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Thermophysical properties of stainless steels

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ABSTRACT

Experimental data available for the thermophysical properties of stainless steels have been searched, compiled, critically evaluated, analyzed, and correlated. Particular attention was given to material characteristics such as alloy composition, microstructure, and conditioning treatments. Thermal conductivity and electrical resistivity at low temperatures, and in some cases above room temperature, are comparatively more sensitive to these material differences.

Properties for which data evaluation has been done include thermal conductivity, heat capacity, thermal linear expansion, thermal diffusivity, thermoradiative properties, electrical resistivity, and magnetic susceptibility, and, in a few cases, thermoelectric power, viscosity, and optical constants. Generally, sufficient data are available for the generation of evaluated data (recommended values) for elevated temperatures, and in many cases for low temperatures also.

Stainless steels covered include the more common austenitic, ferritic, martensitic, and precipitation-hardened types. In all, more than 40 stainless steels are included in this effort.

INTRODUCTION

Stainless steels are a particularly interesting class of materials. Not only is there an extensive application base, but also applications have required thorough investigations of the behavior of, among other factors, the thermophysical properties. Over a period of time a variety of stainless steels have been produced by varying composition and conditioning treatment to achieve desired ends. Further, since these steels have found application in temperature environments extending from the cryogenic region to high temperatures, we would expect to learn much about property behavior by examining effects of these parameters.

The objectives of the present investigation are to critically review the literature for experimental data on thermophysical properties of stainless steels, to identify the

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effects upon property behavior that have been shown to be due to temperature and material composition and conditioning, and to generate recommended values consistent with limitations of the available data and information. A comprehensive and critical literature review of thermophysical properties of stainless steels has been underway for a number of years at CINDAS. An early set of data compilations for thermal properties (Touloukian et al. (1970-1975) was followed by data analysis and evaluation efforts directed at specific properties and steels (Chu and Ho (1978), Desai et al. (1979), Bogaard (1985)). Taken together, these efforts have resulted in a significant amount of information and experimental data being compiled, analyzed, and critically evaluated (Ho (1991)). The present effort is representative of a broadly scoped activity to critically evaluate available thermophysical property data for all stainless steels. The thermophysical properties include thermal (thermal conductivity, specific heat, thermal linear expansion, and thermal diffusivity), thermoradiative (hemispherical total emittance, normal total emittance, normal spectral emittance, and normal spectral reflectance), electrical (electrical and thermoelectric power), optical constants, magnetic susceptibility, and viscosity. Specifically, results are presented for eight stainless steels and seven properties, which show the variety of behavior that may be observed for these materials.

The stainless steels for which property data were critically evaluated fall under the broad headings of austenitic, ferritic, martensitic, and precipitation-hardened types. Chemical compositions (SAE/ASTM (1975)) for the eight representative stainless steels are given in the accompanying Table.

TABLE 1

Chemical Compositions of Selected Stainless Steels

AISI Type	C max	Mn max	Si max	P max	S max	Cr range	Ni range	Others
Austenitic								
304	0.08	2.00	1.00	0.045	0.030	18.0-20.0	8.0-10.5	-
316	0.08	2.00	1.00	0.045	0.030	16.0-18.0	10.0-14.0	a
321	0.08	2.00	1.00	0.045	0.030	17.0-19.0	9.0-12.0	b
347	0.08	2.00	1.00	0.045	0.030	17.0-19.0	9.0-13.0	c
660	0.08	2.00	1.00	0.040	0.030	13.5-16.0	24.0-27.0	d
Ferritic								
430	0.12	1.00	1.00	0.040	0.030	16.0-18.0	-	-
Martensitic								
410	0.15	1.00	1.00	0.040	0.030	11.5-13.5	-	-
Precipitation-Hardened								
631	0.09	1.00	1.00	0.040	0.040	16.0-18.0	6.50-7.75	e

a Mo 2.0-3.0
b Ti 5 x Cmin
c Nb 10 x Cmin
d Al 0.35; B 0.001-0.010; Mo 1.0-1.5; Ti 1.90-2.35; V 0.10-0.50
e Al 0.75-1.50

DISCUSSION

The thermophysical properties for a number of stainless steels are discussed in this section. Specific properties and stainless steels were selected to give a representative presentation of the overall results. Comments will necessarily be qualitative only due to limitation of space.

The thermal conductivity of three stainless steels is shown in Figures 1, 2, and 3. All data for AISI 321 austenitic stainless steel (Figure 1) were reported for solution-treated material. Effects due to conditioning (material structure) are observed for AISI 410 martensitic and 631 precipitation-hardened stainless steel in Figures 2 and 3, respectively. Data analysis was carried out to examine the temperature behavior of lattice thermal conductivity, and correlations of thermal conductivity and electrical resistivity proved helpful in sorting out effects due to heat treatments. Uncertainty estimates for the recommended values depend upon factors such as amount and quality of data and the reproducibility of the data for particular conditioning treatments. The estimates typically range from +/- 5% to +/- 15%.

Specific heat of austenitic stainless steels, AISI 304 and 316, is shown in Figures 4 and 5 respectively. A problem encountered in evaluating data for some steels (not these two) is of ensuring that the true specific heat is indeed being observed. What is of interest for these two stainless steels, however, is that the specific heat of AISI 304 is about 8% larger at room temperature, presumably due to the molybdenum content of AISI 316 steel, and is an indication of the sensitivity of this property to composition differences. The uncertainties estimated for specific heat of stainless steels are generally +/- 5%.

Thermal linear expansion for AISI 316 austenitic and AISI 430 ferritic stainless steels are shown in Figures 6 and 7, respectively. Data reported from direct measurements of the temperature coefficient are also shown. Clearly, the thermal expansion for the austenitic steel is significantly larger than for the ferritic steel. The uncertainties in the recommended values are estimated to be within +/- 5% for thermal expansion and +/- 10% for the temperature coefficient when data scatter is comparatively small as in Figure 6, or +/- 10% and +/- 15%, respectively for the case of more widely scattered data in Figure 7.

Thermal diffusivity of AISI 304 stainless steel is shown in Figure 8. The observation that several of the data sets shown are atypically small in value has not been explained. The uncertainty estimated for the values is about +/- 5%.

The thermoradiative properties for AISI 321 and 347 austenitic stainless steels are shown in Figures 9 and 10, respectively. The surface sensitivity for the normal total emittance in Figure 9 and normal spectral emittance in Figure 10 is much in evidence. The difficulty with data evaluation in the present case is how to make comparisons among data sets when quantitative surface characterization is unavailable since the appropriate techniques have not been developed. About all that can justifiably be done is to indicate where the limits are, within the existing data, highly polished surfaces on the one hand and heavily oxidized for surfaces on the other.

The electrical resistivity of AISI 316 austenitic AISI 631 precipitation-hardened, and AISI 660 austenitic stainless steels are shown in Figures 11, 12, and 13, respectively. The data scatter observed in Figures 11 and 13 and amounting to upwards of +/- 6% is due to material variability for stainless steels having

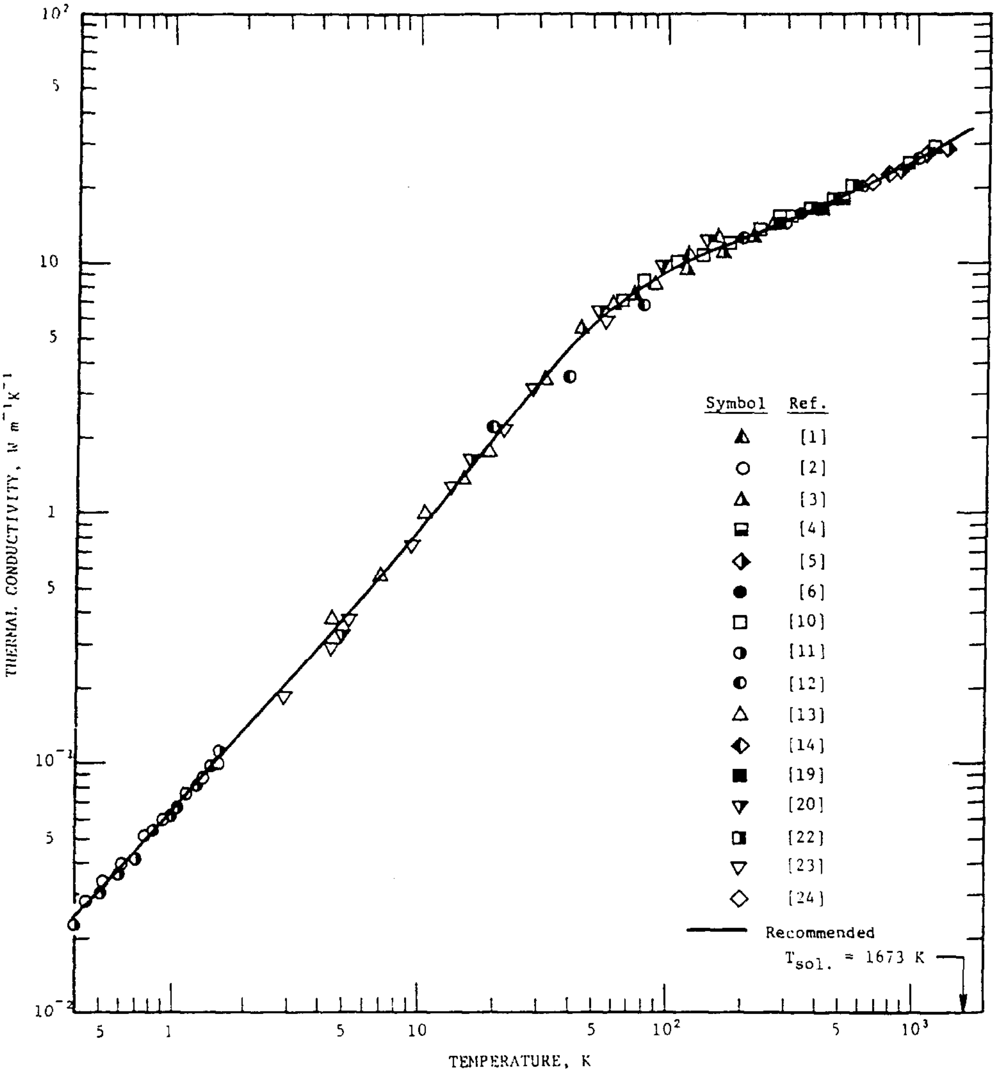


Figure 1. Thermal Conductivity of AISI 321 Stainless Steel.

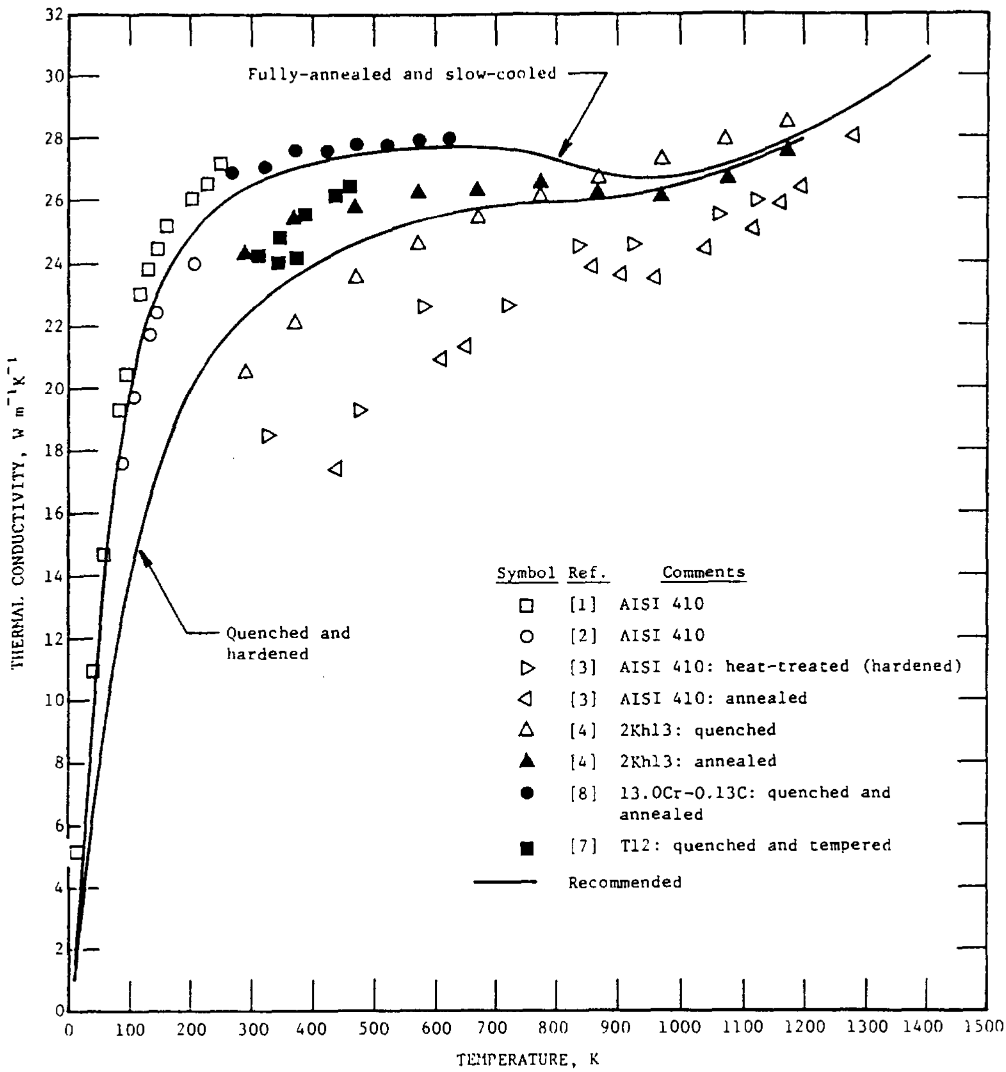


Figure 2. Thermal Conductivity of AISI 410 Stainless Steel.

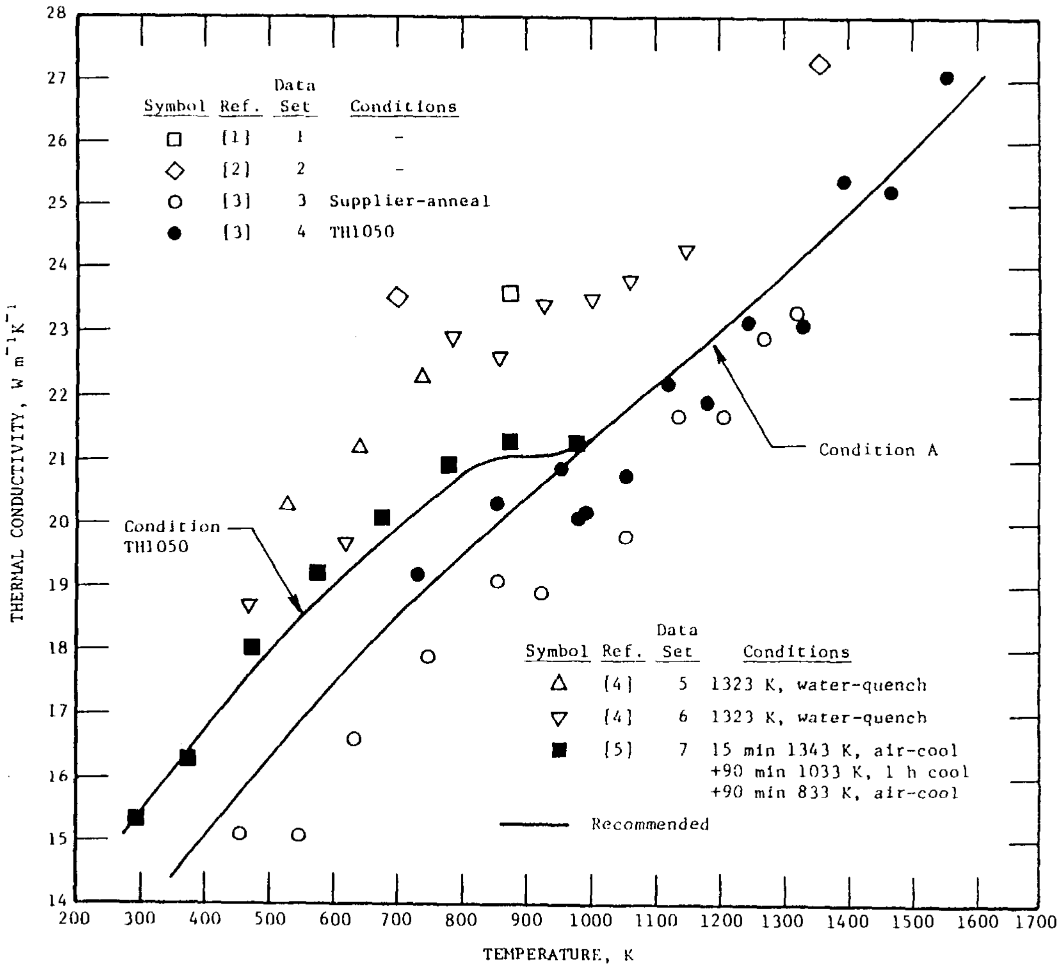


Figure 3. Thermal Conductivity of AISI 631 Stainless Steel [17-7PH].

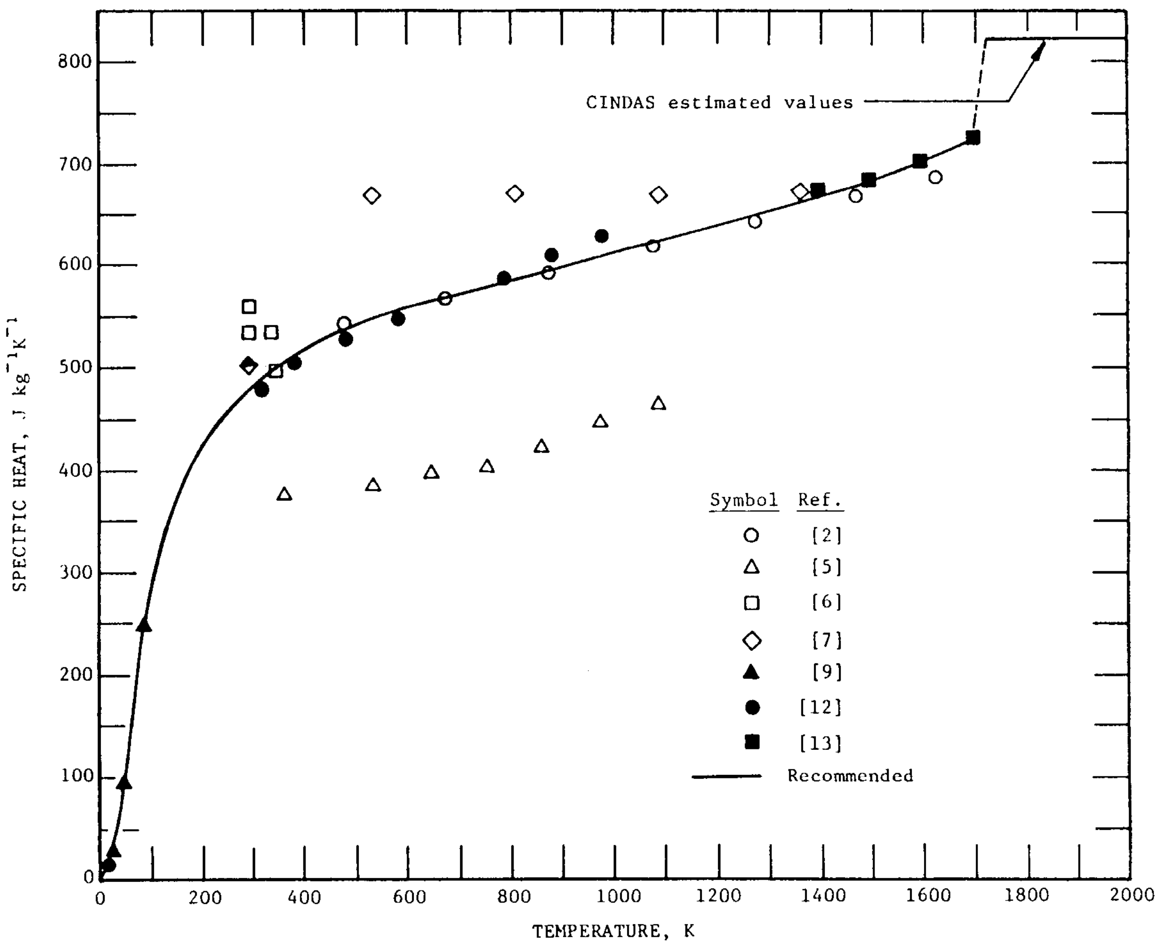


Figure 4. Specific Heat of AISI 304 Stainless Steel.

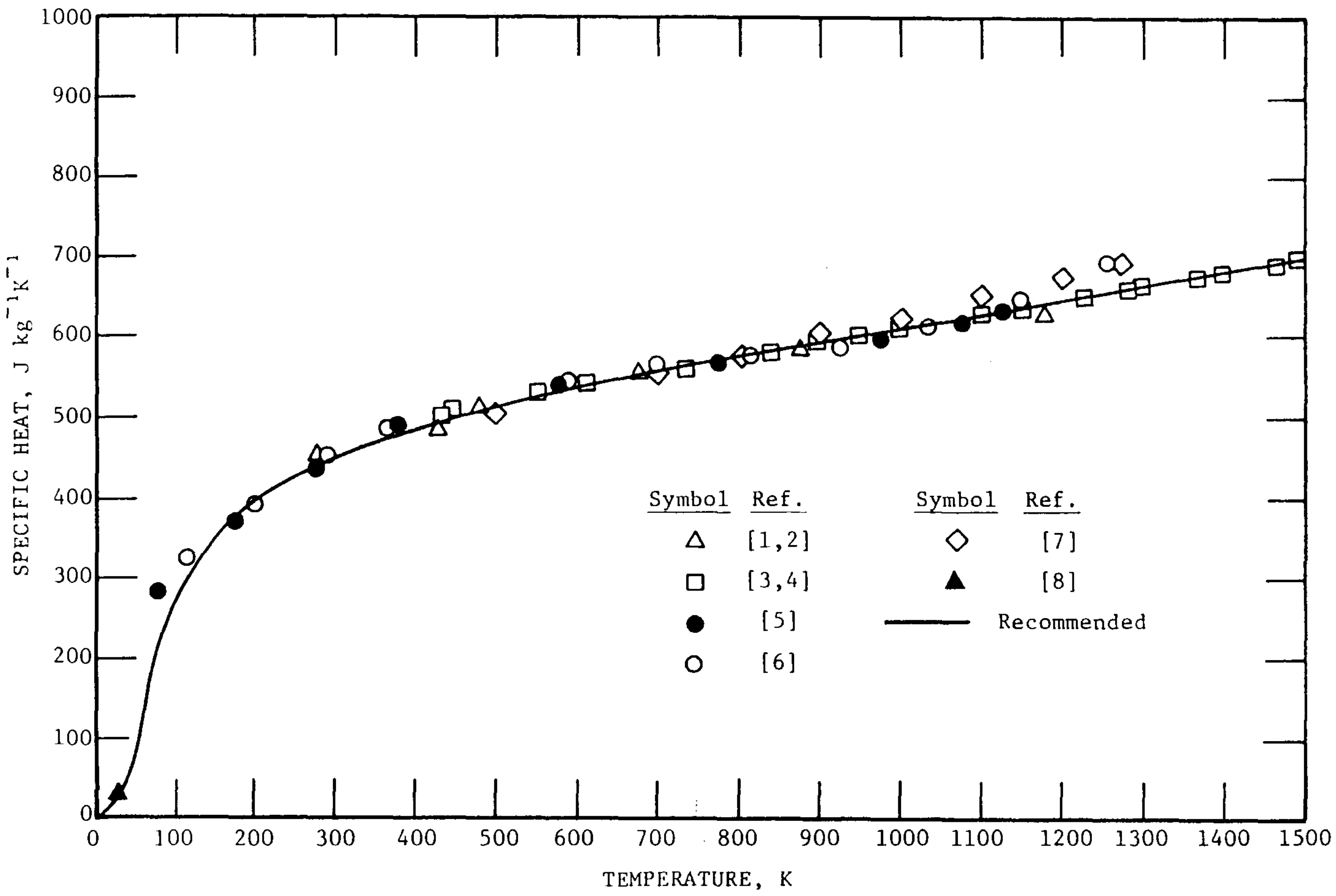


Figure 5. Specific Heat of AISI 316 Stainless Steel.

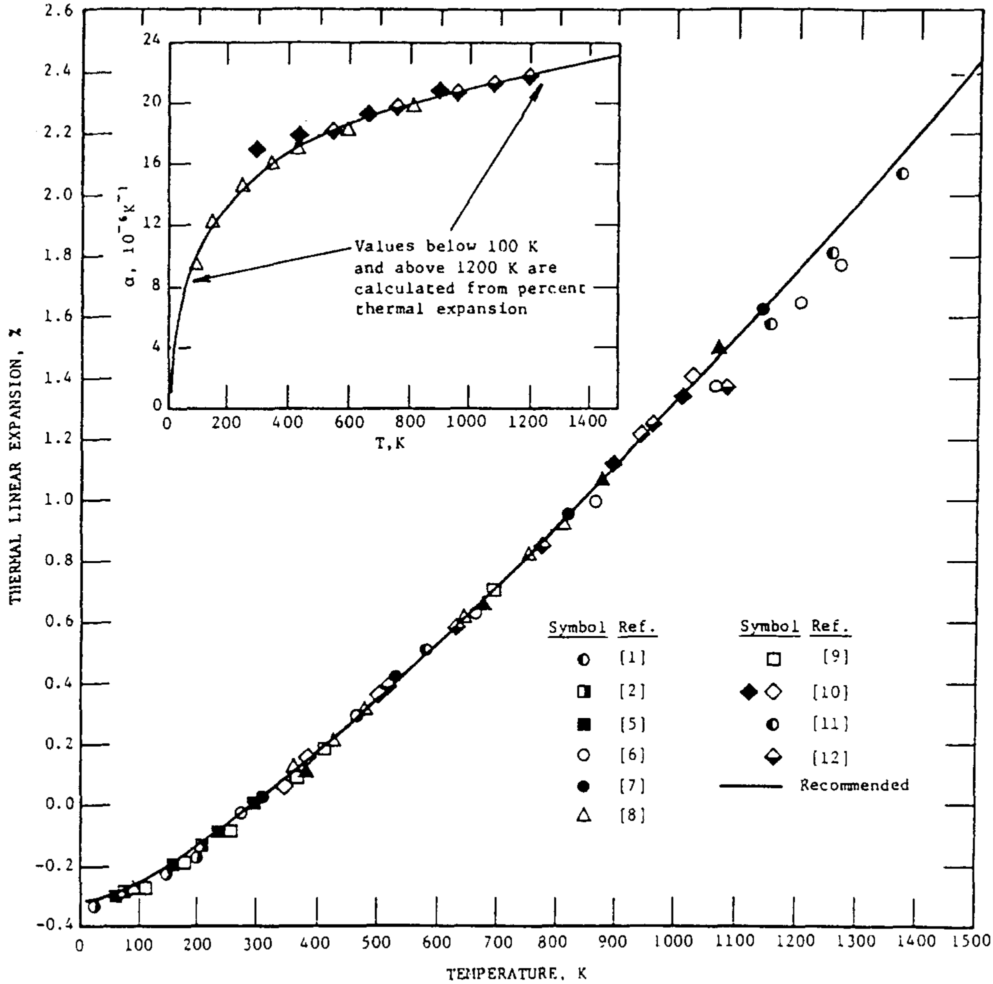


Figure 6. Thermal Linear Expansion of AISI 304 Stainless Steel.

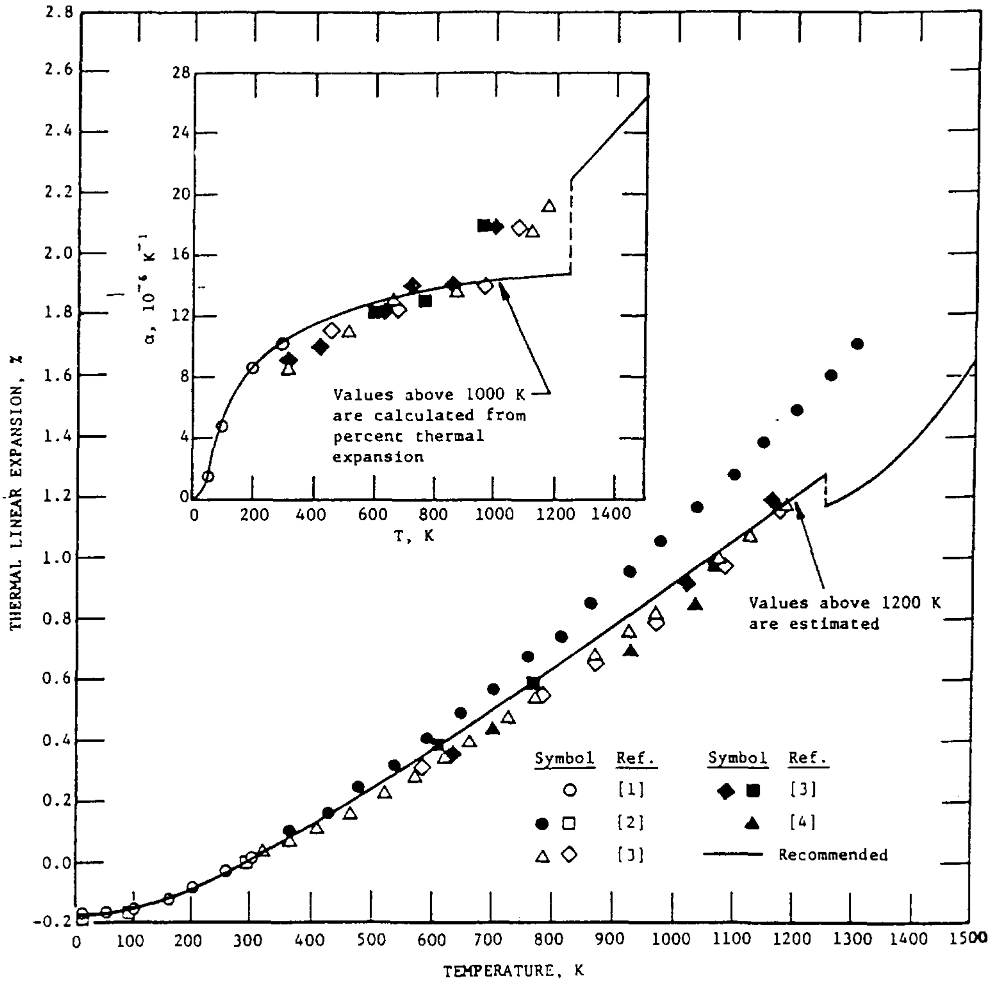


Figure 7. Thermal Linear Expansion of AISI 430 Stainless Steel.

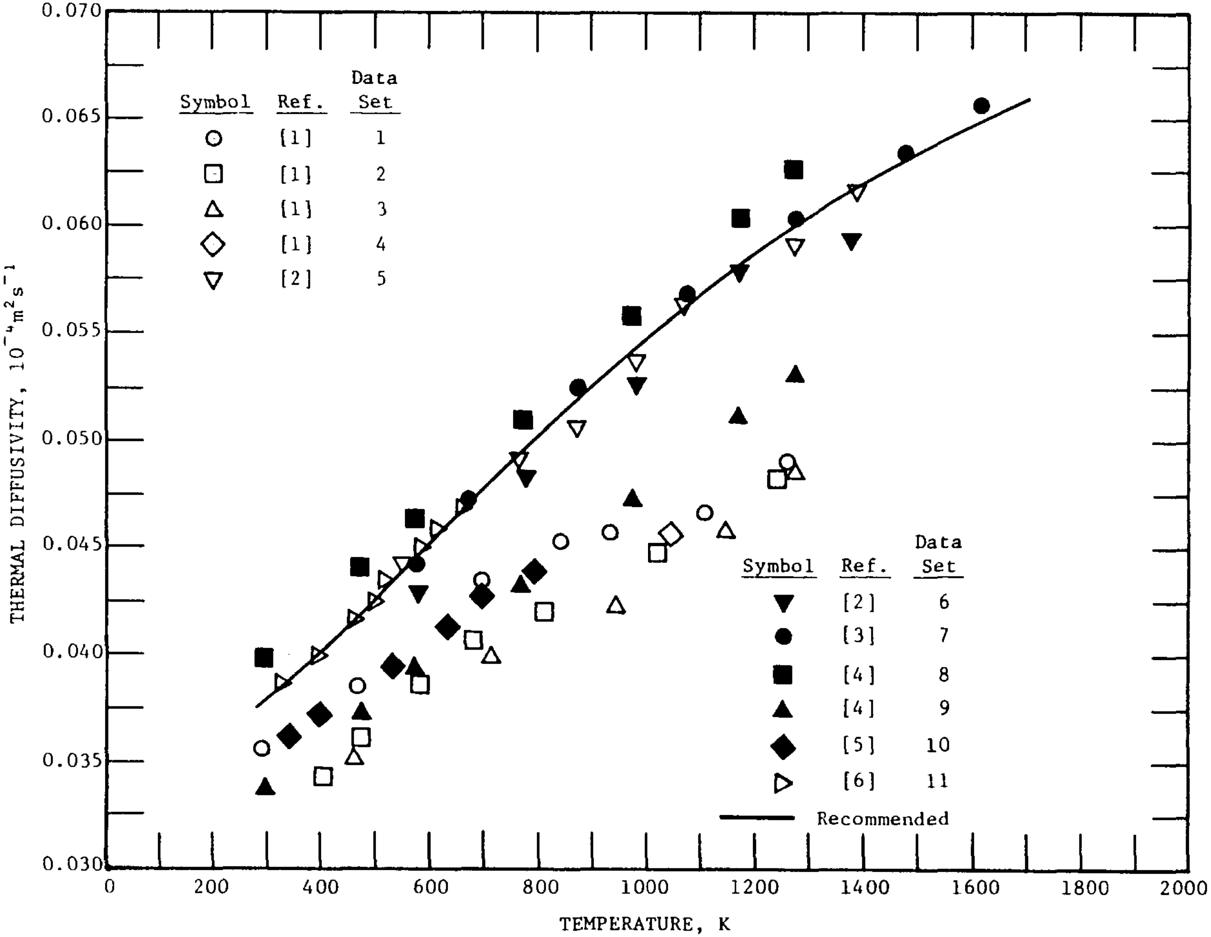
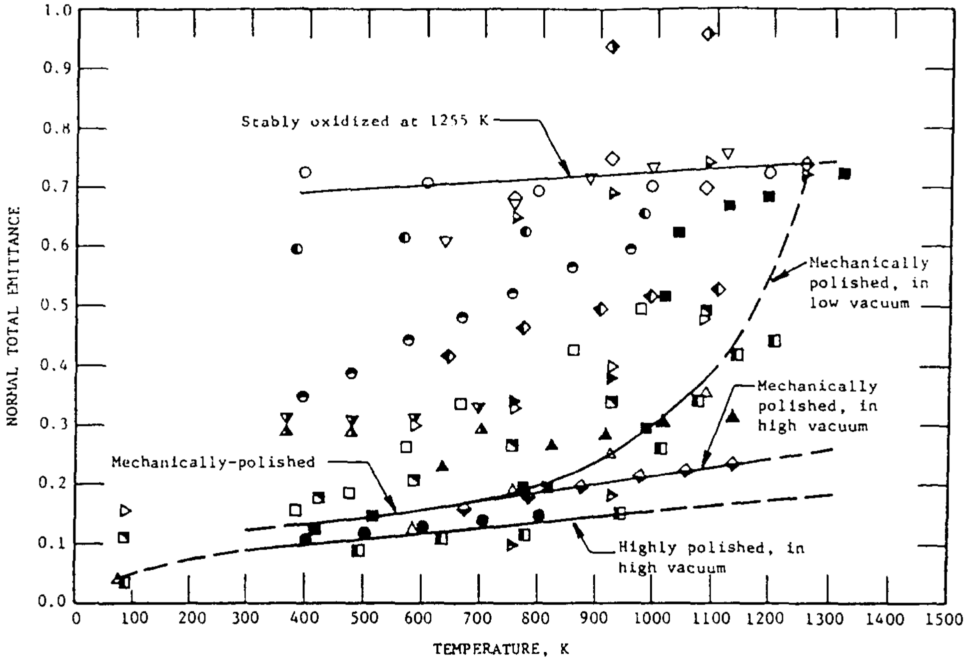
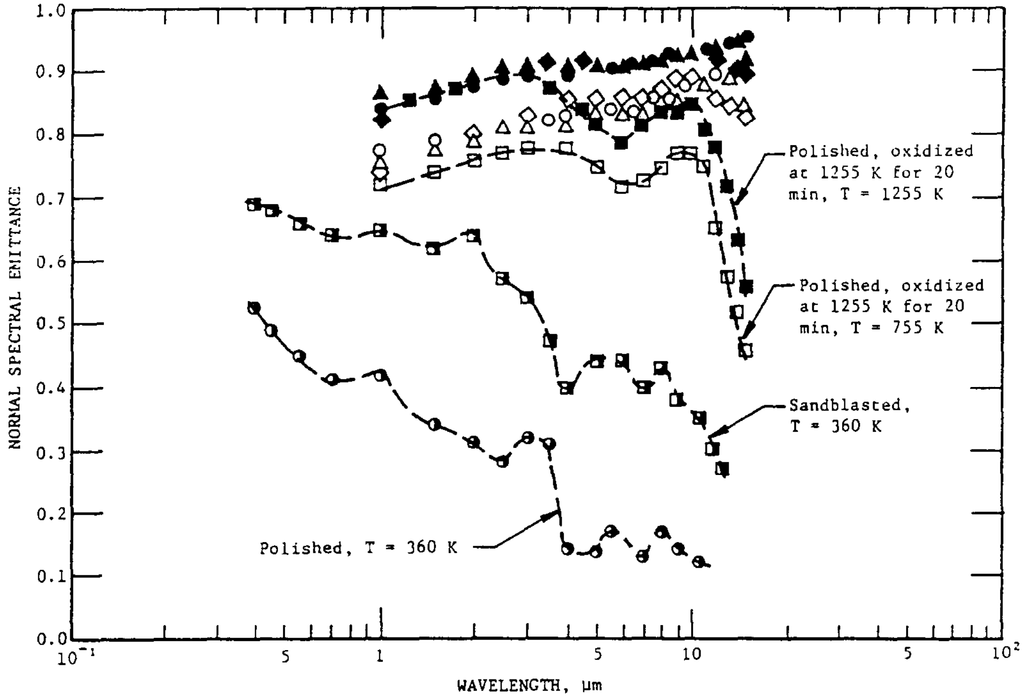


Figure 8. Thermal Diffusivity of AISI 304 Stainless Steel.



Symbol	Ref.	Conditions
△	[8]	Bright finish, vacuum 0.5 torr
◧	[8]	Polished, 0.051 μm roughness, vacuum 0.5 torr
◩	[8]	Dull finish, 0.153 μm roughness, vacuum 0.5 torr
▷	[8]	Above specimen, oxidized in air at red heat for 30 min.
▶	[10]	Electropolished
▷	[10]	Electropolished, oxidized at 1255 K for 30 min.
▶	[10]	Sandblasted
◇	[10]	Sandblasted, oxidized at 1255 K for 30 min.
▽	[12]	As-received
△	[12]	Heat-treatment at 639 K for 307 h
◆	[14]	Machined, ground, annealed then polished
▲	[14]	Electron-beam roughened, crater diameter 950 μm and depth 80 μm
◆	[14]	Similar, crater diameter 420 μm and depth 570 μm
▽	[14]	Similar, crater diameter 400 μm and depth 880 μm
■	[16]	Polished, heated in air at 600 K for 100 h
□	[16]	Polished, heated in air at 1000 K for 2 h
⊖	[16]	Polished, heated in air at 1100 K for 2 h
◐	[16]	Polished, heated in air at 1190 K for 2 h
○	[16]	Polished, heated in air at 1300 K for 2 h
●	[16]	Electropolished
◈	[18]	Oxidized at 1255 K for 15 min.
———		Recommended
— — —		Typical

Figure 9. Normal Total Emittance of AISI 321 Stainless Steel.



Symbol	Ref.	Conditions
△	[9]	As-received, degreased, oxidized at 1255 K for 20 min, T = 755 K
▲	[9]	Above specimen, T = 1255 K
○	[9]	Degreased, etched, oxidized at 1255 K for 20 min, T = 755 K
●	[9]	Above specimen, T = 1255 K
◇	[9]	Degreased, grit blasted, oxidized at 1255 K for 20 min, T = 755 K
◆	[9]	Above specimen, T = 1255 K
□	[9]	Degreased, polished with fine sandpapers, oxidized at 1255 K for 20 min, T = 755 K
■	[9]	Above specimen, T = 1255 K
◑	[11]	Polished, T = 360 K
◨	[11]	Sandblasted, T = 360 K
— — —		Typical

Figure 10. Normal Spectral Emittance of AISI 347 Stainless Steel (Wavelength Dependence).

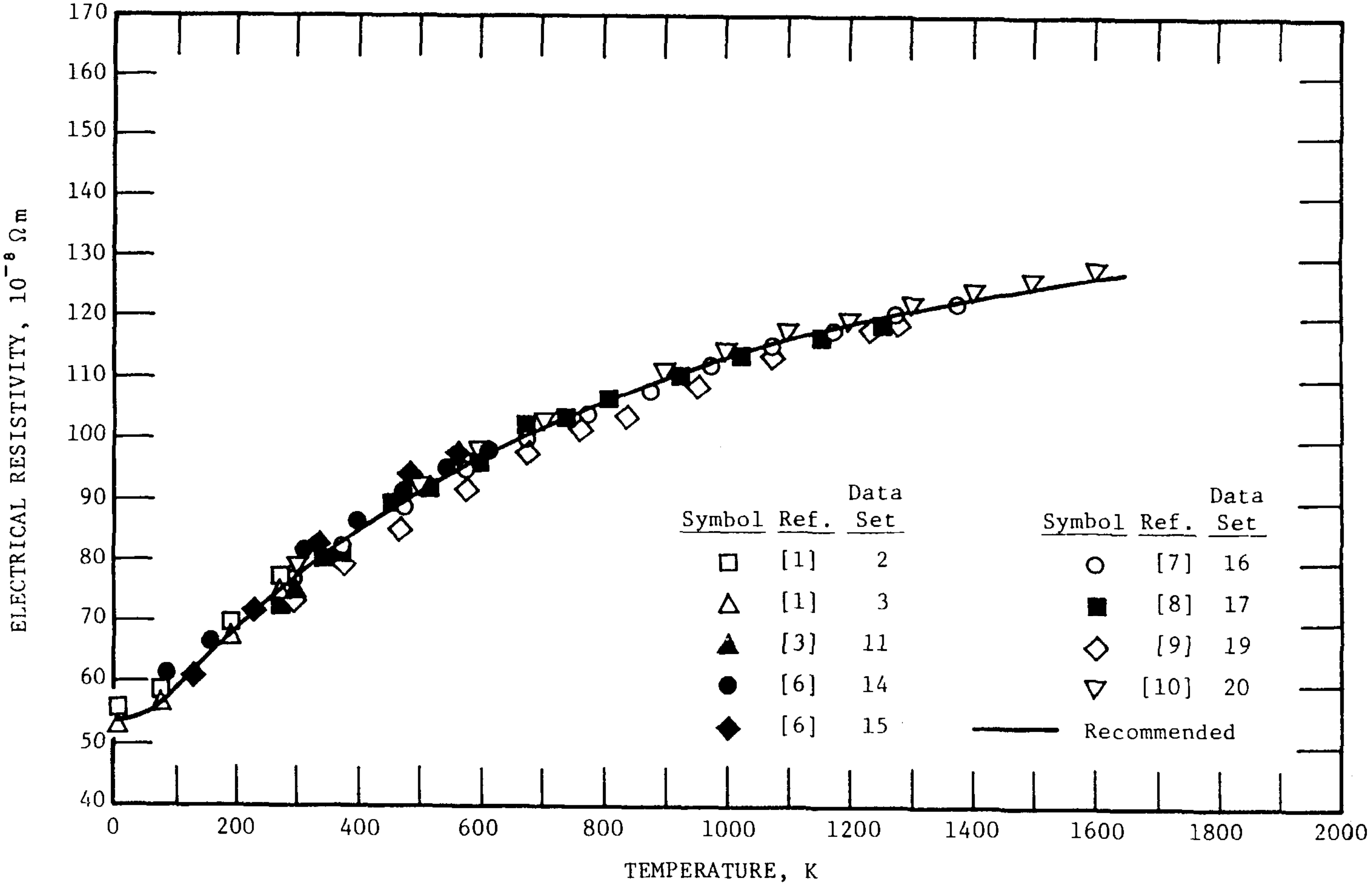


Figure 11. Electrical Resistivity of AISI 316 Stainless Steel.

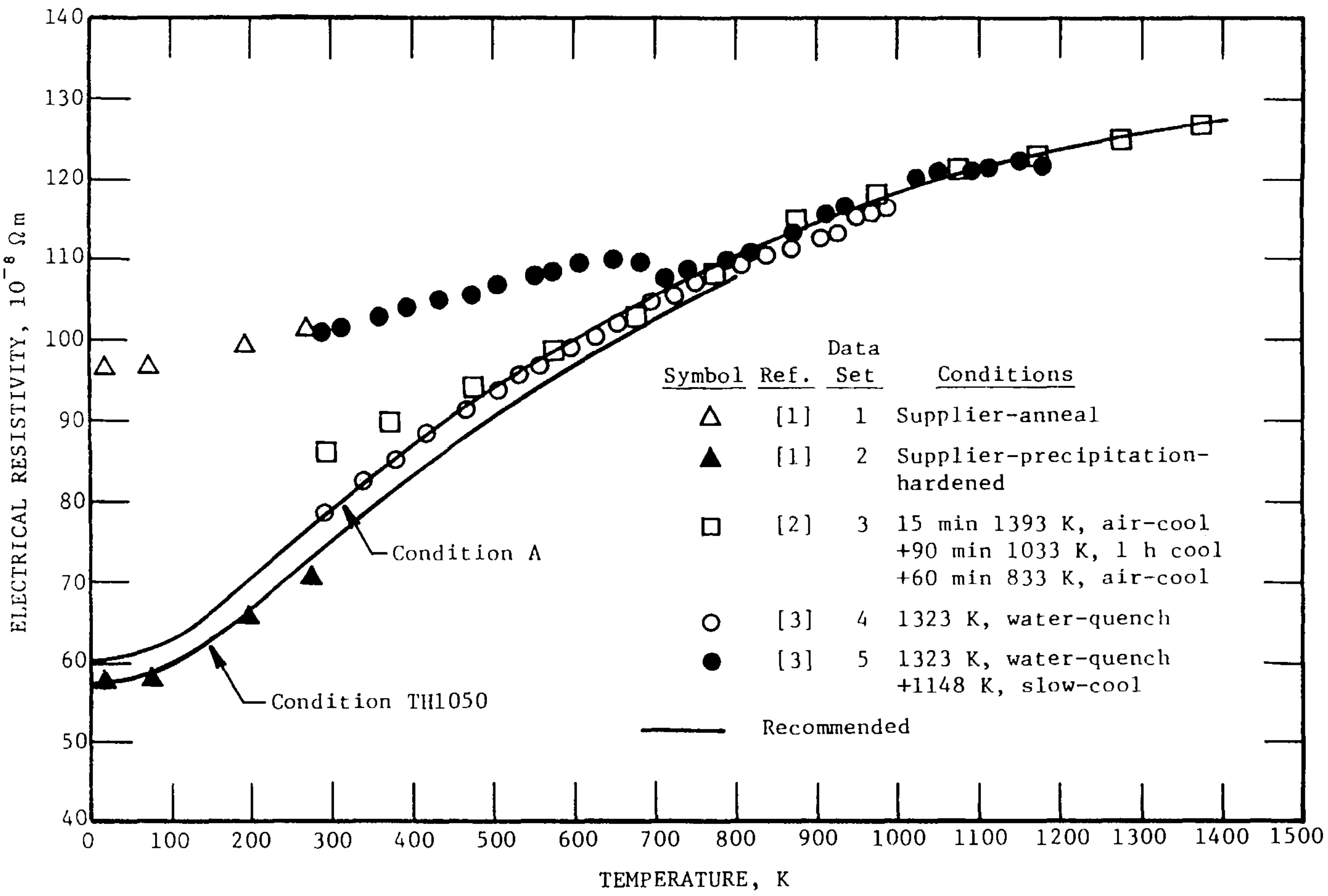


Figure 12. Electrical Resistivity of AISI 631 Stainless Steel [17-7PH].

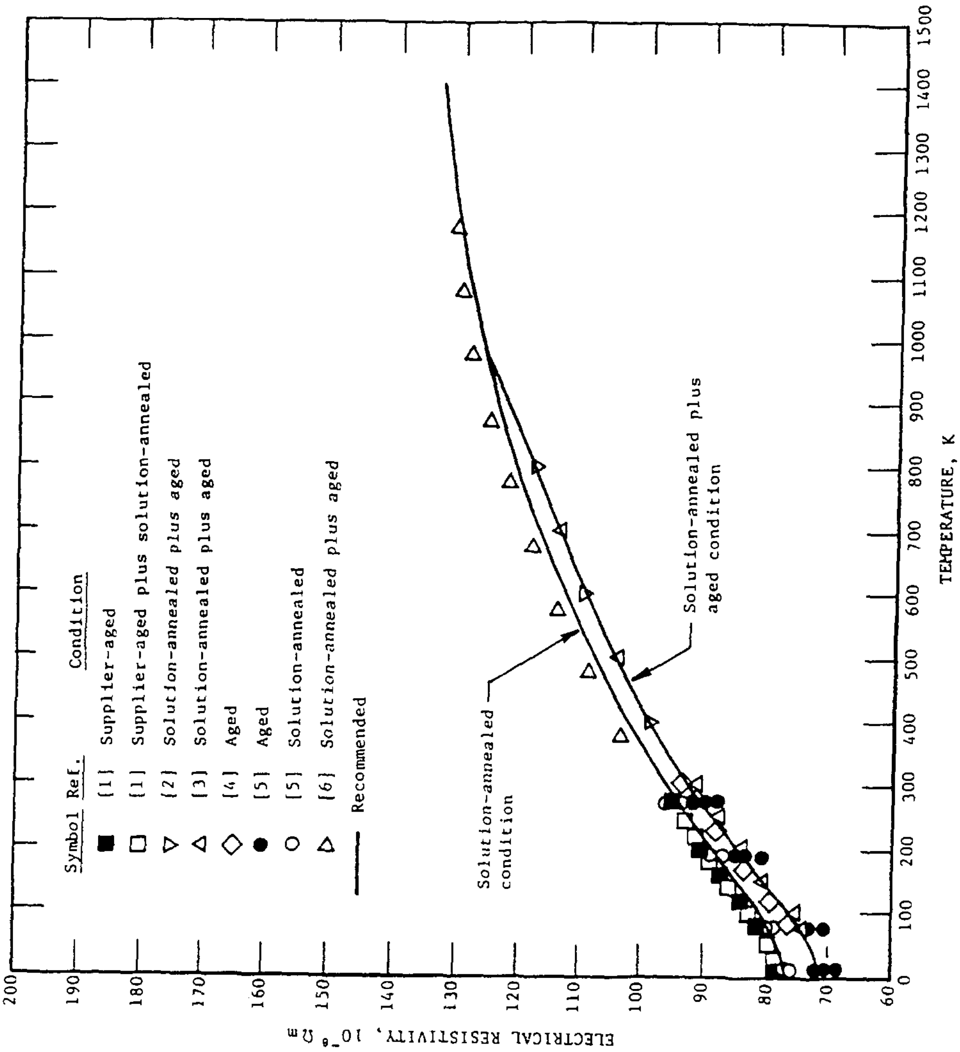


Figure 13. Electrical Resistivity of AISI 660 Stainless Steel [A-286].

nominally similar heat treatments. Further, effects of aging on the electrical resistivity of AISI 631 precipitation-hardened and AISI 660 austenitic stainless steels in Figures 12 and 13, respectively, is clearly evident. The effects are only sketchily indicated in Figure 12, but are well-established in Figure 13. Uncertainties in the electrical resistivity varies from +/- 2 to 3% for well established values to +/- 5% to less well-documented situations.

The magnetic susceptibility of AISI 304 stainless steel is shown in Figure 14. This figure is included to give an indication of the complex magnetic behavior observed at low magnetic field when this material is cooled to low temperatures.

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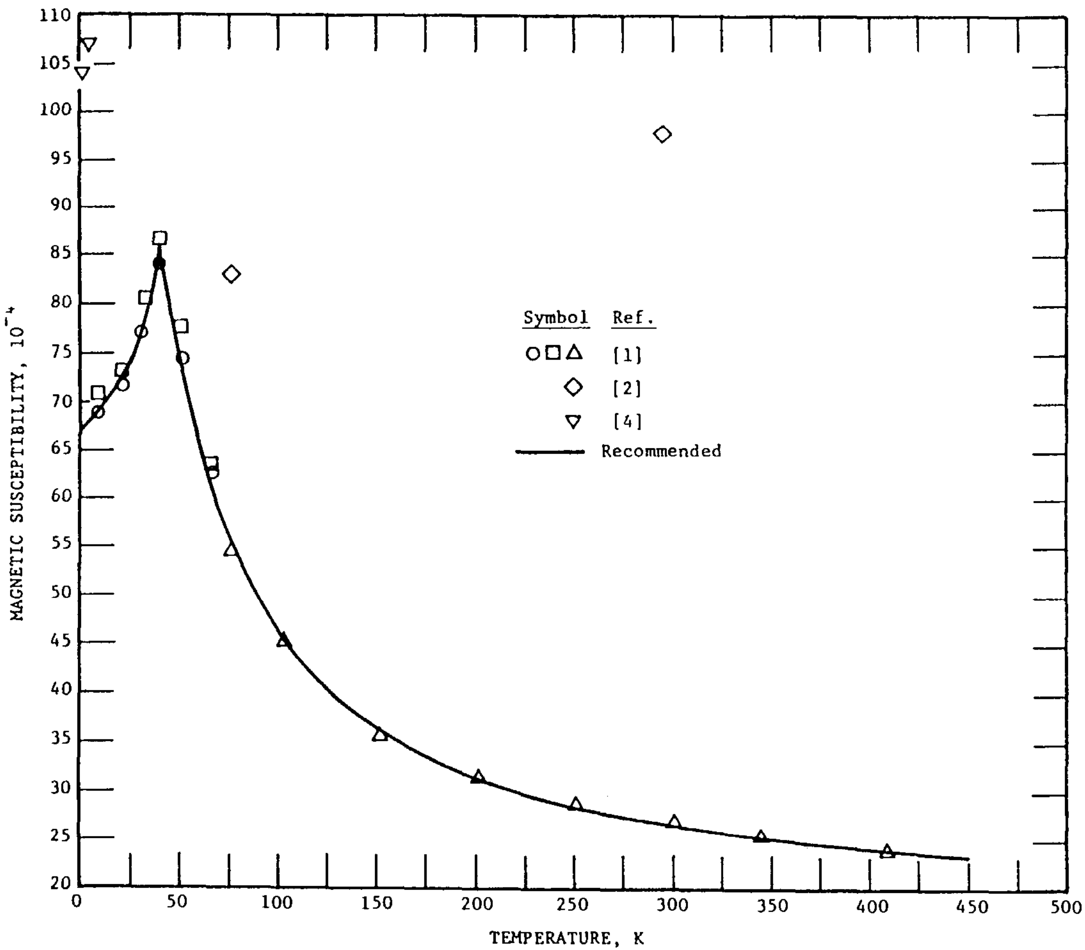

Figure 14. Magnetic Susceptibility of AISI 304 Stainless Steel.

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