7	7.51
80	54.6	8.19
90	55.6	8.72
100	56.7	9.16
150	61.7	10.95
200	66.6	11.96
250	71.1	13.23
273	73.0	13.66
293	74.6	14.03
300	75.2	14.16
350	79.0	15.03
400	82.7	15.86
500	89.3	17.47
600	95.4	19.01
700	100.9	20.53
800	106.0	22.02
900	110.3	23.44
1000	113.9	24.78
1100	117.1	26.10
1200	120.0	27.37
1300	122.7	28.61
1400	125.3	29.88
1500	127.8	31.13
1600	130.0	32.34
1672	131.6	33.21

† The uncertainty in the recommended values is of the order of ± 5%.

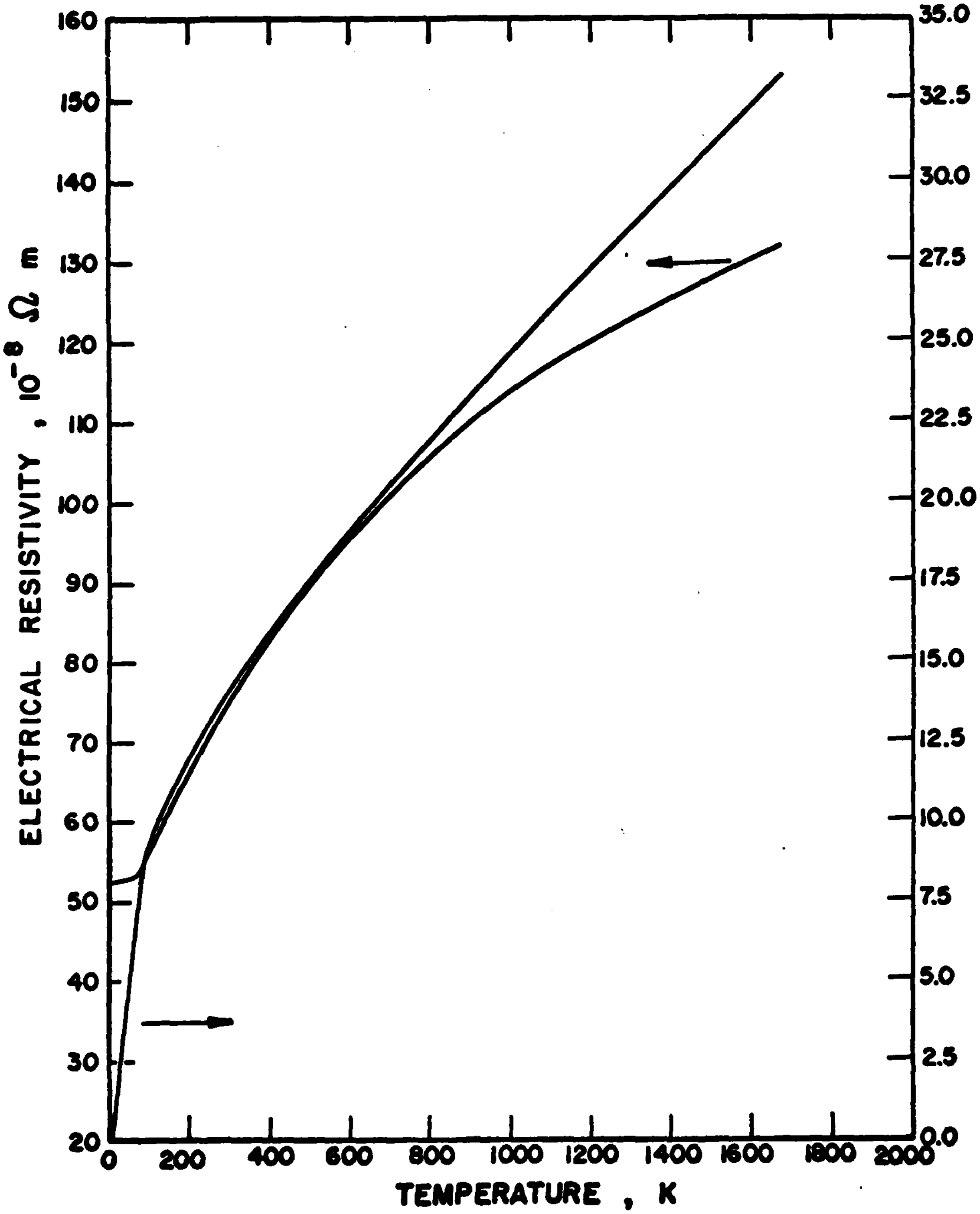

Figure 6. Electrical Resistivity and Thermal Conductivity of AISI 321 Stainless Steel.

7. AISI 347 Stainless Steel

Stainless steel 347 is another carbide-stabilized austenitic stainless steels, with niobium are sometimes tantalum as the stabilizing elements. Its applications and properties are essentially the same as stainless steel 321, except that stainless steel 347 has a better stability because niobium does not oxidize as easily as titanium.

There are four sets of experimental data available for the electrical resistivity of this steel [8, 9, 10, 43]. There are two additional experimental data sets on foreign stainless steels of similar compositions for higher temperatures [37, 44].

These measurements indicate that the electrical resistivity of stainless steel 347 is the same as that of stainless steel 321 to within measurement errors.

Thirteen sets of experimental data are available for the thermal conductivity of this steel [8, 9, 30, 33, 43, 45, 46, 47]. For temperatures higher than 1000 K, these data sets [8, 30, 33] give values too low compared with those for other 300 series stainless steels and are inconsistent with composition variations. The recommended thermal conductivity values are therefore based on the data for a stainless steel of similar composition [37] and on intercomparison with the data for other austenitic stainless steels, especially stainless steel 321. It comes to the conclusion that the small variation in composition between stainless steels 321 and 347 is not significant to justify separate recommendations. For the sake of completeness, the recommended values for the electrical resistivity and thermal conductivity of stainless steel 347 is tabulated in Table 7 and shown in Figure 7.

Besides electrical and thermal properties, the stability of stainless steel 347 under cold work is also very similar to that of stainless steel 321. Thus the effect of cold working on stainless steel 347 is expected to be the same as that on stainless steel 321.

Table 7. Electrical Resistivity and Thermal Conductivity of AISI 347 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	52.4	0.062
4	52.4	0.275
10	52.4	0.796
20	52.3	1.83
30	52.2	3.01
40	52.3	4.14
50	52.6	5.60
60	53.1	6.67
70	53.7	7.51
80	54.6	8.19
90	55.6	8.72
100	56.7	9.16
150	61.7	10.95
200	66.6	11.96
250	71.1	13.23
273	73.0	13.66
293	74.6	14.03
300	75.2	14.16
350	79.0	15.03
400	82.7	15.86
500	89.3	17.47
600	95.4	19.01
700	100.9	20.53
800	106.0	22.02
900	110.3	23.44
1000	113.9	24.78
1100	117.1	26.10
1200	120.0	27.37
1300	122.7	28.61
1400	125.3	29.88
1500	127.8	31.13
1600	130.0	32.34
1672*	131.6	33.21
1727*	151.3	27.90
1800	152.9	28.78

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 5%. At or above melting, the uncertainty is of the order of ± 15%.

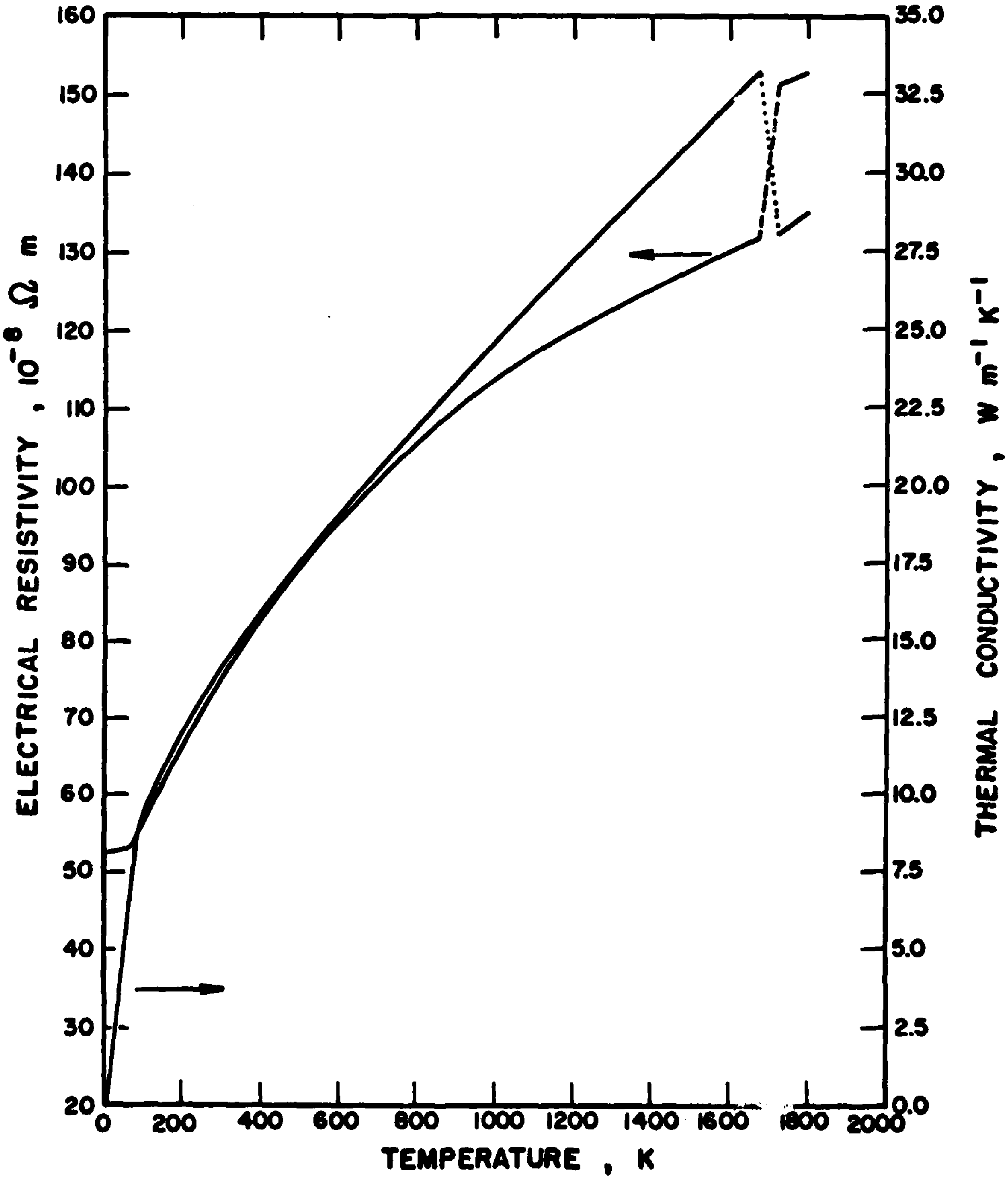

Figure 7. Electrical Resistivity and Thermal Conductivity of AISI 347 Stainless Steel.

8. AISI 410 Stainless Steel

Stainless steel 410, because of its low chromium content and of the absence of nickel, is austenitic at elevated temperatures and ferritic or martensitic at room temperature. It is usually produced in the fully annealed, martensitic condition: being heated to the austenitic range and then slow-cooled in air. In this way, it is hardened by the formation of martensite within the ferrite matrix. It is susceptible to temper embrittlement in the temperature range 700–800 K (750–950 °F); services at these temperatures are therefore to be avoided. Because of its low chromium content, stainless steel 410 is inferior in corrosion resistance than the austenitic stainless steels. It is a low cost, general-purpose stainless steel of wide commercial applications.

There are five sets of data available for the electrical resistivity of this steel. Most of these are compilations for value at room temperature. The only set that contains original data is by Clark et al. [10] and is for room temperature and below. However, there are some data on foreign stainless steels of similar compositions [48, 49, 50]. The recommended values below room temperature are derived from the result of Clark et al. [10]; for higher temperatures, they are based on the results on foreign stainless steels with minor adjustments according to composition variation.

There are two experimental data sets for the thermal conductivity of this steel [14, 45], both for temperatures lower than room temperature. The recommended values for low temperatures are derived from these measurements. For high temperatures, results on foreign stainless steels of similar compositions [49, 50, 5]] analyzed and the recommended values are based on these results. There are no data for temperatures above 1000 K, for which the recommended values are extrapolations from values at lower temperatures.

The recommended values for the electrical resistivity and thermal conductivity of stainless steel 410 are tabulated in Table 8 and shown in Figure 8.

Because stainless steel 410 is heat-treatable, the electrical resistivity and the thermal conductivity of this steel depend somewhat on its annealing condition. The uncertainty in the recommended values are therefore higher than that for the austenitic stainless steels, and is estimated to be ±12% for all temperatures. This includes errors in the estimation procedure as well as the lack of exact information on the metallurgical structure of the steel under different annealing conditions.

Since there is no significant metallurgical transformation in stainless steel 410 upon cold working, the electrical resistivity is not expected to change significantly. The thermal conductivity may be affected through the lattice component, which is more sensitive to defects, especially dislocations. It is estimated that for severely cold worked material, the thermal conductivity may decrease by 3% at 200 K, 10% at 100 K, and 20% below 50 K.

Table 8. Electrical Resistivity and Thermal Conductivity of AISI 410 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)
1	38.2	0.09
4	38.2	0.43
10	38.2	1.32
20	38.2	3.40
30	38.2	6.14
40	38.3	8.97
50	38.4	11.64
60	38.7	14.03
70	39.1	16.00
80	39.6	17.73
90	40.1	19.28
100	40.7	20.42
150	44.6	23.69
200	49.3	24.98
250	53.8	25.78
273	55.9	26.06
293	57.7	26.26
300	58.3	26.33
350	62.8	26.71
400	67.3	26.99
500	76.3	27.31
600	85.0	27.46
700	93.2	27.50
800	100.4	27.30
900	106.4	26.63
1000	111.1	26.04
1100	114.0	26.16
1200	116.3	26.98
1300	118.6	28.04
1400	120.9	29.20
1500	123.2	30.36
1600	125.6	31.52
1700	127.9	32.68
1755*	129.2	33.32
1805*	148.5	29.70
1900	150.7	30.81

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 12%. At or above melting, the uncertainty is of the order of ± 15%.

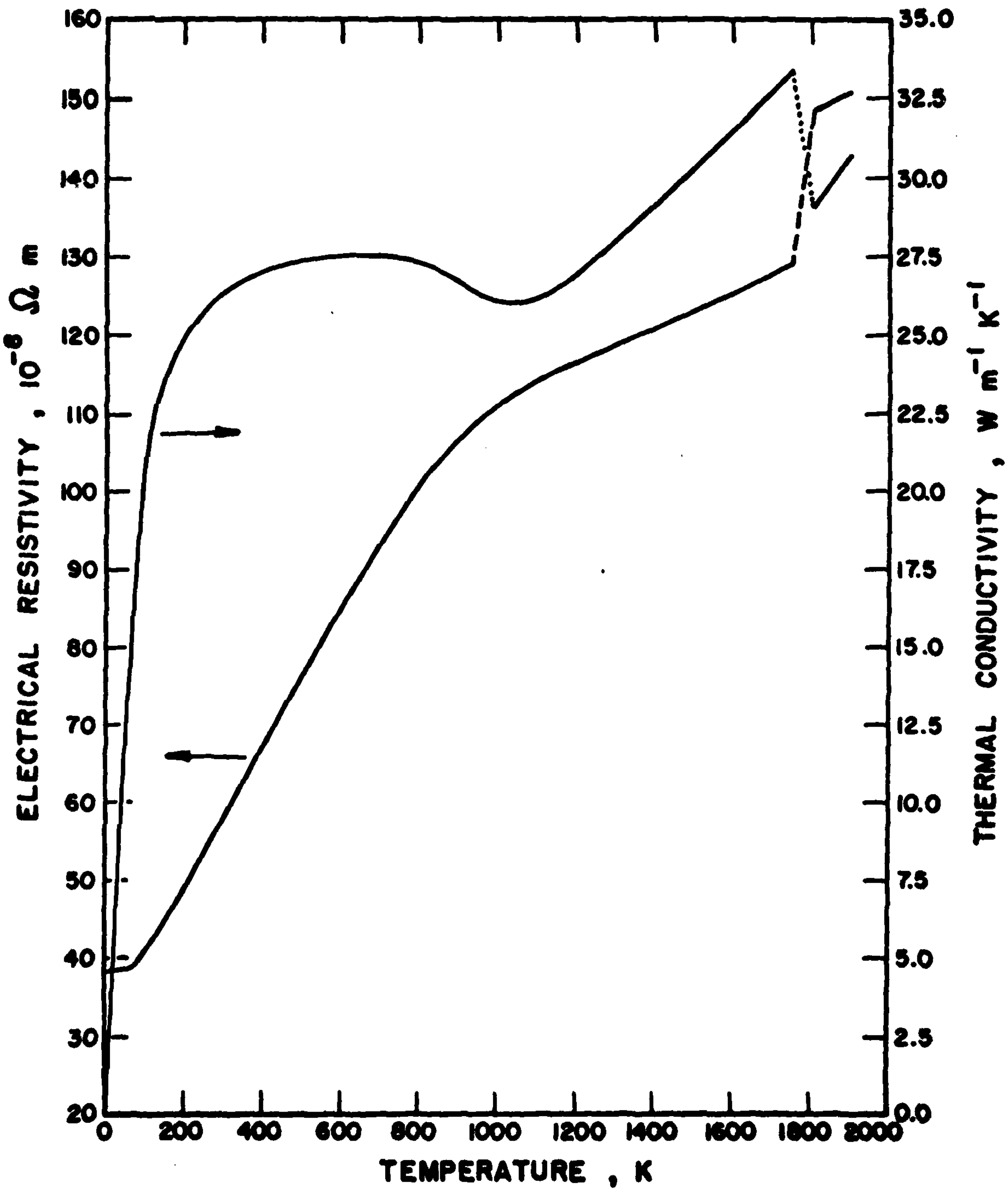

Figure 8. Electrical Resistivity and Thermal Conductivity of AISI 410 Stainless Steel.

9. AISI 430 Stainless Steel

Because of its high chromium content, stainless steel 430 is ferritic at all temperatures. It is not hardenable by heat treatment, even though it may develop some austenitic structure on heating. The amount of austenite is probably not sufficient to alter significantly its properties. Similarly, no significant martensite is formed on cooling. It is susceptible to the embrittlement at 750 K (885 °F), and therefore is usually annealed above this temperature.

There are five data sets available for the electrical resistivity of this steel. Only one [10] contains original results and is for temperatures below 300 K. In addition, there are two data sets on foreign stainless steels of similar compositions for higher temperatures [13]. The recommended values are based on these results.

There are five sets of experimental data on the thermal conductivity of this steel above room temperature [52, 53, 54]. Three of these are values from different experimental runs, and show a temperature dependence that is too strong compared with the other two sets, by Silverman [52] and by Moeller and Wilson [53]. The recommended values are based on the latter results, which cover slightly different temperature ranges and are in agreement in the region where their measurement temperatures overlap. For low temperatures, the recommended values are extrapolated, with consideration given to the temperature variations of its electrical resistivity and of the thermal conductivity of other stainless steels.

The recommended values for the electrical resistivity and thermal conductivity of stainless steel 430 are tabulated in Table 9 and shown in Figure 9.

As in the case for stainless steel 410, there is no metallurgical transformation in stainless steel 430 upon cold working. The electrical resistivity is therefore not significantly altered. The reduction in thermal conductivity due to dislocations generated by severe cold working is estimated to be 2% at 200 K, 8% at 100 K, 16% at 50 K and 20% at liquid helium temperatures.

Table 9. Electrical Resistivity and Thermal Conductivity of AISI 430 Stainless Steel †

Temperature (K)	Electrical Resistivity (10^{-8} Ω-m)	Thermal Conductivity (W m^{-1} K^{-1})
1	39.4	0.089
4	39.4	0.40
10	39.4	1.17
20	39.4	2.78
30	39.4	4.64
40	39.5	6.73
50	39.7	8.76
60	40.2	10.65
70	40.7	11.20
80	41.2	13.58
90	41.9	14.77
100	42.6	15.76
150	47.2	19.08
200	51.8	20.55
250	56.6	21.42
273	58.7	21.68
293	60.6	21.82
300	61.1	21.86
350	65.3	22.11
400	69.4	22.32
500	77.9	22.66
600	86.8	22.98
700	95.4	23.10
800	103.4	23.62
900	110.7	23.93
1000	115.8	24.47
1100	117.9	25.25
1200	119.7	26.23
1300	121.5	27.35
1400	123.4	28.55
1500	125.4	29.80
1600	127.3	31.05
1700	129.2	32.30
1750*	130.2	32.93
1775*	149.7	28.98
1800	150.2	29.29

* Melting Range.

† The uncertainty in the recommended values is of the order of ± 7% below 1200 K, ± 12% at or above 1200 K, and ± 15% at or above melting.

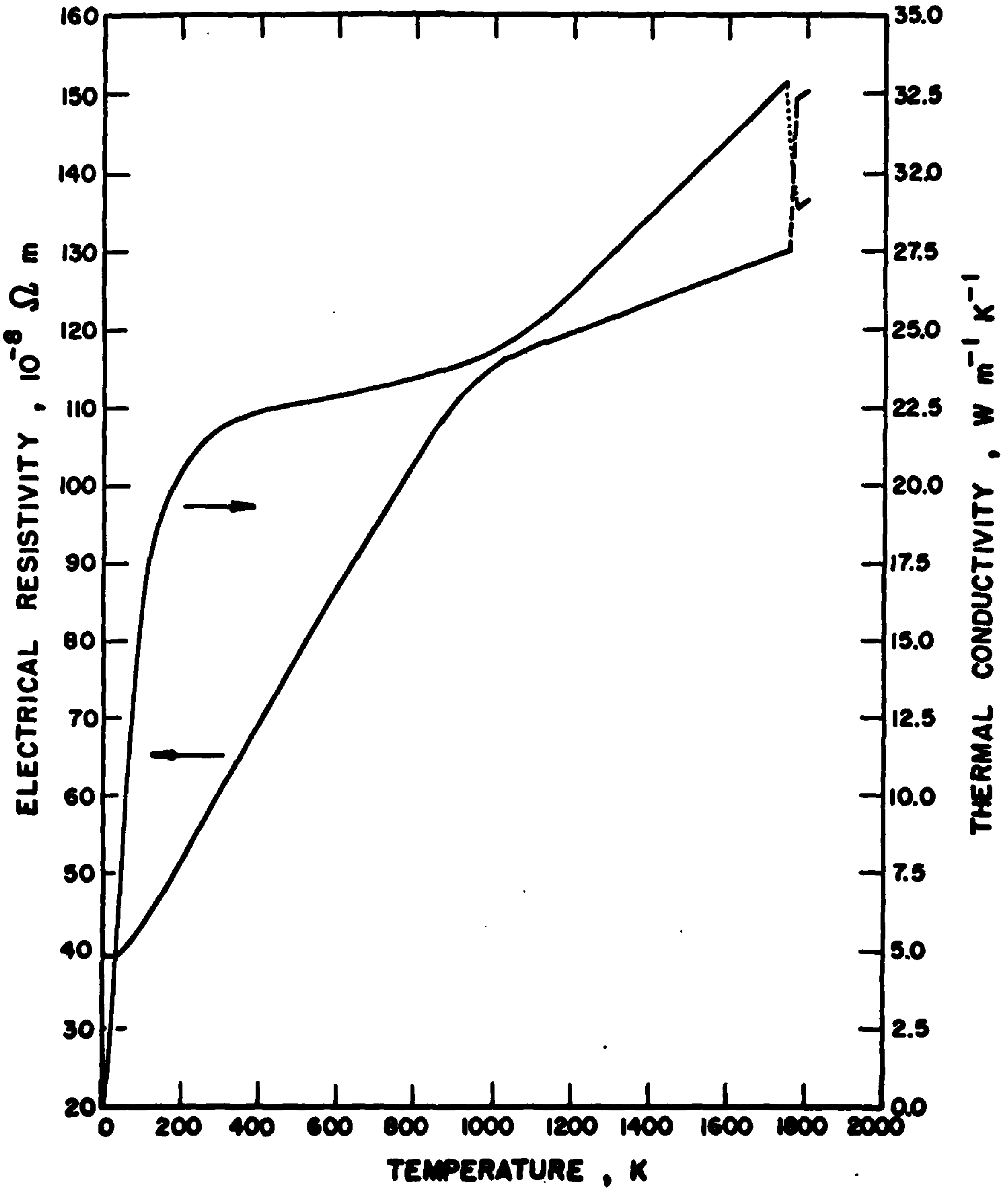

Figure 9. Electrical Resistivity and Thermal Conductivity of AISI 430 Stainless Steel.

V. CONCLUSIONS

The present study of the electrical resistivity and the thermal conductivity of seven austenitic (AISI 303, 304, 304L, 316, 317, 321 and 347) stainless steels indicates that there is consistent similarity in the magnitude and in the temperature dependence of each of the properties. For example, between the most common types 304 and 316, the electrical resistivity values are within about 15% of each other, and the thermal conductivity values are within about 30%. The largest differences occur at approximately 50 K or below. At room temperature and above, the differences are smaller, and at temperatures just below the melting point, they are only about 3%. For the purpose of comparison, the recommended electrical resistivity values for stainless steels 304 and 317 are shown together again in Figure 10; these, respectively, are the least and the most resistive, electrically and thermally, among the austenitic stainless steels studied. In Figure 11 are shown similarly the thermal conductivities of these two stainless steels.

The martensitic 410 and the ferritic 430 stainless steels are quite different from the austenitic stainless steels and from each other at moderate and low temperatures. For comparison, their electrical resistivities and thermal conductivities are shown again in Figures 10 and 11. It is seen that, above 1200 K, the electrical and the thermal properties of these steels converge, as is the case for most of the steels.

As evidenced by the available experimental data on both the electrical resistivity and the thermal conductivity of the nine stainless steels reviewed and discussed in this work, it is clear that for some of the stainless steels the available data are very scarce and serious gaps exist for the temperature dependence for all of them. The resulting recommended self-consistent values that cover the full range of temperature go far beyond the limited experimental data and are, therefore, very useful.

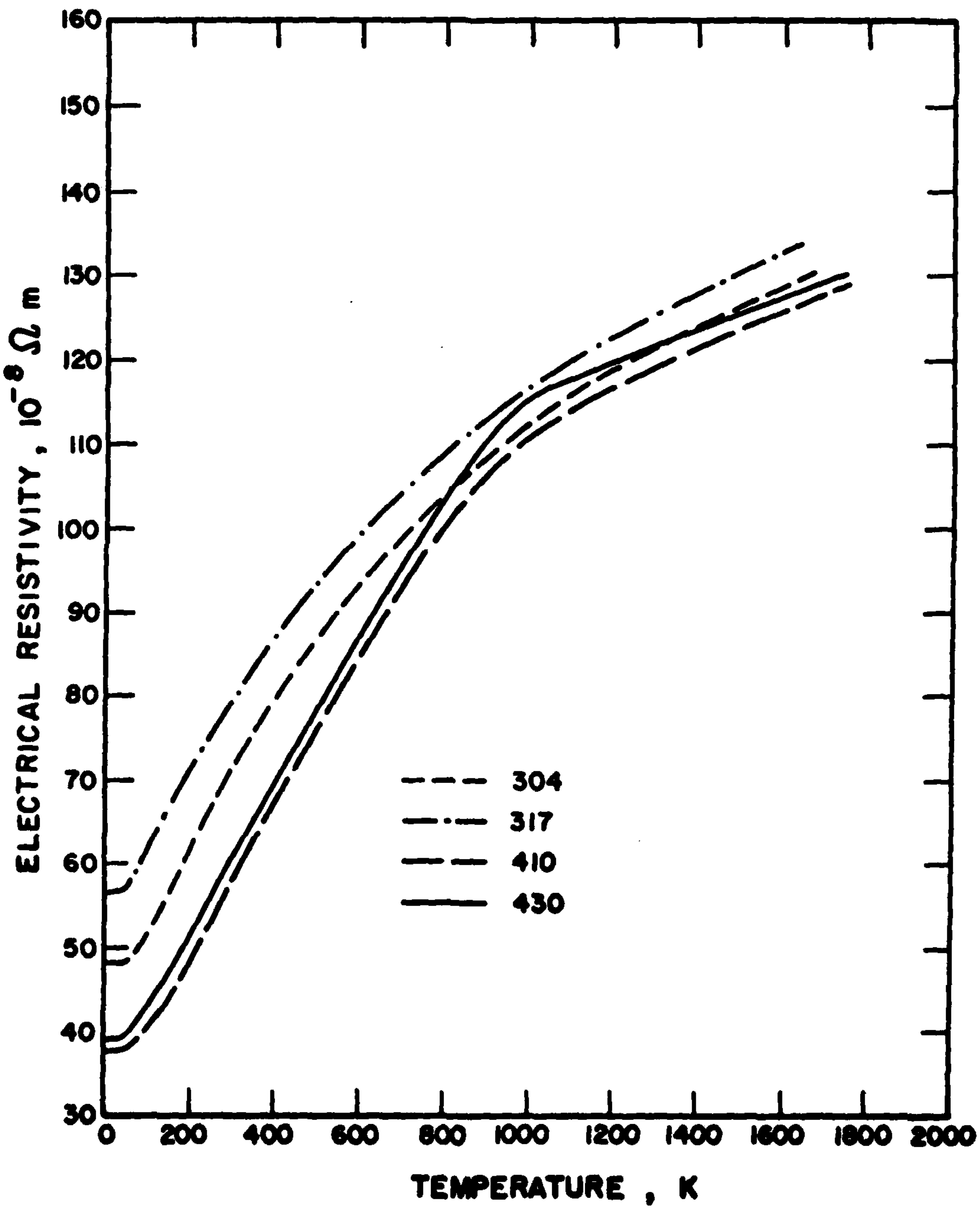

Figure 10. Electrical Resistivities of AISI 304, 317, 410, and 430 Stainless Steels.

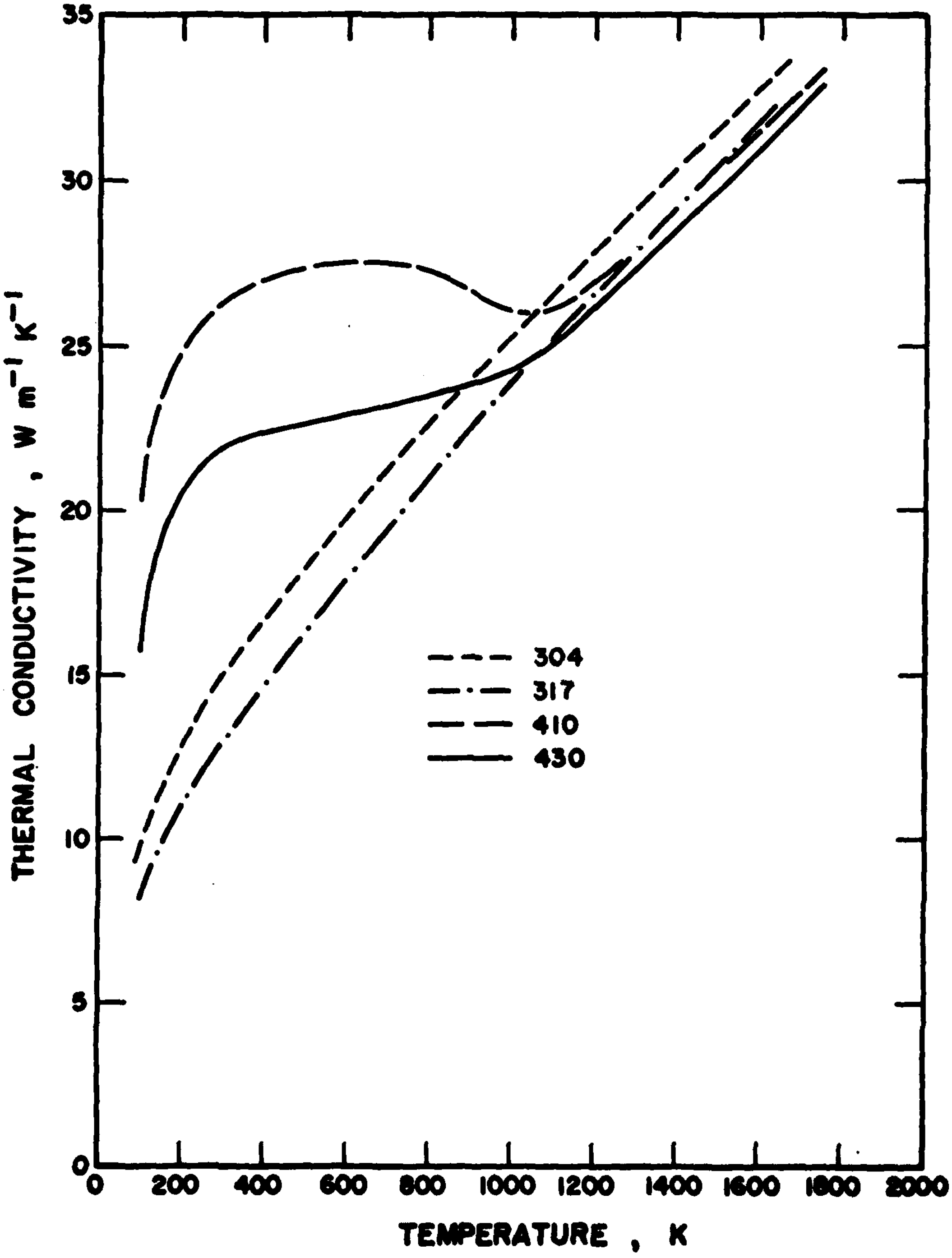

Figure 11. Thermal Conductivities of AISI 304, 317, 410, and 430 Stainless Steels.

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