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THERMOPHYSICAL PROPERTIES OF SELECTED AEROSPACE MATERIALS

PART II: THERMOPHYSICAL PROPERTIES OF SEVEN MATERIALS

THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS CENTER
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This work presents the most comprehensively compiled experimental data and information on five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information.

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20. ABSTRACT (Cont)

The five thermophysical properties are thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. The seven selected materials are aluminum alloy 2024, AISI 304 stainless steel, Pyroceram (Corning 9606), silicon nitride, boron fiber epoxy composite, glass fiber epoxy composite, and graphite fiber epoxy composite.

The experimental data and the recommended values for each property of each material are presented in both tabular and graphical forms, together with a discussion text and a specification table. The former reviews the available data and information, discusses the considerations involved in the data analysis and synthesis and in arriving at the final assessment and recommendation and specified the uncertainty of the recommended values, and the latter gives the information on the specimen characterization and measurement method and condition for each set of experimental data.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, the general background information on the behavior of each of the five thermophysical properties and on the procedures used for the data evaluation and the generation of recommended values is provided. A concise description of each of the seven selected materials is also given.

THERMOPHYSICAL PROPERTIES OF SELECTED AEROSPACE MATERIALS

PART II: THERMOPHYSICAL PROPERTIES OF SEVEN MATERIALS

Y. S. TOULOUKIAN and C. Y. HO, Editors

THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS CENTER
CINDAS - Purdue University

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PREFACE

This volume was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a DOD Information Analysis Center operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under Contract No. DSA900-76-C-0860 with the Defense Supply Agency (DSA), Alexandria, Virginia, with Mr. J. L. Blue (Hq. DSA) as the IAC Program Manager and Mr. Samuel Valencia (Army Materials and Mechanics Research Center) as the Contracting Officer's Technical Representative.

The overall program is aimed at providing data and information on all the important thermophysical properties of selected aerospace materials. The effort in the last year was concentrated on the thermal radiative properties (hemispherical, normal, and angular spectral emittance, reflectance, absorptance, and transmittance) of twenty-seven selected aerospace materials, resulting in the publication entitled "Thermophysical Properties of Selected Aerospace Materials. Part I: Thermal Radiative Properties," copies of which are available from TEPIAC/CINDAS. The effort in the current year has been concentrated on five other thermophysical properties of seven materials, resulting in this volume which constitutes Part II of this series of publications.

This special project has been carried out by a team of TEPIAC staff, with the following individuals in responsible charge:

Dr. P. D. Desai -- Specific Heat, Heat of Fusion, and Thermal Linear Expansion
Dr. K. Y. Wu -- Thermal Conductivity and Thermal Diffusivity

It is hoped that this reference work will prove useful to a large technical community as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is felt that the critical evaluation, analysis and reference data recommendation, whenever possible, constitute perhaps the most unique aspect of this work.

In putting a volume of this magnitude together it is nearly impossible to avoid some errors and omissions. It is hoped that we were able to keep these to a minimum. The editors and contributors would be most grateful if those who use this work bring to their attention any additional known data or any possible errors that might have been inadvertently committed.

Y. S. TOULOUKIAN
Director of CINDAS
Distinguished Atkins Professor of Engineering
Purdue University

October 1976
West Lafayette, IN 47906

SUMMARY

This work presents the most comprehensively compiled experimental data and information on five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information.

The five thermophysical properties are thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. The seven selected materials are aluminum alloy 2024, AISI 304 stainless steel, Pyroceram (Corning 9606), silicon nitride (Si_3N_4), boron fiber epoxy composite, glass fiber epoxy composite, and graphite fiber epoxy composite.

The experimental data and the recommended values for each property of each material are presented in both tabular and graphical forms, together with a discussion text and a specification table. The former reviews the available data and information, discusses the considerations involved in the data analysis and synthesis and in arriving at the final assessment and recommendation, and specifies the uncertainty of the recommended values, and the latter gives the information on the specimen characterization and measurement method and condition for each set of experimental data.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, the general background information on the behavior of each of the five thermophysical properties and on the procedures used for the data evaluation and the generation of recommended values is provided. A concise description of each of the seven selected materials is also given.

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1. INTRODUCTION

This work presents both the available experimental data that were exhaustively searched and comprehensively compiled for five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information. The five thermophysical properties are: (1) thermal conductivity, (2) specific heat, (3) heat of fusion, (4) thermal linear expansion, and (5) thermal diffusivity. The seven selected materials are: (1) aluminum alloy 2024, (2) AISI 304 stainless steel, (3) Pyroceram (Corning 9606), (4) silicon nitride (Si_3N_4), (5) boron fiber epoxy composite, (6) glass fiber epoxy composite, and (7) graphite fiber epoxy composite.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, Section 2 provides the general background information on the behavior of each of the thermophysical properties covered, the procedures used for the data evaluation and the generation of recommended values, and on the format and detail of the data presentation. The experimental data and the recommended values for the five properties of the seven materials are presented in Section 3 in both tabular and graphical forms, together with a discussion text for each property of each material, in which the individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, and the uncertainty of the recommended values is stated. Since the information on some of the selected materials is not generally known, a concise description of each of the materials is given at the beginning of each of the subsections in Section 3. The complete bibliographic citations for the 156 references are given in Section 4.

2. GENERAL BACKGROUND

The purpose of this section is to provide general background information on the thermophysical properties covered in this work, the procedures for the data evaluation and the generation of recommended values, and on the format of presentation of data. It is hoped that this information will assist the reader to properly interpret and fully utilize the data and information presented in this work and also enhances the usefulness of the data themselves.

2.1. Thermophysical Properties

In this work five thermophysical properties are covered: thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. These are briefly discussed below.

Thermal Conductivity

In metals and alloys the principal carriers of heat are electrons and lattice vibrational waves. In a pure metal the heat conduction by electrons is predominant at all temperatures and the contribution to heat conduction by lattice waves is comparatively very small.

In an alloy, especially at low temperatures, however, the contribution by lattice waves is often comparable to and sometimes even greater than that by electrons. Consequently, in estimating or analyzing the thermal conductivity data for an alloy, the consideration of both electronic and lattice components of the thermal conductivity is necessary. At very low temperatures the electronic thermal resistivity arises from the scattering of electrons by solute atoms, and at higher temperatures the scattering of electrons by lattice waves becomes significant.

In nonmetallic solids the conduction of heat is mainly by lattice vibrational waves. The quanta of vibrational energy are called phonons, and the thermal conductivity of nonmetallic solids is determined both by the specific heat and the mean free path of the phonons. The mean free path is limited by the various phonon scattering processes, which give rise to thermal resistance. At temperatures close to absolute zero the phonons are scattered by the crystal boundaries, and the thermal conductivity of a nonmetallic crystal varies as T^3 (the temperature dependence of the lattice specific heat) and is size dependent. As the temperature is increased, other scattering mechanisms become effective: scattering of phonons by static imperfections (impurities, isotopes,

and all kinds of lattice defects) and scattering of phons by other phonons (Umklapp processes). The last mentioned process increases rapidly with temperature, until the mean free path decreases more rapidly with temperature than the specific heat increases. At this point, still at very low temperature, the thermal conductivity passes through a maximum and then decreases, in some perfect crystals exponentially. Around the Debye temperature and above, the phonon-phonon (Umklapp) scattering is predominant and the thermal conductivity should vary as T^{-1}. In some cases the crystals are at least partially transparent to infrared radiation, and there is an additional radiative component of thermal conductivity, which increases rapidly with temperature at high temperatures. In other cases such as in mixed crystals and in disordered crystals, the thermal conductivity varies slower than T^{-1} due to the combined resistance of Umklapp processes which varies as T and of phonon-defect scattering processes which at high temperatures is more or less independent of temperature. In the extreme cases of highly disordered solids such as in amorphous or vitreous materials, the disorder determines the phonon mean free path which consequently becomes constant at high temperatures, and the thermal conductivity increases with temperature, being roughly proportional to the specific heat of the material.

The thermal conductivity of a composite material is affected by many factors such as the thermal conductivities of the components, the composition and structure of the composite, the manufacturing process, the heat treatment, and the direction of heat flow. Thus it is a highly complicated quantity and can only be roughly estimated by semiempirical relations.

Specific Heat

In nonmetallic solids the specific heat is solely due to lattice vibrations, and the lattice specific heat is thus the total specific heat. In metals and alloys, however, in addition to the lattice specific heat there is another component due to the contribution from the electrons, though the electronic component is relatively small except at low temperatures.

The lattice specific heat of a solid at moderate and high temperatures (above the Debye temperature) is nearly constant, increasing only slightly with temperature. The Dulong and Petit law states that the specific heat of all solid elements at room temperature is nearly the same and equals about 6.4 cal mol^{-1} K^{-1}. This law is closer to the truth for heavy elements with atomic weights greater than 38. For chemical compounds the Kopp-Neumann law states that the molar specific heat of a compound is equal to the sum of the atomic specific heats of its constituent elements. The Kopp-Neumann law can also be applied approximately to alloys.

At low temperatures the lattice specific heat decreases sharply with decreasing temperature, tending toward zero and varying as T^3 as the temperature approaches the absolute zero. This fact has been explained by the theory of Debye.

The electronic specific heat of a metal or alloy varies linearly with temperature. At high temperatures it is small compared with the lattice specific heat. At low temperatures, however, it becomes comparable with the lattice component, and can even exceed it at the lowest temperatures, at which, though, both components are rather small.

The specific heat of a solid which exhibits any kind of transitions such as phase, magnetic, order-disorder, etc. is anomalous and a peak occurs in the specific heat versus temperature curve in the vicinity of the transition. This is because an extra amount of heat must be supplied to the solid to bring about such a transition.

Heat of Fusion

The heat of fusion of a substance is the amount of heat required to change a given mass of a substance from the solid to the liquid state without change in temperature. For solutions of two or more components, the melting process normally occurs over a range of temperatures, and a distinction is made between the melting point, the point at which the first trace of liquid appears, and the freezing point, the highest temperature at which the last trace of solid disappears. The heat of fusion of pure elements or congruently melting compounds can be measured directly or can be rigorously calculated from the slopes of the liquidus and solidus.

The heat of fusion studies for the materials covered in this work are nonexistent. This may be either due to the melting process occuring over a wide range of temperature as in case of alloys or due to the tendency of the material to dissociate (Si_3N_4) and to soften (Pyroceram and Composites) at elevated temperature. In many cases the heat of fusion of a material may be calculated from the heats of fusion of the components, if the latter are available.

Thermal Linear Expansion

Most materials increase in size upon heating. The total thermal linear expansion from absolute zero to the melting point is about 2 to 3% for most solids. Thermal expansion arises from the fact that the thermal vibrations of the atoms or molecules about their equibrium positions in the crystalline lattice are anharmonic, that is, the forces acting between pairs of atoms or molecules are not proportional to their relative displacements. If the thermal vibrations were perfectly harmonic, as is generally assumed in the theory of the specific heat, there would be no thermal expansion, by either classical or quantum mechanical reasoning.

In this work the recommended values are given for both the percent thermal linear expansion, $\Delta L/L_0(\%)$, and the instantaneous coefficient of thermal linear expansion, α. These are defined as:

$$\frac{\Delta L}{L_0}(\%) = \frac{L_T - L_0}{L_0} \times 100$$

and

$$\alpha = \frac{d}{dT}\left(\frac{\Delta L}{L_0}\right) = \frac{1}{L_0}\frac{dL}{dT}$$

where L_T and L_0 are lengths of the material (or lattice parameters) at temperature T and at 293 K, respectively.

Grüneison found that the instantaneous coefficient of thermal expansion is approximately linearly proportional to the constant-volume specific heat. Thus at absolute zero temperature, the expansion coefficient is zero, as does the specific heat. As the temperature is increased from absolute zero, the expansion coefficient increases rather rapidly from zero and finally levels off to a nearly constant value.

The thermal expansion of a solid which exhibits a phase transition has a discontinuity in the vicinity of the transition, at which the expansion coefficient is momentarily infinite.

Thermal Diffusivity

Thermal diffusivity is a ratio of the thermal conductivity to the specific heat per unit volume. When heat flows through a material under nonsteady-state conditions, one may visualize the thermal diffusivity as an indication of the ratio of the amount of heat flowing out of a volume of the material to the amount of heat retained within the volume.

Since the range of variation of the thermal conductivity with temperature is small relative to that of the specific heat, the behavior of the thermal diffusivity is influenced more markedly by the behavior of the specific heat, and the thermal diffusivity versus temperature curve looks somewhat like an inversed specific heat curve. In other words, the thermal diffusivity of a material generally is very high at the lowest temperatures; as the temperature is increased the thermal diffusivity decreases rapidly and finally levels off at higher temperatures.

Thermal diffusivity of a material can be measured directly and can also be calculated from the values of thermal conductivity, specific heat, and density.

2.2. Data Evaluation and Generation of Recommended Values

Due to the difficulties in accurate measurement of thermophysical properties of solids and in adequate characterization of test specimens, the available experimental data from the world literature are in many cases widely divergent and subject to large uncertainty. It is, therefore, very important to critically evaluate and analyze the available data and to generate recommended values. The procedure involves critical evaluation of the validity and reliability of the data and related information, resolution and reconciliation of disagreements in conflicting data, correlation of data in terms of various controlling parameters, curve fitting with theoretical or empirical equations, comparison of results with theoretical predictions or with results derived from theoretical relationships or from generalized empirical correlations, etc. Besides critical evaluation and analysis of existing data, theoretical methods and semiempirical techniques are employed to fill data gaps and to synthesize fragmentary data so that the resulting recommended values are internally consistent and cover as wide a range of temperature as possible.

Considering the thermal conductivity, for example, in the critical evaluation of the validity and reliability of a particular set of thermal conductivity data, the temperature dependence of the data was examined and any unusual dependence or anomaly carefully investigated, the experimental technique was 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 was examined to see whether all the necessary corrections had been appropriately applied, and the estimation of uncertainties was checked to ensure that all the possible sources of errors had been considered.

Experimental data could probably be judged to be reliable only if all sources of systematic error had been 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 analytical model used to derive the value of thermal conductivity. These and other possible sources of errors are carefully considered in critical evaluation of experimental data. The uncertainty of a set of data depends, however, not only on the estimated error or 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 might 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.

If the information given by the author is entirely inadequate to make any value judgment, the data assessment becomes subjective. At times judgments might 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, the majority of unreliable and erroneous data were eliminated. The remaining data were then subjected to further analysis, correlation, and synthesis. If a number of data sets are available for a well-characterized material, correlation of the data in terms of the affecting parameters could be made. Applying the principle of corresponding states, reduced property values might be correlated with reduced temperature and other reduced parameters. Furthermore, by using theoretical relationships, several properties of a given material could be cross-correlated to check for internal consistency of the data or for data estimation.

Depending upon the level of confidence the data analyst has placed on the values and upon the degree of adequacy of characterization of the material for which the values are generated, the reported values are designated as "recommended values" or "provisional values". In this work all the values generated are properly designated, and the accuracy or uncertainty of the values is clearly stated.

2.3. Presentation of Data

In each of the subsections of Section 3, the property data and information are presented in the following order: (1) discussion text, (2) table of recommended values, (3) figure presenting recommended curve(s) and experimental data, (4) table giving experimental information, and (5) table of experimental data.

In the discussion text, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties of the recommended values are stated.

The values given in the table are designated either as recommended or provisional values depending upon the level of confidence placed on the values and, hence, upon the uncertainty assigned. The ranges of uncertainties of recommended and provisional values for specific heat, percent thermal linear expansion, and density are $\leq \pm 5\%$ and $> \pm 5\%$, respectively. Those for thermal conductivity, thermal diffusivity, and instantaneous coefficient of thermal linear expansion are $< \pm 15\%$ and $\geq \pm 15\%$, respectively. In the tables the third significant figure is generally given for the property values; this, however, is only for internal comparison and for tabular smoothness and should not be considered indicative of the degree of accuracy or uncertainty. The uncertainty of the values is always explicitly stated.

In the figure presenting recommended curve(s) and experimental data, the curve numbers correspond to those listed in the accompanying table on measurement information and table of experimental data. When several sets of data are too close together to be distinguishable, some of the data sets, though listed in the tables, are omitted from the figure for the sake of clarity.

The table containing measurement information gives for each set of experimental data the following information: the curve number, the publication reference number, author's name, year of publication, experimental method used for the measurement, temperature range covered by the data, name and specimen designation, composition, specification and characterization of the specimen and information on measurement condition, which are contained in the original paper. In these tables the code designations used for the experimental methods for property measurements are listed below.

For thermal conductivity measurements:

C	Comparative method
E	Direct electrical heating method
L	Longitudinal heat flow method
P	Periodic or transient heat flow method
R	Radial heat flow method

For specific heat measurements:

A	Adiabatic method
DSC	Differential scanning calorimeter
DTA	Differential thermal analysis
I	Ice calorimeter

For thermal linear expansion measurements:

I	Interferometer method
L	Dilatometer method
X	X-ray diffraction method
V	Variable-induction transformer

In the table of experimental data, all the available data shown or not shown in the figure are tabulated.

3. THERMOPHYSICAL PROPERTIES OF SELECTED MATERIALS

3.1. Aluminum Alloy 2024

Aluminum Alloy 2024, formerly known as Aluminum Alloy 24S, is a wrought alloy with copper as the principal alloying element. Its nominal composition [1] is (by weight) 4.5% Cu, 1.5% Mg, 0.6% Mn, and balance Al. It is perhaps the best known and most widely used aircraft alloy.

Some physical [2] and mechanical properties [3] of this alloy are as follows: solidus temperature, 775 K; liquidus temperature, 911 K; specific gravity, 2.77; tensile (ultimate) strength, 19.0-51.0 kg/mm^2; Brinell hardness number (500 kg load, 10 mm ball), 47-130. The mechanical properties vary over a wide range due to differences in applied heat treatments.

This alloy requires solution heat-treatment to obtain optimum properties. In the well heat-treated condition, the mechanical properties of this alloy are similar to, and sometimes exceed, those of mild steel. A particular heat treatment is specified by a letter "T" after the 2024 designation, followed by one of the numerals from 1 to 10, such as Aluminum Alloy 2024-T4. Briefly, these heat treatments are as follows [3]:

T1 - cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.

T2 - annealed (cast products only).

T3 - solution heat-treated and then cold worked.

T4 - solution heat-treated and naturally aged to a substantially stable condition.

T5 - cooled from an elevated temperature shaping process and then artificially aged.

T6 - solution heat-treated and then artificially aged.

T7 - solution heat-treated and then stabilized.

T8 - solution heat-treated, cold worked, and then artificially aged.

T9 - solution heat-treated, artificially aged, and then cold worked.

T10 - cooled from an elevated temperature shaping process, artificially aged, and then cold worked.

Each of these treatments [1] has a unique effect on the mechanical properties of the alloy. The designations, however, do not define the time and temperature of the heat treatments, and the details of the practice may be varied as desired or convenient if the end result as expressed by specified mechanical properties is unchanged. Should a variation of a basic operation be applied to the alloy, resulting in different characteristics, other digits are added to the basic designation, such as Aluminum Alloy 2024-T81,

Aluminum Alloy 2024-T851, etc. The second and third numerals in the heat treatment designation are arbitrary, generally having no logical significance. In the earlier designations the heat treatments were not catalogued as above. An alloy might be designated as Aluminum Alloy 24S-T, where the T only means that the alloy was tempered to a stable condition.

This alloy does not have as good corrosion resistance properties as most other aluminum alloys and under certain conditions may be subjected to intergrannular corrosion. Therefore, it is widely used in the clad, anodized, or alodined states. In the clad [3] state the alloy is protected from corrosion by a thin surface of a pure metal or alloy with a higher solution potential. The term alclad is used when the cladding material is pure aluminum. The anodizing [1] process involves forming a conversion coating on the metal surface by anodic oxidation. Alodining is also a process of forming a conversion coating, with the coating being some other type of material such as a phosphate or chromate. These processes greatly increase the resistance of Aluminum Alloy 2024 to corrosion.

a. Thermal Conductivity

There are eighteen sets of data available, all measured below 730 K, and four of these reach down to low temperatures. Most of the measurements are for specimens designated either as 2024-T4 or 2024-T351. The available experimental data are tabulated in Table 1-3 and shown partially in Figure 1-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 1-2. One data set (curve 18) for a Duraluminum specimen is also included in the compilation to assist in the data analysis at low temperatures.

The recommended values tabulated in Table 1-1 and shown in Figure 1-1 are for both as-received and annealed alloy samples. Those for as-received alloy are for an as-received alloy 2024-T4 with a residual electrical resistivity of 3.2 $\mu\Omega$ cm. The recommended values at cryogenic temperatures are based on the data of Powell et al. [4] (curve 4). At temperatures between 120 and 600 K, the recommended values are based on the data of Lucks et al. [6] (curve 1). Above 600 K, the data of Lucks et al. [6] (curve 2) and of Evans [7] (curves 13 and 14) decrease sharply as the temperature increases. These authors employed the comparative technique using Armco iron or lead as standards in their thermal conductivity measurements. Since Armco iron has a strong but negative temperature dependence at high temperatures and lead melts at 600.652 K, the results of these authors above 600 K are questionable. Hence, the recommended

values above 600 K do not follow the experimental data, but are extended to the solidus point according to the general trend of the temperature dependence established for the thermal conductivity of Al + Cu and Al + Mg binary alloys [8]. In the molten state, the recommended values were calculated from the equation:

$$\frac{1}{k} = \sum_i \frac{x_i}{k_i}$$

where x_i is the atomic fraction, and k_i is the thermal conductivity of the ith constituent element of the alloy. The error of the calculated values should be small since x_{Al} is much larger than the other x_i's.

If the alloy is heated at an elevated temperature (above 400 K) for a long period of time, the thermal conductivity will increase remarkably. The recommended values for the thermal conductivity of such annealed alloy having residual electrical resistivity of about 0.70 $\mu\Omega$ cm are also presented. These values depart from those for the as-received alloy below about 600 K and follow the data of Lucks et al. (curve 2) to 150 K. Above 600 K the values follow the general trend of the temperature dependence of thermal conductivity established for Al + Cu and Al + Mg binary alloys [8].

The uncertainty of the recommended values is believed to be within ± 10% at temperatures below 200 K, ± 5% from 200 to 600 K, ± 8% from 600 K to the solidus point, and within ± 10% and -16% in the liquid region.

TABLE 1-1. RECOMMENDED THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	
	As received	Annealed
4	0.0316	
7	0.0566	
10	0.0822	
15	0.126	
20	0.169	
25	0.210	
30	0.251	
40	0.326	
50	0.394	
60	0.456	
70	0.510	
80	0.560	
90	0.608	
100	0.650	
150	0.842	1.55
200	1.01	1.63
250	1.14	1.70
273.15	1.19	1.73
293	1.23	1.76
300	1.24	1.77
350	1.33	1.82
400	1.41	1.86
450	1.60	1.88
500	1.77	1.89
550	1.83	1.88
600	1.85	1.86
650	1.83	1.83
700	1.80	1.80
750	1.76	1.76
775†	1.73	1.73
911†	0.872	0.872
950	0.888	0.888
1000	0.905	0.905
1100	0.937	0.937

† Melting Range 775–911 K.

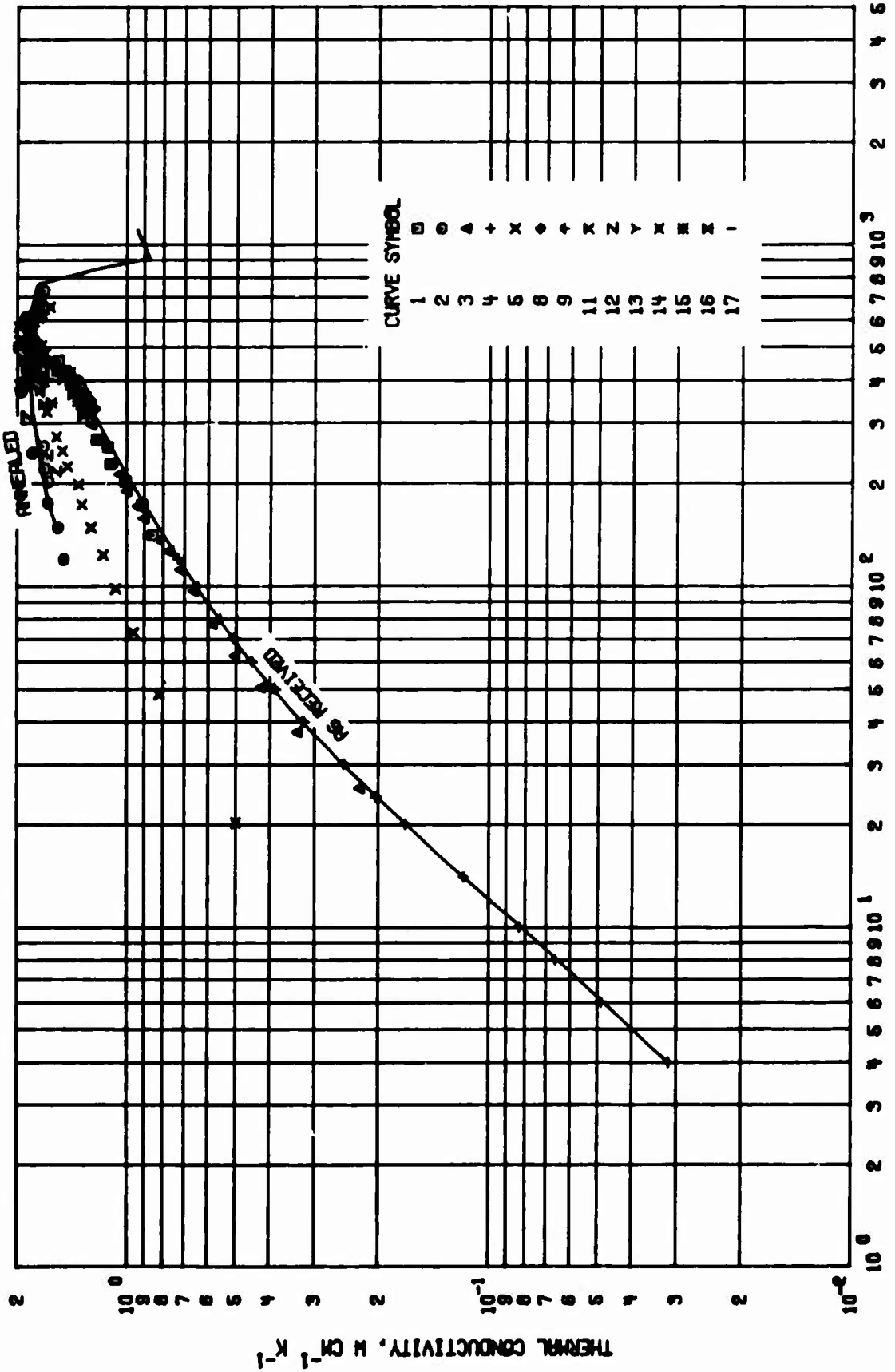

FIGURE 1-1. THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 .

TABLE 1-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Al	Cu	Fe	Mg	Mn	Ni	Composition (continued), Specifications, and Remarks
1	6	Lucks, C.F., Thompson, H.B., Smith, A.R., Curry, F.P., Deem, H.W., and Bing, G.F.	1951	C	140-552	24S-T4		4.5		1.5	0.6		As received; Armco iron used as comparative material.
2	6	Lucks, C.F., et al.	1951	C	119-731			4.5		1.5	0.6		The above specimen heated to 300 C.
3	9	Powers, R.W., Ziegler, J.B., and Johnston, H.L.	1951	L	26-296	24S		4.49	0.34	1.47	0.66		0.13 Si, 0.02 Ti, 0.01 Cr, and 0.01 Zn; as reported by Alcoa; reported error <2.0%.
4	4	Powell, R.L., Hall, W.J., and Roder, H.M.	1960	L	4.0-120	2024-T4		4.58	0.1	1.7	0.1		0.1 each Ga, Si, V, Zn, 0.05 Cr, 0.01 each Sn, Ti, and 0.001 each Ca, Ag, Zr; grain size 0.08 mm by 0.052 mm (longitudinal) and 0.048 mm (transverse); solution heat-treated; electrical resistivity 3.2, 3.2, 3.3, 3.5, 4.2, 5.5, and 6.1 μΩ cm at 4, 10, 40, 60, 100, 200, and 300 K, respectively; smoothed values reported.
5	10	Rhodes, B.L., Moeller, C.E., and Sauer, H.J.	1965	L	20-573	Al-2014-T6	92.61	4.57	0.44	0.45	0.93		0.88 Si, 0.06 Zr, 0.04 Ti, and 0.02 Cr.
6*	11	Garth, R.C. and Sailer, V.L.	1949	L	298.2	24S-T4							3.500 in. diameter by 4.000 in. high.
7*	11	Garth, R.C. and Sailer, V.L.	1949	L	298.2	24S-O							The above specimen annealed.
8	12, 13	Williams, D.R. and Blum, H.A.	1966	L	329-419	Al 2024-T351	Bal.	4.5		1.5	0.6		Nominal composition; specimen ~0.4 cm in diameter and ~0.37 meters long; thermal conductivity values averaged over 2 runs measured by W&R method.
9	12, 13	Williams, D.R. and Blum, H.A.	1966	L	329-417	Al 2024-T351	Bal.	4.5		1.5	0.6		Similar to the above specimen except measured by a "no-loss" method.
10*	12, 13	Williams, D.R. and Blum, H.A.	1966	C	329-417	Al 2024-T351	Bal.	4.5		1.5	0.6		Similar to the above specimen except measured by comparative method and Armco iron used as comparative material.
11	14	Smuda, P.A., Fletcher, L.S., and Gyorog, D.A.	1967	L	314-450			4.5		1.5	0.6		Nominal composition; two cylinders 1.625 in. diameter by 4.50 in. long joined by a central heater; as received.
12	14	Smuda, P.A., et al.	1967	L	215-523			4.5		1.5	0.6		The above specimen annealed.
13	7	Evans, J.E., Jr.	1951	C	384-634	Al alloy 24S	Bal.	4.5		1.5	0.6		Nominal composition; NBS M.P. standard lead used as comparative material.
14	7	Evans, J.E., Jr.	1951	C	382-655	Al alloy 24S	Bal.	4.5		1.5	0.6		The above specimen; second run.
15	15	Clausing, A.M.	1963	L	338-427	2024-T4		3.8-4.9	0.50	1.2-1.8	0.30-0.9		0.50 Si, 0.25 Zn, 0.10 Cr, and 0.15 others (nominal composition); cylindrical specimen.

* Not shown in figure.

TABLE 1-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Al	Cu	Fe	Mg	Mn	Ni	Composition (continued), Specifications, and Remarks
16	15	Clausing, A.M.	1963	L	344, 419	2024 T4		3.8-4.9	0.50	1.2-1.8	0.30-0.9		The above specimen annealed at 467 K.
17	16	Abbott, R.E.	1967	L	311, 319	2024 T4		3.8-4.9	0.50	1.2-1.8	0.30-0.9		0.50 Si, 0.25 Zn, 0.10 Cr, and 0.15 others (nominal composition); 1.375 in. diameter by 2.5 in. long; machined.
18*	5	Zavaritskii, N.V., and Zeldovich, A.G.	1956	L	3.3-81	Duraluminum D16		4.4		1.5	0.6		7.5 x 6.5 mm tube; reported error < 5.0%.

* Not shown in figure.

TABLE 1-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

T	k
CURVE 1	
140.8	0.854
172.9	0.912
202.5	1.008
227.4	1.109
229.3	1.109
241.1	1.125
254.7	1.125
267.9	1.205
349.0	1.318
354.0	1.347
361.8	1.360
366.9	1.393
367.8	1.389
374.5	1.351
381.7	1.339
383.6	1.377
387.1	1.372
391.5	1.427
392.1	1.423
393.7	1.410
395.5	1.389
400.4	1.385
402.2	1.423
408.3	1.423
414.1	1.448
414.7	1.381
417.0	1.402
417.4	1.406
426.2	1.473
427.5	1.435
434.6	1.485
435.8	1.469
437.4	1.481
439.9	1.556
451.4	1.607
455.4	1.586
456.8	1.540
457.4	1.699
458.6	1.703
458.8	1.548
460.3	1.724
473.0	1.745
480.6	1.766
482.3	1.732
489.8	1.732

T	k
CURVE 1 (cont.)	
507.7	1.774
521.3	1.791
551.9	1.845
CURVE 2	
119.2	1.485
147.8	1.544
175.0	1.648
201.4	1.644
220.2	1.686
232.5	1.711
244.3	1.816
256.2	1.699
358.2	1.812
370.4	1.950
382.9	1.745
396.0	1.782
396.6	1.912
413.1	1.900
429.6	1.887
446.4	1.854
510.2	1.933
543.9	1.946
569.6	1.879
578.3	1.858
589.9	1.879
612.2	1.891
613.7	1.837
634.9	1.866
656.2	1.761
681.7	1.732
702.0	1.745
730.8	1.690
CURVE 3	
25.43	0.226
37.24	0.335
50.26	0.427
62.28	0.506
77.28	0.586
96.41	0.661
111.40	0.720
126.16	0.774

T	k
CURVE 3 (cont.)	
136.01	0.824
141.17	0.832
157.16	0.904
171.06	0.937
189.04	1.004
212.10	1.050
230.38	1.096
248.12	1.146
267.50	1.197
286.14	1.226
296.17	1.247
CURVE 4	
4	0.0315
6	0.0489
8	0.0661
10	0.0832
14	0.117
20	0.170
24	0.203
30	0.249
40	0.322
50	0.390
60	0.452
70	0.508
80	0.557
100	0.645
120	0.727
CURVE 5	
20.2	0.50
48.2	0.82
73.2	0.96
98.2	1.07
123.2	1.16
148.2	1.25
173.2	1.32
198.2	1.35
223.2	1.45
248.2	1.50
273.2	1.56
323.2	1.66
373.2	1.79

T	k
CURVE 5 (cont.)	
423.1	1.81
473.2	1.88
523.2	1.94
573.2	1.98
CURVE 6*	
298.2	1.35
CURVE 7*	
298.2	1.83
CURVE 8	
328.7	1.22
347.1	1.25
364.9	1.29
382.5	1.32
400.0	1.35
416.8	1.39
CURVE 9	
328.7	1.28
347.1	1.29
364.9	1.34
382.5	1.43
400.0	1.37
416.8	1.42
CURVE 10*	
328.7	1.20
347.1	1.22
364.9	1.27
382.5	1.29
400.0	1.33
416.8	1.40
CURVE 11	
314.4	1.314
321.0	1.338
335.2	1.319

T	k
CURVE 11 (cont.)	
347.8	1.334
362.8	1.404
387.9	1.428
403.3	1.497
418.6	1.504
432.9	1.552
449.5	1.630
CURVE 12	
215.4	1.565
240.3	1.658
313.5	1.885
339.8	1.693
354.8	1.687
369.9	1.755
378.8	1.729
396.9	1.765
413.0	1.819
440.5	1.843
460.4	1.911
484.8	1.907
501.8	1.980
523.4	1.925
CURVE 13	
384.3	1.69
387.6	1.64
388.7	1.70
392.6	1.64
395.4	1.67
398.2	1.63
401.5	1.64
402.6	1.61
444.3	1.71
453.2	1.71
464.8	1.73
468.7	1.70
471.5	1.71
479.8	1.73
490.4	1.68
500.9	1.68
517.0	1.78
528.7	1.85

T	k
CURVE 13 (cont.)	
535.4	1.80
542.6	1.85
549.3	1.83
555.4	1.84
562.6	1.80
575.4	1.80
578.2	1.80
580.9	1.80
580.9	1.77
593.7	1.78
597.6	1.78
610.9	1.72
614.3	1.75
615.9	1.72
627.6	1.69
633.7	1.72
633.7	1.69
CURVE 14	
352.0	1.87
387.6	1.97
392.6	1.96
398.2	1.82
433.7	1.83
441.5	1.87
449.3	1.83
458.2	1.75
475.4	1.77
489.3	1.85
496.5	1.80
505.4	1.72
512.0	1.90
522.6	1.97
530.4	2.02
542.6	2.08
554.3	2.02
567.6	2.02
592.0	1.80
603.2	1.70
608.2	1.75
617.6	1.80
617.6	1.75
624.3	1.67
639.8	1.69
654.8	1.63

* Not shown in figure.

TABLE 1-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 (continued)

T	k
CURVE 15	
338	1.333
343	1.263
344	1.296
346	1.362
349	1.314
421	1.424
421	1.450
421	1.473
427	1.532
427	1.565
CURVE 16	
344	1.615
419	1.705
CURVE 17	
311	1.25
319	1.27
CURVE 18*	
3.28	0.0490
3.90	0.0619
4.22	0.0703
5.20	0.0879
5.95	0.0971
6.22	0.116
8.0	0.137
10.4	0.172
12.4	0.209
16.2	0.259
19.4	0.293
22.0	0.305
24.5	0.377
30.5	0.464
39.0	0.586
50.5	0.749
63.5	0.837
81.0	0.879

* Not shown in figure.

b. Specific Heat

There are 20 sets of experimental data available for the specific heat of Aluminum Alloy 2024. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 1-5. The experimental data are tabulated in Table 1-6 and partially shown in Figure 1-2.

Most of the measurements were carried out within the temperature range 75-700 K. The recommended values shown in Figure 1-2 and tabulated in Table 1-4 agree well with most of the measurements reported in the experimental data table with the exception of the data of Makarounis and Jenkins [17] (curve 3) which are about 10% higher than the recommended values. The data of Suzuki [18] (curve 11) show a sudden increase above 600 K. Suzuki [18] (curves 13-20) also found anomalies near 473 and 550 K for the specimens aged at various temperatures and times. Specific heat values for this alloy calculated using the Kopp-Neumann mixing rule agree well at temperatures below 500 K and about 4-10% lower at higher temperatures. The specific heat of pure aluminum is about 5-15% lower than that of this alloy.

The melting range for this alloy is 775-911 K. No experimental data for the specific heat of this alloy in the liquid state were located in the literature. Considering the agreement of the specific heat values calculated using the Kopp-Neumann mixing rule with the experimental data for the solid alloy, this mixing rule should well be applied to the specific heat values for the molten alloy. The specific heat values for the molten alloy are thus calculated. In the calculations the specific heat values for the constituent elements are taken from Hultgren et al. [19]. The values for the molten pure aluminum are about 4% lower than the tabulated values for the molten alloy.

The uncertainty of the recommended values for the solid alloy is believed to be within ± 5%. The values for the molten alloy are provisional and their uncertainty is within ± 10%.

TABLE 1-4. RECOMMENDED SPECIFIC HEAT OF ALUMINUM ALLOY 2024

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
100	0.113
150	0.158
200	0.188
250	0.200
273.15	0.205
293	0.208
300	0.209
350	0.216
400	0.221
450	0.226
500	0.233
550	0.241
600	0.249
650	0.258
700	0.269
750	0.280
775†	0.286
911†	0.300‡
1000	0.300‡
1100	0.300‡
1200	0.300‡

† Melting region 775-911 K.
‡ Provisional value.

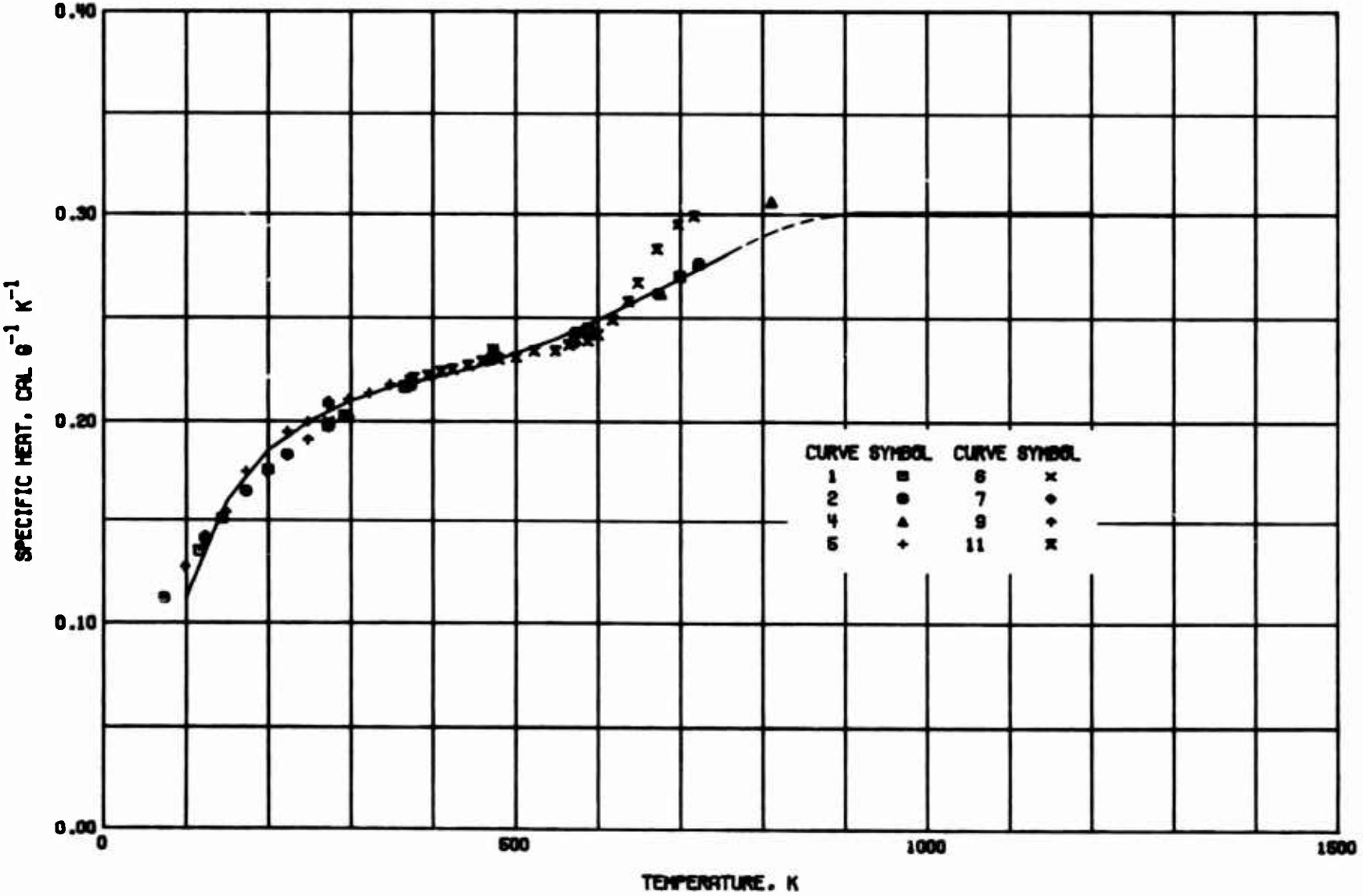

FIGURE 1-2. SPECIFIC HEAT OF ALUMINUM ALLOY 2024 .

TABLE 1-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	20	Lucks, C.F. and Deem, H.W.	1958		116-700		Specimen with nominal composition from Alcoa; measurements using ice calorimeter.
2	21	Lucks, C.F., Matolich, J., and Vanvelzor, J.A.	1954		73-723		Specimen with nominal composition.
3*	17	Makarou[illegible], O. and Jenkins, R.J.	1962		97-468		Specimen with nominal composition; Hanovia liquid platinum was applied on both surfaces of the specimen for good conduction; front surface was painted for opaqueness.
4	22	Schattyn, J.M.	1964		272-811		No details given.
5	23	Makaroumis, O.	1966		173-373		Values calculated from spectral properties of its surface and irradiance energy.
6	24	Dietz, J.L.	1956		273-573		Data of Battelle Memorial Institute.
7	24	Dietz, J.L.	1956		273-573		Data of Battelle Memorial Institute.
8*	25	Zoller, P. and Dillinger, J.R.	1969		1.6-4		Specimen from Alcoa, a slight up-turn in C_p/T values below 2 K obeserved; data is represented by $C = \gamma T + BT^3$ ($\gamma = 1.390$ m J mole K^{-2}, $B = 0.0287$ m J mole^{-1} K^{-4}), molecular weight = 27.780.
9	26	Makaroumis, O.	1967		98-298		Values calculated from spectral properties of its surface and irradiance energy.
10*	26	Makaroumis, O.	1967		90-298		Data of Battelle Memorial Institute (after 6145, part III).
11	18	Suzuki, T.	1949				4.31 Cu, 0.29 Si, 0.14 Fe, and Al balance; specimen was melted in high frequency induction furnace, hot worked and recrystallized by annealing in vacuum at 773 K for several hr.
12*	18	Suzuki, T.	1949		373-504		Similar to the above specimen except specimen quenched from 793 K in water at room temperature.
13*	18	Suzuki, T.	1949		373-606		Similar to the above specimen except the specimen aged at 293 K for 30 days.
14*	18	Suzuki, T.	1949		373-728		Similar to the above specimen except the specimen aged at 383 K for 23.5 hr.
15*	18	Suzuki, T.	1949		373-697		Similar to the above specimen except the specimen quenched from 793 K and aged at 423 K for 1 hr.
16*	18	Suzuki, T.	1949		373-607		Similar to the above specimen except the specimen aged for 1.5 hr.
17*	18	Suzuki, T.	1949		373-601		Similar to the above specimen except the specimen aged for 2 hr.
18*	18	Suzuki, T.	1949		373-609		Similar to the above specimen except the specimen aged for 5 hr.
19*	18	Suzuki, T.	1949		379-603		Similar to the above specimen except the specimen aged for 10 hr.
20*	18	Suzuki, T.	1949		378-692		Similar to the above specimen except the specimen aged for 22.5 hr.

* Not shown in figure.

TABLE 1-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024

[Temperature, T, K; Specific Heat, C_p, cal · K^{-1} g^{-1}]

T	C_p
CURVE 1	
116	0.135
144	0.151
200	0.176
293	0.203
366	0.217
477	0.231
589	0.245
700	0.270
CURVE 2	
73	0.112
123	0.141
173	0.165
223	0.184
273	0.198
373	0.218
473	0.231
573	0.243
673	0.262
723	0.276
CURVE 3*	
97	0.103
98	0.106
103	0.111
105	0.113
111	0.124
115	0.128
123	0.140
129	0.145
133	0.148
135	0.157
139	0.160
163	0.169
163	0.172
165	0.175
169	0.178
169	0.198
177	0.179
185	0.186
190	0.187
214	0.193
215	0.202
217	0.198
217	0.200
CURVE 3 (cont.)*	
217	0.208
215	0.211
217	0.213
221	0.216
281	0.220
295	0.218
299	0.222
315	0.224
331	0.226
334	0.229
343	0.229
349	0.234
375	0.233
393	0.236
399	0.235
411	0.238
435	0.238
439	0.234
440	0.237
443	0.241
445	0.235
455	0.242
466	0.242
468	0.236
CURVE 4	
272	0.198
372	0.218
466	0.230
572	0.243
677	0.262
722	0.276
811	0.306
CURVE 5	
173	0.175
223	0.195
248	0.200
273	0.208
298	0.211
323	0.214
348	0.218
373	0.220
CURVE 5	
273	0.200
373	0.220
473	0.235
573	0.240
CURVE 7	
273	0.210
373	0.220
473	0.235
573	0.238
CURVE 8*	
1.6	0.155
2	0.200
3	0.328
4	0.491
CURVE 9	
98	0.127
123	0.142
148	0.154
173	0.165
198	0.174
223	0.183
248	0.191
273	0.197
298	0.202
CURVE 10*	
90	0.097
93	0.103
98	0.110
103	0.116
108	0.122
113	0.127
118	0.134
123	0.136
133	0.145
148	0.158
173	0.172
198	0.186
223	0.196
248	0.201
CURVE 10 (cont.)*	
273	0.206
298	0.210
CURVE 11	
377	0.221
394	0.222
410	0.224
424	0.225
443	0.227
460	0.229
480	0.230
501	0.231
523	0.234
549	0.234
565	0.237
588	0.239
600	0.242
618	0.249
637	0.258
649	0.267
672	0.283
697	0.295
717	0.299
CURVE 12*	
373	0.220
383	0.221
399	0.230
407	0.230
420	0.227
431	0.231
441	0.233
451	0.232
460	0.229
471	0.229
483	0.229
494	0.227
504	0.224
CURVE 13*	
373	0.227
379	0.229
392	0.229
402	0.234
CURVE 13 (cont.)*	
416	0.239
431	0.238
448	0.237
468	0.239
487	0.235
495	0.233
512	0.230
522	0.228
532	0.221
539	0.211
546	0.200
555	0.186
563	0.174
570	0.176
575	0.190
582	0.209
586	0.222
597	0.240
606	0.250
CURVE 14*	
373	0.224
389	0.228
400	0.230
413	0.238
421	0.244
427	0.249
436	0.260
442	0.265
452	0.270
456	0.270
461	0.262
469	0.252
476	0.244
487	0.241
496	0.235
508	0.227
518	0.217
526	0.203
538	0.180
567	0.192
572	0.207
582	0.225
589	0.236
599	0.247
611	0.262
CURVE 14 (cont.)*	
624	0.271
648	0.277
666	0.274
677	0.269
687	0.267
692	0.279
700	0.290
707	0.298
728	0.313
CURVE 15*	
373	0.219
383	0.224
393	0.229
404	0.231
413	0.229
425	0.228
429	0.230
438	0.233
448	0.236
458	0.232
468	0.230
482	0.230
493	0.230
507	0.223
518	0.209
523	0.190
530	0.174
535	0.160
543	0.144
548	0.142
554	0.151
566	0.170
576	0.188
584	0.203
590	0.219
599	0.237
609	0.248
623	0.263
643	0.272
660	0.273
680	0.271
697	0.265

* Not shown in figure.

TABLE 1-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024 (continued)

T	C_p
CURVE 16*	
373	0.220
383	0.224
393	0.224
406	0.227
418	0.229
433	0.229
444	0.229
454	0.232
463	0.240
474	0.242
484	0.237
490	0.232
496	0.228
509	0.218
519	0.200
529	0.185
537	0.170
549	0.157
556	0.167
566	0.183
575	0.204
583	0.223
592	0.239
607	0.248
CURVE 17*	
373	0.222
381	0.222
389	0.223
402	0.223
416	0.223
433	0.225
448	0.233
459	0.233
467	0.241
479	0.247
488	0.242
497	0.238
507	0.232
517	0.223
524	0.209
534	0.191
540	0.174
550	0.159
558	0.171
569	0.192
578	0.213
587	0.228
601	0.240
CURVE 18*	
373	0.220
387	0.222
402	0.223
411	0.225
424	0.224
435	0.224
443	0.232
454	0.239
464	0.247
472	0.261
478	0.266
483	0.249
488	0.236
500	0.232
512	0.228
522	0.213
534	0.191
542	0.168
554	0.155
564	0.169
574	0.192
582	0.216
594	0.233
609	0.244
CURVE 19*	
379	0.220
388	0.222
397	0.224
413	0.224
433	0.231
447	0.236
459	0.248
463	0.260
472	0.273
477	0.263
486	0.247
498	0.237
508	0.225
519	0.215
527	0.196
536	0.172
545	0.152
558	0.167
571	0.198
583	0.220
603	0.235
CURVE 20*	
378	0.222
388	0.224
398	0.225
413	0.225
427	0.231
440	0.244
449	0.261
459	0.274
475	0.270
487	0.255
499	0.241
512	0.231
522	0.209
531	0.189
542	0.164
556	0.164
567	0.191
578	0.215
592	0.240
608	0.257
620	0.266
625	0.266
646	0.275
663	0.277
677	0.272
692	0.271

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of Aluminum Alloy 2024 were located in the literature. This alloy contains about 93 percent of Aluminum, and its specific heat and thermal linear expansion are very close to those of pure Aluminum. Therefore, the heat of fusion of 96 ± 2 cal g^{-1} of pure Aluminum reported by Hultgren et al. [19] may be adopted as the heat of fusion of Aluminum Alloy 2024.

d. Thermal Linear Expansion

There are 18 sets of experimental data available for the thermal linear expansion of Aluminum Alloy 2024. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 1-8. The experimental data are tabulated in Table 1-9 and partially shown in Figure 1-3.

Most of the measurements within the temperature range 293-650 K are for an alloy of type 24S, which is the previous designation for type Al-2024. There is one or two data sets for each alloy of the types T-3, T-4, and T-6. The recommended values shown in Figure 1-3 and tabulated in Table 1-7 agree well with all measurements. Since the agreement between various investigations is fairly good, it can be concluded that various heat treatments do not have any significant effect on this property. It is worth noting that the thermal expansion values for this alloy are very close to those for pure aluminum which is primarily due to the high aluminum content (94 wt.%) of this alloy. The uncertainty of the recommended values is within ± 5%. The recommended values above 700 K were extrapolated according to the general trend of the expansion curve for this alloy between 500 and 700 K and that for pure aluminum.

The values of the instantaneous coefficient of thermal linear expansion, α, are obtained by differentiation of empirical equations which are used to fit the recommended thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is within ± 10%.

The melting range for this alloy is 775-911 K. No experimental data for the thermal expansion or density of this alloy in the molten state were located in the literature. The values for the density given in Table 1-7 were calculated from the Kopp-Neumann mixing rule using the density values of constituent elements from TPRC Report 16 [27]. These density values are provisional and are considered accurate to within ± 7%.

TABLE 1-7 RECOMMENDED THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α	T	$\Delta L/L_0$	α
20	-0.428	8.7	273.15	-0.042	20.8
25	-0.420	8.8	293	0.000	21.6
30	-0.414	9.2	300	0.014	21.9
40	-0.407	9.8	350	0.127	23.7
50	-0.400	10.4	400	0.249	25.1
60	-0.390	10.9	450	0.378	26.4
70	-0.378	11.4	500	0.515	27.5
80	-0.367	12.0	550	0.655	28.4
90	-0.354	12.5	600	0.798	29.1
100	-0.340	13.1	650	0.946	29.7
150	-0.268	15.6	700	1.095	30.0
200	-0.184	17.9	750	1.245	30.1
250	-0.090	20.0	775†	1.325	30.1

† Solidus Temperature.

PROVISIONAL DENSITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Density, d, g cm^{-3}]

T	d
911†	2.446
1000	2.428
1100	2.408
1200	2.388
1300	2.368
1400	2.348
1500	2.328

† Liquidus Temperature.

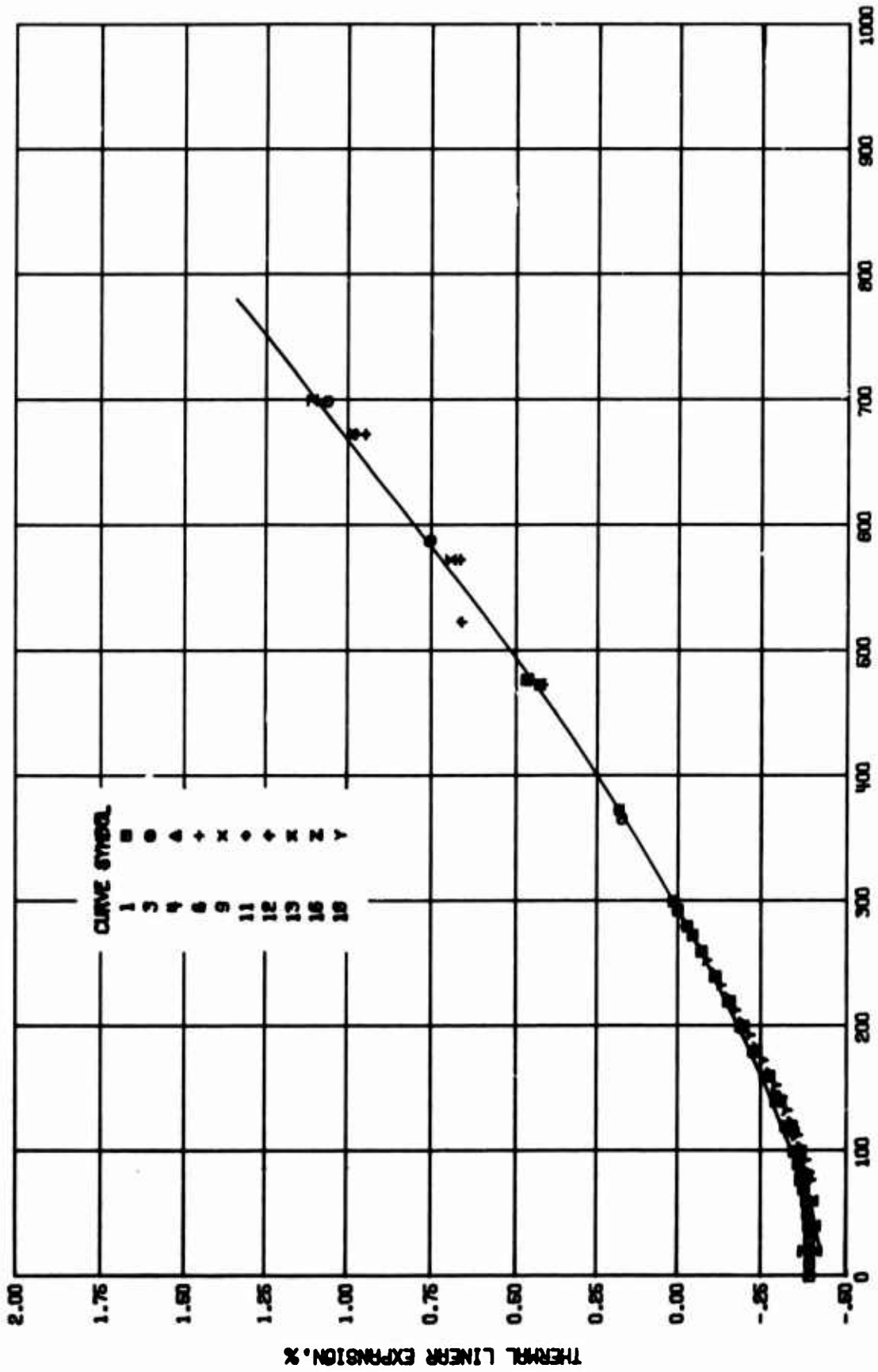

FIGURE 1-3. THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024.

TABLE 1-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Al	Cu	Fe	Si	Mn	Mg	Ni	Composition (continued), Specifications, and Remarks
1	28	Clark, A. F.	1968	L	0-300		93.6	4.1	0.2	0.1	0.5	1.4		0.1 Zn; specimen machined to 20.32 cm long, 0.64 cm sq; Rockwell hardness B-25.
2*	28	Clark, A. F.	1968	L	0-300		Bal.	4.1	0.2					0.1 Zn; similar to the above specimen; Rockwell hardness B-83.
3	20	Lucks, C. F. and Deem, H. W.	1958	L	116-699	T4								0.375 in. diameter, 3 in. long; material from Aluminum Co. of America.
4	29	Arp, V., Wilson, J. H., Winrich, L., and Sikora, P.	1962	L	20-293		92.6	4.1	1.4	0.5	0.2	0.1	0.1	0.1 Zn; hardness R_B83, A.S.M. condition T-86.
5*	30	Valentich, J.	1965	L	106-516									No details given; zero-point correction is -0.1%.
6	31	Hidnert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10	0.67	1.41	0.01	0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; specimen solution heat treated 1 hr at 766 K, quenched in water and aged to room temperature; expansion measured with increasing temperature.
7*	31	Hidnert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10				0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
8*	31	Hidnert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10				0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; similar to the above specimen, then aged 100 hr at 644 K; expansion measured with increasing temperature.
9	31	Hidnert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10				0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
10*	31	Hidnert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10				0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; similar to the above specimen except aged 500 hr at 700 K; expansion measured with increasing temperature.
11	31	Hidnert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10				0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
12	32	Willey, L. A. and Fink, W. L.	1945	I	293-573	Alcoa 24S		4.5	1.5	0.6				Sheet wrought form cold-rolled to 0.064 in. thick; tested in as-rolled condition.
13	32	Willey, L. A. and Fink, W. L.	1945	I	293-573	Alcoa 24S	Bal.	4.5			0.6	1.5		Similar to the above specimen except annealed to 623 K.
14*	32	Willey, L. A. and Fink, W. L.	1945	I	213-373	Alcoa 24S	Bal.	4.5						Similar to the above specimen except heat-treated and aged according to standard practice.
15*	33	Hertz, J.	1962		77-300	T-3								No details given; zero-point correction is 0.014%.

* Not shown in figure.

TABLE 1-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024 (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Al	Cu	Fe	Si	Mn	Mg	Ni	Composition (continued), Specifications, and Remarks
16	34	Technology Utilization Div., NASA	1969		20-700	Al 2024-T6								Specimen prepared in accordance with Rocketdyne Materials and Processes Specifications or equivalent (government or ASTM); dilatometric measurements.
17*	34	Technology Utilization Div., NASA	1969		77-755	Al 2024-T4								Specimen prepared using the above specifications.
18	35	Belov, A.K.	1968	L	293-77									No details given.

* Not shown in figure.

TABLE 1-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1	
0	-0.392
10	-0.392
20	-0.392
30	-0.391
40	-0.389
50	-0.386
60	-0.382
70	-0.375
80	-0.367
90	-0.358
100	-0.347
120	-0.323
140	-0.294
160	-0.262
180	-0.228
200	-0.191
220	-0.153
240	-0.113
260	-0.071
273	-0.044
280	-0.029
293	0.000
300	0.015
CURVE 2*	
0	-0.396
10	-0.396
20	-0.396
30	-0.396
40	-0.394
50	-0.391
60	-0.387
70	-0.380
80	-0.372
90	-0.363
100	-0.351
120	-0.325
140	-0.295
160	-0.262
180	-0.227
200	-0.190
220	-0.151
240	-0.111
260	-0.070
273	-0.043
280	-0.028

T	$\Delta L/L_0$
CURVE 2 (cont.)*	
293	0.000
300	0.015
CURVE 3	
116	-0.345
144	-0.294
199	-0.194
293	0.000
366	0.174
477	0.464
588	0.755
699	1.062
CURVE 4	
20	-0.411
40	-0.408
60	-0.400
80	-0.385
100	-0.364
120	-0.338
140	-0.308
160	-0.275
180	-0.237
200	-0.198
220	-0.158
240	-0.116
260	-0.073
273	-0.044
280	-0.029
293	0.000
CURVE 5*	
106	-0.394
166	-0.278
223	-0.153
293	0.000
347	0.132
401	0.286
450	0.413
516	0.583
CURVE 6	
293	0.000

T	$\Delta L/L_0$
CURVE 6 (cont.)	
373	0.185
473	0.421
573	0.666
673	0.946
CURVE 7*	
293	0.000
373	0.179
473	0.423
673	0.996
CURVE 8*	
293	0.000
373	0.184
473	0.425
573	0.686
673	0.984
CURVE 9	
293	0.000
373	0.182
473	0.427
673	0.988
CURVE 10*	
293	0.000
373	0.182
473	0.422
573	0.680
673	0.969
CURVE 11	
673	0.980
473	0.430
373	0.184
293	0.000
CURVE 12	
293	0.000
373	0.182
473	0.419
523	0.661

T	$\Delta L/L_0$
CURVE 13	
293	0.000
373	0.182
473	0.430
573	0.692
CURVE 14*	
213	-0.172
293	0.000
373	0.186
CURVE 15*	
77	-0.371
97	-0.351
100	-0.341
109	-0.332
118	-0.317
127	-0.304
137	-0.292
145	-0.273
158	-0.258
178	-0.224
186	-0.208
196	-0.188
207	-0.168
224	-0.133
235	-0.116
245	-0.096
252	-0.078
263	-0.060
272	-0.039
277	-0.026
291	-0.007
293	0.000
300	0.014
CURVE 16	
20	-0.375
77	-0.365
477	0.470
700	1.110
CURVE 17*	
77	-0.373

T	$\Delta L/L_0$
CURVE 17 (cont.)*	
144	-0.300
200	-0.185
293	0.000
366	0.166
422	0.325
477	0.466
533	0.624
590	0.769
644	0.936
700	1.107
755	1.300
CURVE 18	
293	0.000
283	-0.023
273	-0.045
263	-0.068
253	-0.090
243	-0.112
233	-0.134
223	-0.156
213	-0.177
203	-0.198
193	-0.219
183	-0.239
173	-0.258
163	-0.277
153	-0.295
143	-0.312
133	-0.327
123	-0.342
113	-0.356
103	-0.368
93	-0.380
83	-0.390
77	-0.396

* Not shown in figure.

e. Thermal Diffusivity

Ten sets of data, all measured within the temperature range 100 to 700 K, are available in the literature. The experimental data are tabulated in Table 1-12 and shown in Figure 1-4. The information on specimen characterization and measurement condition for the data sets is given in Table 1-11.

The recommended values were calculated from the equation:

$$\alpha = \frac{k}{C_p d}$$

where k is the thermal conductivity, C_p is the specific heat, and d is the density. The recommended values for k and C_p given in previous sections were used for the calculation, and the recommended thermal expansion values were used to derive density values as a function of temperature. The recommended values tabulated in Table 1-10 and shown in Figure 1-4 are for an as-received 2024-T4 alloy having a residual electrical resistivity of 3.2 $\mu\Omega$ cm and a room temperature density of 2.77 g cm^{-3} and for an annealed 2024 alloy having residual electrical resistivity of about 0.70 $\mu\Omega$ cm. The recommended values for the as-received alloy agree with the data of Lucks et al. [20] (Curve 7) to within ± 12%. The data of Butler and Inn [36, 37] (Curves 1-6) exhibit a much weaker temperature dependence. This discrepancy is believed to be due to different heat treatments. It may be noted that the thermal diffusivity of the specimen measured by Butler and Inn increases after repeated heating to high temperatures. The recommended values for the annealed alloy agree with the data of Lucks et al. [20] (Curve 8) to within ± 8%.

The uncertainty of the recommended values is believed to be within ± 12% at temperatures below 200 K and ± 8% above.

TABLE 1-10. RECOMMENDED THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Thermal Diffusivity, α, $cm^2\ s^{-1}$]

T	α	
	As received	Annealed
100	0.496	1.000
150	0.441	0.813
200	0.449	0.738
250	0.469	0.723
273.15	0.478	0.721
293	0.487	0.719
300	0.491	0.719
350	0.517	0.722
400	0.553	0.727
450	0.609	0.715
500	0.656	0.697
550	0.665	0.677
600	0.654	0.656
650	0.634	0.634
700	0.612	0.612
750	0.583	0.583
775	0.568	0.568

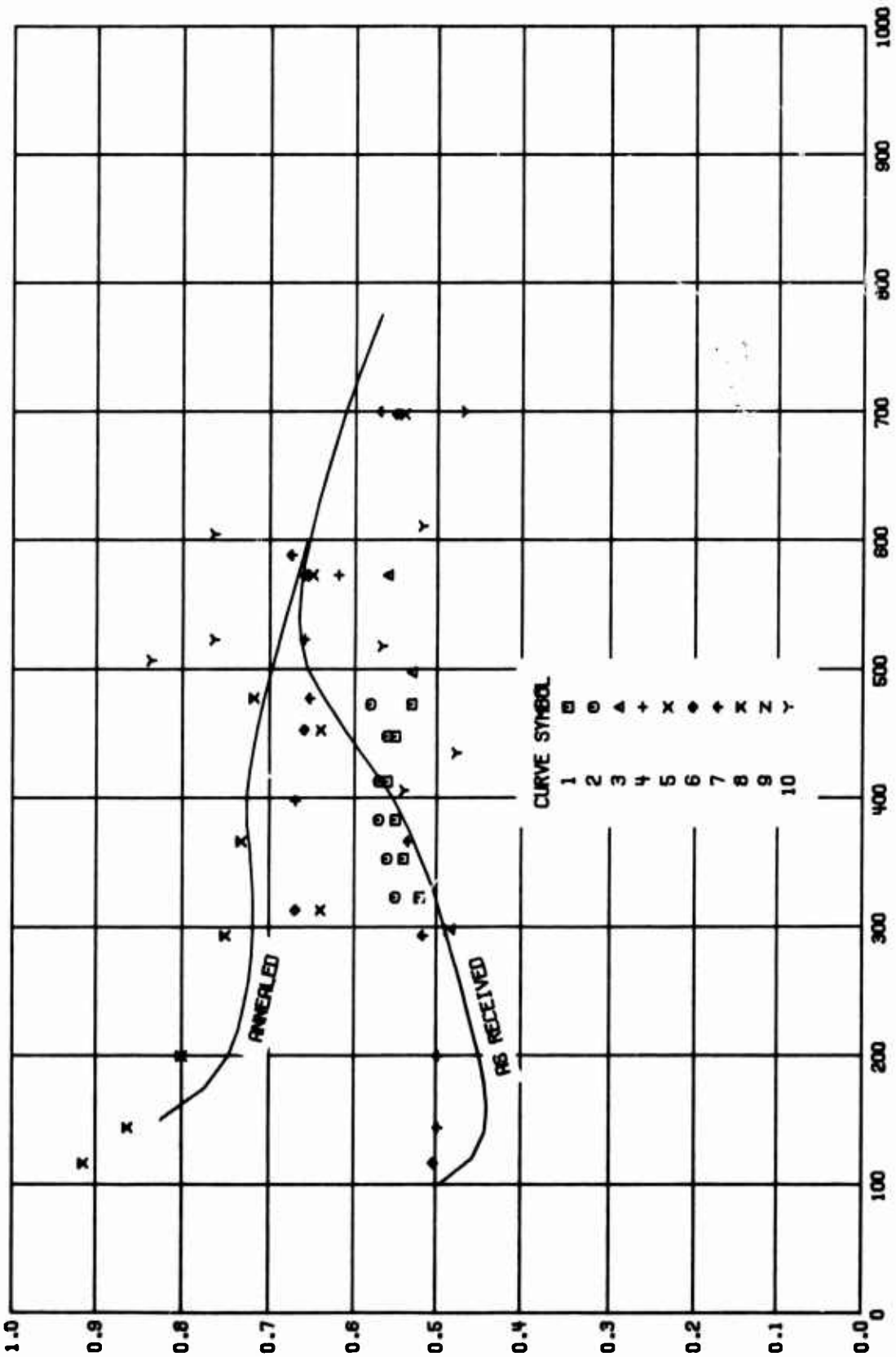

FIGURE 1-4. THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024 .

TABLE 1-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Al	Cu	Cr	Fe	Mg	Mn	Si	Zn	Composition (continued), Specifications, and Remarks
1	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	323-473	2024-T86	→	3.8/ 4.9	0.10 max	0.50 max	1.2/ 1.8	0.30/ 0.9	0.50 max	0.25 max	90.90-93.20 Al (by difference), and 0.15 max others; nominal composition from Alcoa Aluminum Handbook, p. 44, 1962; cylindrical specimen 0.9525 cm in diameter and length lying in the range from 1 to 2.5 cm; nominal heat treatment (from above source): solution heat treatment, strain hardening, and then artificial aging; subjected to irradiance from carbon arc lamp heat source; spectral distribution approximates that of a 5700 K black body source; specimen blackened with camphor black; measured under a vacuum of ~5 microns; reported error 5-10%.
2	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	323-473	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
3	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	388-573	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
4	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	398-573	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
5	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	313-698	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
6	36, 37	Butler, C.P. and Inn, E.C.Y.	1957	T	313-698	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
7	6, 20	Lucks, C.F., Deem, H.W., Thompson, H.B., Smith, A.R., Curry, F.P., and Bing, G.F.	1951		116-700	2024-T4		4.5			1.5	0.6			Supplied by Aluminum Co. of America; condition as received T4 (solution heat treatment followed by natural aging at room temperature to a substantially stable condition); thermal diffusivity calculated from measured conductivity, specific heat, and density.
8	6, 20	Lucks, C.F., et al.	1951		116-700	2024-T4									Same as the above alloy measured again for thermal conductivity after being heated above 574.8 K; thermal diffusivity calculated from measured conductivity, specific heat, and density.
9	38	Tomsic, M.	1969	P	298	2024-T6		4.5			1.5	0.6			Nominal composition; cylindrical specimen; measuring temperature assumed 25 C.
10	39	Cushman, J.B., Jr.	1964	T	406-700	2024-T4									1 in. diameter by 4 in. long; measured by a modified Joming and Quench method.

TABLE 1-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Thermal Diffusivity, α, $cm^2 s^{-1}$]

T	α
CURVE 1	
323.2	0.52
353.2	0.54
383.2	0.55
413.2	0.56
448.2	0.55
473.2	0.53
CURVE 2	
323.2	0.55
353.2	0.56
383.2	0.57
413.2	0.57
448.2	0.56
473.2	0.58
CURVE 3	
388.2	0.55
448.2	0.56
498.2	0.53
573.2	0.56
CURVE 4	
398.2	0.67
523.2	0.66
573.2	0.62
CURVE 5	
313.2	0.64
453.2	0.64
573.2	0.65
698.2	0.54
CURVE 6	
313.2	0.67
453.2	0.66
573.2	0.66
698.2	0.55
CURVE 7	
116.4	0.503
144.2	0.498
199.8	0.498
293.2	0.516
366.4	0.534
477.6	0.653
588.7	0.674
699.8	0.568
CURVE 8	
116.4	0.914
144.2	0.862
199.8	0.800
293.2	0.751
366.4	0.733
477.6	0.718
588.7	0.674
699.8	0.568
CURVE 9	
298	0.485
CURVE 10	
406	0.539
435	0.477
507	0.835
518	0.566
523	0.764
605	0.764
611	0.517
700	0.466

3.2. AISI 304 Stainless Steel

The family of steels known as "stainless steels" covers a wide range of composition. About 35 to 40 different combinations of ingredients have been used by various manufacturers. Primarily all stainless steels have chromium as the major alloying element. The nominal composition of AISI 304 Stainless is 18.00-20.00% Cr, 8.00-10.50% Ni, 2.00% (max.) Mn, 1.00% (max.) Si, 0.08% (max.) C, 0.045% (max.) P, 0.030% (max.) S, and balance Fe. The composition of 304L is essentially the same except that the carbon content is lowered to 0.03% (max.).

Chromium, when added to iron in excess of 10%, makes the alloy heat and corrosion resistant. Other elements are added to obtain special characteristics. The most important of these in the case of stainless steels is nickel which increases the corrosion resistance and workability of the alloy. This addition causes a structural change which is known as austenitic, making the alloy nonhardenable and nonmagnetic. It is possible to weld AISI 304 stainless in moderate thickness without requiring subsequent heat treatment to restore corrosion resistance.

Various properties and uses of this alloy are discussed in detail in [1]. Some of the physical properties are summarized as follows:

Density:	7.9 g cm^{-3}
Melting range:	1670-1727 K
Electrical resistivity at room temperature:	72 $\mu\Omega$ cm
Modulus of elasticity in tension:	28 x 10^6 psi
Modulus of elasticity in torsion:	12.5 x 10^6 psi

a. Thermal Conductivity

Thirty-three sets of experimental data are available, mostly measured between room temperature and 1200 K. All the measurements are for specimens in solid state, including some for porous samples. The experimental data are tabulated in Table 2-3 and shown partially in Figure 2-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 2-2.

The recommended values for the thermal conductivity of AISI 304 stainless steel are given in Table 2-1 and shown in Figure 2-1. The values below 100 K are for a steel having residual electrical resistivity of about 48.4 $\mu\Omega$ cm. At cryogenic temperatures the values are based on the data of Stutius and Dillinger [40] (curve 28). Above 25 K

the values follow the data of Powers et al. [41] (curve 5), Moeller [42] (curves 10-13), Deverall [43] (curve 1), Taylor et al. [44] (curve 15), Moeller and Finch [45] (curves 10-13), and Tye et al. [46] (curve 32) to 1200 K. Above 1200 K the recommended values are extrapolated.

The solidus and liquidus temperatures of AISI 304 stainless steel are around 1670 and 1727 K, and no thermal conductivity values are recommended in this region. In molten state from 1800 to 2000 K, the recommended values are calculated from the equation:

$$k = \frac{LT}{\rho}$$

where the Lorenz number L is taken as L_o ($=2.443 \times 10^{-8}$ V^2 K^{-2}) and the electrical resistivity ρ is obtained from [47] for an Fe + 10% Ni alloy, which in the solid state has the same ρ values as AISI 304. The values of ρ and L used in the calculations are certainly different from the true values for the 304 stainless steel, thereby contributing major portion of the uncertainty to the recommended thermal conductivity values for the molten steel.

The uncertainty of the recommended values is estimated to be within ± 10% below 25 K, ± 5% from 25 to 1200 K, and ± 10% between 1200 and 1600 K. The values for the molten steel are provisional, with an estimated uncertainty of about ± 20%.

TABLE 2-1. RECOMMENDED THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	T	k
4	0.00288	500	0.183
7	0.00531	550	0.191
10	0.00796	600	0.198
15	0.0129	650	0.205
20	0.0183	700	0.212
25	0.0241	750	0.219
30	0.0304	800	0.226
40	0.0438	850	0.233
50	0.0566	900	0.240
60	0.0675	950	0.247
70	0.0750	1000	0.254
80	0.0810	1100	0.267
90	0.0869	1200	0.280
100	0.0919	1300	0.293
150	0.111	1400	0.305
200	0.126	1500	0.317
250	0.138	1600	0.327
273.15	0.143	1670†	0.333
293	0.147	1727†	0.288
300	0.149	1800	0.294
350	0.158	1900	0.304
400	0.166	2000	0.315
450	0.175		

† Approximate melting range.

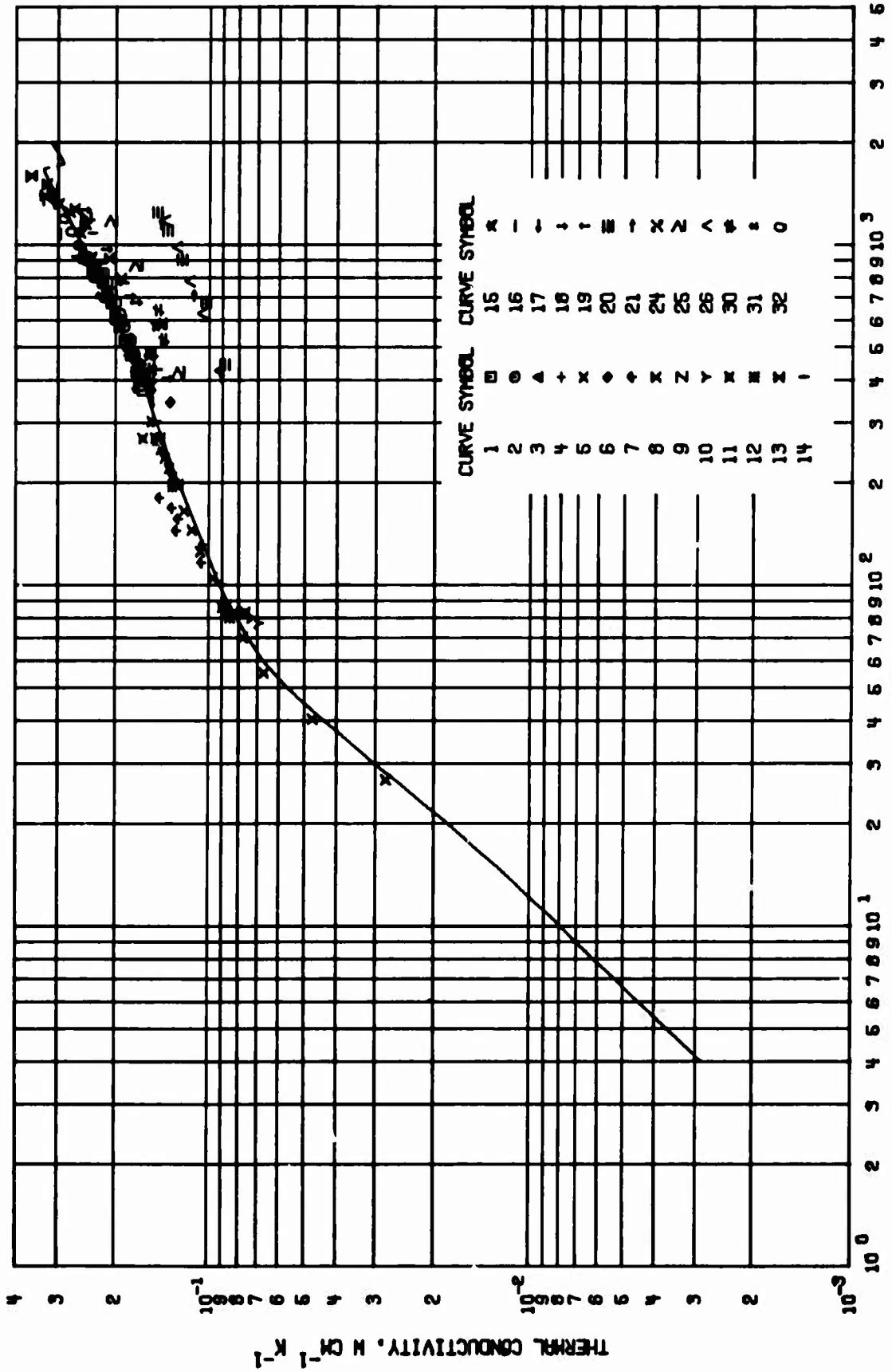

FIGURE 2-1. THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Ni	C	Mn	Si	Composition (continued), Specifications, and Remarks
1	43	Deverall, J.E.	1959	L	373-773			18.51	9.09	0.053	0.67	0.53	0.028 S and 0.025 P; 1 in. diameter by 14.25 in. long; measured in an insulated guarded apparatus; smoothed values reported; reported error 5.0%.
2	43	Deverall, J.E.	1959	L	423-823			18.51	9.09	0.053	0.67	0.53	Same material as the above specimen; 0.75 in. diameter by 10 in. long; measured in a vacuum apparatus; smoothed values reported.
3	48	Ewing, C.T., Grand, J.A., and Miller, R.R.	1952	L	473-916			18.0/ 20.0	8.0/ 11.0	<0.08	<2.0		Nominal composition; 1.625 in. in diameter.
4	48	Ewing, C.T., et al.	1952	L	470-926			18.0/ 20.0	8.0/ 11.0	<0.08	<2.0		The above specimen.
5	41	Powers, R.W., Ziegler, J.B., and Johnston, H.L.	1951	L	27-250			18.68	8.84	0.05	1.12	0.43	0.06 Cu, 0.031 N, 0.023 S, and 0.017 P; supplied by Carnegie Illinois Steel Corp.
6	49	Brophy, J.H. and Sinnott, M.J.	1960	R	344-482			18/ 20	8/ 12	<0.08	<2.0	<1.00	<0.045 P and <0.03 S (nominal composition); disk-like specimens 2.75 in. O.D.
7	50	Smith, C.F.	1963	L	100-180			18/ 20	8/ 12	<0.08	<2.00	<1.00	<0.045 P and <0.030 S (nominal composition); 0.144 in. diameter by 10.125 in. long; machined; measured in a vacuum of $< 5 \times 10^{-6}$ mm Hg.
8	51, 52	Feith, A.D., Hein, R.A., Johnstone, C.P., and Flagella, P.N.	1968	R	795-1593		Bal.	18.37	9.89	0.024	1.31	0.70	0.09 Mo, 0.05 Cu, 0.041 P, and 0.012 S; specimen ~0.95 cm I.D., ~5.04 cm O.D., and 1.25 cm thick; centerless grounded, fully annealed; electrical resistivity reported as 72.31, 74.42, 79.29, 90.88, 91.07, 94.31, 97.99, 102.45, 105.05, 109.48, 112.46, 111.86, 113.82, 119.08, 123.29, 127.0, 130.57, 130.42, 130.62, 130.53, 131.32, 130.59, and 132.47 μΩ cm at 26, 46, 111, 265, 279, 311, 373, 442, 522, 583, 657, 697, 755, 854, 1031, 1189, 1255, 1328, 1339, 1345, 1354, 1361, and 1378 C, respectively; reported error ±6-8%.
9	51, 52	Feith, A.D., et al.	1968	P	791-1590		Bal.	18.37	9.89	0.024	1.31	0.70	Similar to the above specimen except thermal conductivity values calculated from the measurements of thermal diffusivity (using the average data of 2 specimens 0.635 cm in diameter, one 0.127 cm thick, and another 0.152 cm thick) and enthalpy of specimens fabricated from the same raw material as used for the thermal conductivity; reported values obtained from smooth curve; reported error ±2%.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Ni	C	Mn	Si	Composition (continued), Specifications, and Remarks
10	42, 45	Moeller, E. and Finch, H. L.	1969	L	77-871			18/ 20	8/ 12	<0.08	<2.00	<1.00	<0.045 P and <0.030 S (nominal composition); specimen 1.27 cm in diameter and 2.54 cm long; reported error ±5%.
11	42, 45	Moeller, E. and Finch, H. L.	1969	L	83-270			18/ 20	8/ 12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 10.2 cm in diameter and 7.6 cm long.
12	42, 45	Moeller, E. and Finch, H. L.	1969	L	80-270			18/ 20	8/ 12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 5.1 cm in diameter and 6.6 cm long.
13	42, 45	Moeller, E. and Finch, H. L.	1969	L	83-267			18/ 20	8/ 12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 5.1 cm in diameter and 7.6 cm long.
14	44, 53	Taylor, R.E., Powell, R.W., Nalbantyan, M., and Davis, F.	1968	E	923-1082			18/ 20	8/ 12	<0.08	<2.00	<1.00	<0.045 P and <0.030 S (nominal composition); specimen 7 in. long; heated at 1050 C for 2 hr at 10^{-4} torr; measured in a vacuum of ~10^{-6} torr; thermal conductivity data calculated by using Krishnan and Jain's method; reported error ±1.3%.
15	44, 53	Taylor, R.E., et al.	1968	E	912-1081			18/ 20	8/ 12	<0.08	<2.00	<1.00	The above specimen; thermal conductivity data calculated by using Lebedev's method; reported error ±2.3%.
16	44, 53	Taylor, R.E., et al.	1968	E	763-1072			18/ 20	8/ 12	<0.08	<2.00	<1.00	The above specimen; thermal conductivity data calculated by using Taylor's method.
17	54	Brown, W.T., Jr. and Bergles, A.E.	1968	E	345-527			18.00 20.00	8.00 12.00	<0.08	<2.00	<1.00	Nominal composition; tube specimen 0.2518 in. in O.D., 0.1243 in. in I.D., and 4.88 in. long; electrical resistivity 69.3, 71.1, 71.9, 74.5, 76.8, 79.5, 82.3, 83.8 and 86.2 μΩ cm at 311, 338, 349, 389, 422, 465, 509, 532, and 575 K respectively.
18	55	Tye, R.P.	1970	C	404-1264			18.00- 20.00	8.00- 12.00	<0.03	<2.00	<1.00	Nominal composition; 63.9 x 63.8 x 20.6 mm; electrical resistivity 92.6, 100, 117, 130, 140.5, 148.5, and 152 μΩ cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 9.3%; heat flow perpendicular to the weave pattern; measured in vacuum from 3×10^{-3} to 2×10^{-4} torr; Inconel used as comparative material.
19	55	Tye, R.P.	1970	C	428-1182			18.00- 20.00	8.00- 12.00	<0.03	<2.00	<1.00	The above specimen measured in a nitrogen atm.
20	55	Tye, R.P.	1970	C	442-1243			18.00- 20.00	8.00- 12.00	<0.03	<2.00	<1.00	Nominal composition; 64.6 x 64.4 x 26.19 mm; electrical resistivity 147.5, 159, 187, 208.5, 225, 237.5, and 243 μΩ cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 20.3%; heat flow perpendicular to the weave pattern; measured in vacuum from 5×10^{-3} to 6×10^{-4} torr; Inconel used as comparative material.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Ni	C	Mn	Si	Composition (continued), Specifications, and Remarks
21	55	Tye, R.P.	1970	C	406-1151			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	The above specimen measured in a nitrogen atm.
22*	55	Tye, R.P.	1970	C	518-1216			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	Nominal composition; 62.75 x 62.59 x 24.46 mm; electrical resistivity 300, 327, 384, 424, 451, 478, and 492 μΩ cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 38.5%; heat flow perpendicular to the weave pattern; measured in vacuum from 2×10^{-4} to 3×10^{-4} torr; Inconel used as comparative material.
23*	55	Tye, R.P.	1970	C	415-1168			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	The above specimen measured in a nitrogen atm.
24	56	Tye, R.P.	1973	C	412-1083			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	Nominal composition; 2.54 cm diameter by 2.54 cm long; electrical resistivity 72.0, 78.8, 93.0, 104.5, 112, and 116.5 μΩ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; Inconel 702 used as comparative material; reported error < 10%.
25	56	Tye, R.P.	1973	C	421-1173			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	Fabricated from sintered spherical powder particles obtained from 304L stainless steel stock; 2.56 cm diameter by 2.53 cm thick; electrical resistivity 95, 112, 122, 135, 146, and 157 μΩ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 9.2%; Inconel 702 used as comparative material.
26	56	Tye, R.P.	1973	C	425-1176			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	Same fabrication and measuring methods as the above specimen; 2.56 cm diameter by 2.54 cm thick; electrical resistivity 135, 147.5, 175, 195, 213, and 231 μΩ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 21.38%.
27*	56	Tye, R.P.	1973	C	472-1178			18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00	Same fabrication and measuring methods as the above specimen; 2.54 cm diameter by 2.52 cm thick; electrical resistivity 230, 250, 291, 315, 332, and 338 μΩ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 31.0%.
28*	40	Stutins, W. and Dillinger, J.R.	1973	L	0.39-1.7			18-20	8-12	<0.08	<2	<1	Nominal composition; 0.6 cm diameter by 4 cm long; electrical resistivity 47.1, 47.6, and 70.2 μΩ cm at 4.2, 77, and 295 K, respectively; Néel temperature >295 K.
29*	40	Stutins, W. and Dillinger, J.R.	1973	L	0.45-1.5			18-20	8-12	<0.03	<2	<1	Similar to the above specimen except electrical resistivity 49.9, 50.6, and 70.4 μΩ cm at 4.2, 77, and 295 K, respectively.

* Not shown in figure.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Ni	C	Mn	Si	Composition (continued), Specifications, and Remarks
30	57	Bondi, P. and Ferro, V.	1967	L	401-641			18-20	8-10	≤0.08	≤2	≤1	Nominal composition; reported error 3%.
31	57	Bondi, P. and Ferro, V.	1967	L	712, 813			18-20	8-10	≤0.08	≤2	≤1	Nominal composition; plate specimen; reported error 3%.
32	46	Tye, R.P., Hayden, R.W., and Spinney, S.C.	1972	L	300-1200		Bal.	18.49	8.61	0.051	1.69	0.40	0.21 Cu, 0.21 Mo, 0.12 Co, and 0.029 S (nominal composition); 12.7 mm diameter by 100 mm long; annealed; density 7.900-7.920 g cm^{-3}; electrical resistivity 46.7, 71.7, 79.1, 86.2, 92.7, 98.7, 104.0, 108.0, 112.2, 115.5, and 118.5 μΩ cm at 4.2, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.
33*	58	Careaga, J.A., Mayer, E.R., and Del Castillo, L.	1970	L	89-207			18-20	8-12	≤0.08	≤2	≤1	Nominal composition (from Metals Handbook); cylindrical specimen.

* Not shown in figure.

TABLE 2-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF STAINLESS STEEL 304

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
CURVE 1	
373.2	0.165
423.2	0.173
473.2	0.180
523.2	0.188
573.2	0.195
623.2	0.202
673.2	0.208
723.2	0.214
773.2	0.221
CURVE 2	
423.2	0.168
473.2	0.175
523.2	0.180
573.2	0.188
623.2	0.194
673.2	0.200
723.2	0.206
773.2	0.213
823.2	0.219
CURVE 3	
473.2	0.182
487.2	0.183
575.2	0.195
599.2	0.198
682.2	0.210
699.2	0.213
751.2	0.221
809.2	0.230
818.2	0.229
831.2	0.232
916.2	0.248
CURVE 4	
470.2	0.179
588.2	0.196
608.2	0.200
736.2	0.216
798.2	0.225
811.2	0.229
926.2	0.254

T	k
CURVE 5	
26.74	0.0280
40.34	0.0473
55.18	0.0669
69.96	0.0778
87.28	0.0870
104.92	0.0970
125.06	0.107
144.81	0.114
165.15	0.121
206.64	0.132
220.02	0.135
235.13	0.140
250.10	0.144
CURVE 6	
344.3	0.134
372.1	0.155
388.7	0.151
410.9	0.163
415.4	0.165
445.4	0.167
482.1	0.176
CURVE 7	
100	0.090
116	0.106
131	0.105
144	0.128
156	0.126
168	0.132
180	0.145
CURVE 8	
795	0.192
839	0.237
910	0.210
1143	0.248
1185	0.247
1248	0.277
1273	0.267
1319	0.299
1349	0.297
1358	0.321

T	k
CURVE 8 (cont.)	
1396	0.329
1423	0.309
1461	0.312
1507	0.324
1593	0.361
CURVE 9	
791	0.192
905	0.211
1151	0.248
1194	0.248
1241	0.277
1270	0.269
1315	0.298
1352	0.322
1392	0.329
1420	0.310
1450	0.313
1495	0.324
1590	0.362
CURVE 10	
77	0.0695
80	0.0729
302	0.1488
302	0.1545
304	0.1443
575	0.1974
865	0.2353
871	0.2331
CURVE 11	
83.0	0.0764
86.1	0.0904
197.6	0.1295
269.0	0.1649
269.8	0.1506
CURVE 12	
80.3	0.0852
81.2	0.0865
194.7	0.1320

T	k
CURVE 12 (cont.)	
195.4	0.1294
268.1	0.1441
270.2	0.1441
CURVE 13	
83.0	0.0832
196.9	0.1266
267.4	0.1470
CURVE 14	
923	0.264
1082	0.237
CURVE 15	
91[illegible]	0.252
912	0.240
1081	0.257
CURVE 16	
763	0.217
915	0.259
920	0.257
921	0.248
1072	0.296
CURVE 17	
345.0	0.154
382.2	0.175
397.2	0.157
432.2	0.158
445.6	0.152
465.0	0.178
474.4	0.184
477.8	0.161
484.4	0.177
527.2	0.180
CURVE 18	
404.2	0.137
675.7	0.173

T	k
CURVE 18 (cont.)	
706.2	0.181
968.3	0.215
1263.7	0.250
CURVE 19	
428.2	0.148
706.2	0.181
770.2	0.190
1181.7	0.243
CURVE 20	
442	0.089
677	0.103
901	0.123
1098	0.137
1243	0.148
CURVE 21	
406	0.091
704	0.113
1151	0.144
CURVE 22*	
518.2	0.049
799.2	0.056
1013.7	0.064
1216.2	0.072
CURVE 23*	
415	0.045
768	0.063
1168	0.074
CURVE 24	
412	0.1678
598	0.1928
726	0.2105
864	0.2286
1083	0.2593

T	k
CURVE 25	
421	0.1235
584	0.1412
602	0.1442
868	0.1696
1173	0.2032
CURVE 26	
425	0.0928
627	0.1063
780	0.1165
983	0.1279
1176	0.1396
CURVE 27*	
472	0.0609
715	0.0747
778	0.0743
1000	0.0888
1178	0.0943
CURVE 28*	
0.386	0.000263
0.446	0.000344
0.529	0.000406
0.596	0.000475
0.697	0.000541
0.851	0.000658
1.00	0.000785
1.24	0.000953
1.45	0.00109
1.65	0.00125
CURVE 29*	
0.453	0.000287
0.470	0.000287
0.511	0.000301
0.559	0.000331
0.603	0.000375
0.652	0.000391
0.695	0.000415
0.745	0.000460
0.806	0.000502

* Not shown in figure.

TABLE 2-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF STAINLESS STEEL 304 (continued)

T	k
CURVE 29 (cont.)*	
0.869	0.000556
0.929	0.000604
0.982	0.000649
1.02	0.000658
1.10	0.000698
1.19	0.000753
1.29	0.000791
1.39	0.000843
1.51	0.000927
CURVE 30	
401	0.155
423	0.155
477	0.153
526	0.141
579	0.150
641	0.147
CURVE 31	
712	0.224
813	0.221
CURVE 32	
300	0.1490
400	0.1665
500	0.184
600	0.202
700	0.218
800	0.234
900	0.247
1000	0.261
1100	0.275
1200	0.289
CURVF 33*	
89.0	0.0586
105.1	0.0705
113.3	0.0740
124.4	0.0805
133.2	0.0830
140.5	0.0785
161.9	0.100
172.3	0.114
187.9	0.133
197.9	0.137
207.4	0.141

* Not shown in figure.

b. Specific Heat

There are seven sets of experimental data available for the specific heat of AISI 304 Stainless Steel. One data set (curve 4) which is for a Russian 1Kh18N9T steel having similar composition is also included. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 2-5. The experimental data is tabulated in Table 2-6 and shown in Figure 2-2.

With the exception of the first two curves, the measurements were carried out within the temperature range 295-1623 K. The recommended values shown in Figure 2-2 and tabulated in Table 2-4 are derived primarily from the investigation of Feith et al. [51, 59] (curve 3) and also using the specific heat data for other 300 series stainless steels. The specific heat data of Lyusternik [60] (curve 4) for a Russian steel of type 1Kh18N9T agree well (0-5% lower) with the recommended values. The specific heat values calculated using the Kopp-Neumann mixing rule also agree well except in the region 800-1200 K, where the phase transformation of Fe occurs. The heat content data of Neel et al. [61] (curve 7) are about 25% higher, while those of Smith [62] (curve 6) show a wide scatter resulting in about 10-20% higher specific heat values. The specific heat data of Venuti and Seibel [63] (curve 5) are about 25% lower than the recommended values. It is worth noting that the selected specific heat values for pure iron [19] are within ± 5% of the specific heat values for this steel except in the phase transformation region 1100-1200 K. The uncertainty of the recommended values is about ± 5%.

The melting region of this steel is 1670-1727 K. No experimental data for the specific heat of this or any other similar steel in the molten state were located in the literature. Considering the agreement between the experimental data and the calculated values for the solid steel from the Kopp-Neumann mixing rule, the provisional values for the molten steel tabulated in Table 2-4 were calculated using the above procedure. In the calculation the specific heat values for constituent elements in the molten state were taken from Hultgren et al. [19]. Selected values for pure iron in the molten state [19] are about 2% higher than the provisional values for the steel. The uncertainty of the provisional values is ± 10%.

TABLE 2-4. RECOMMENDED SPECIFIC HEAT OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
100	0.065
150	0.082
200	0.096
250	0.106
273.15	0.110
293	0.113
300	0.114
350	0.119
400	0.123
450	0.126
500	0.129
550	0.131
600	0.133
650	0.135
700	0.136
750	0.138
800	0.139
850	0.140
900	0.142
950	0.144
1000	0.146
1100	0.149
1200	0.153
1300	0.156
1400	0.159
1500	0.163
1600	0.166
1670†	0.169
1727†	0.194‡
1800	0.194‡
2000	0.194‡

† Approximate melting range.
‡ Provisional value.

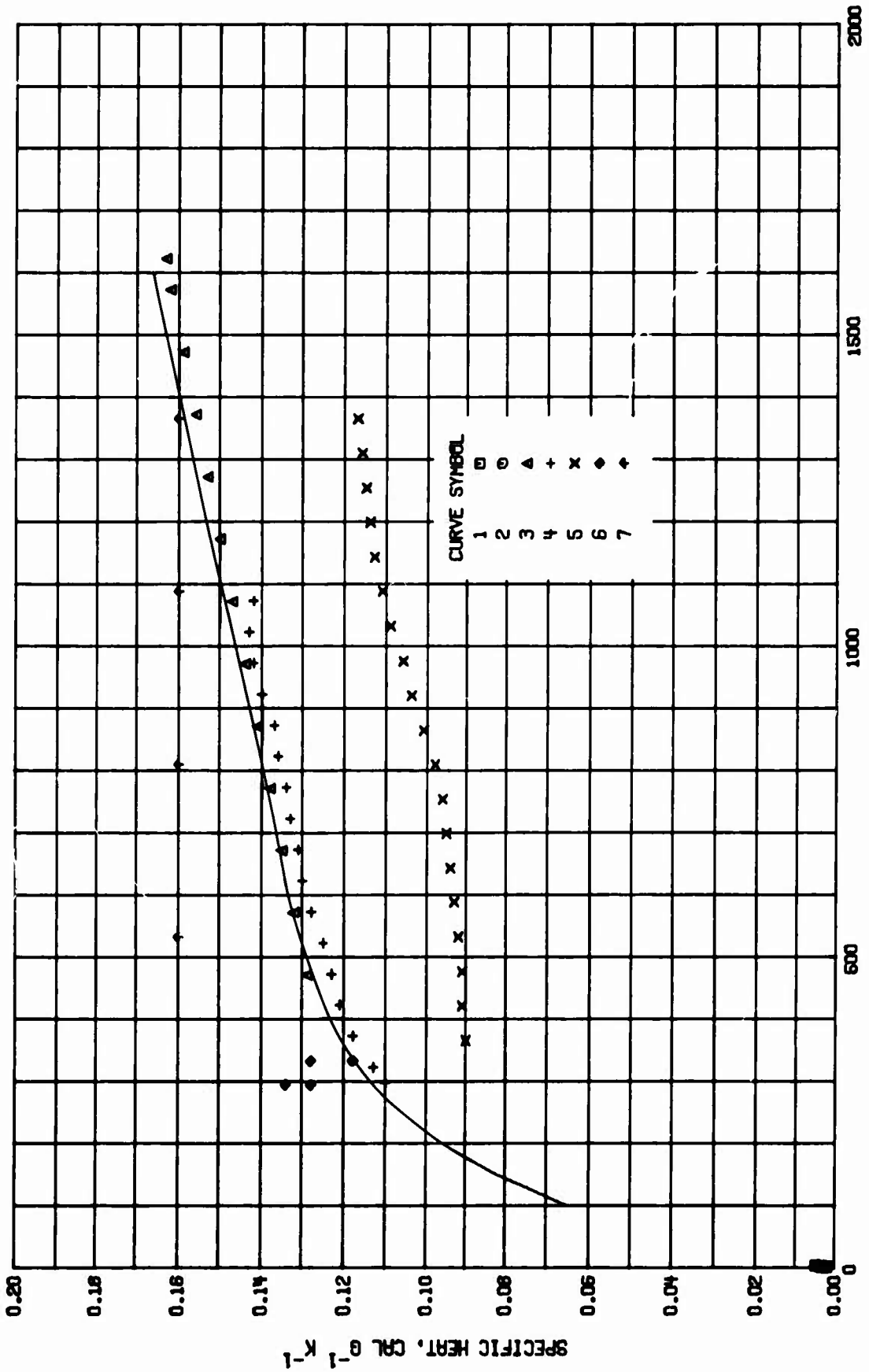

FIGURE 2-2. SPECIFIC HEAT OF AISI 304 STAINLESS STEEL.

TABLE 2-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF AISI 304 STAINLESS STEEL

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Mn	Si	C	Ni	P	Composition (continued), Specifications, and Remarks
1	64	Zoller, P., Decker, P.R., and Dillinger, J.R.	1969		1.7-4.2	AISI type 304 s.s.	Bal.	19.5	1.34	1.06	0.324	7.63	0.041	0.034 S; specimen from the U.S. Steel, tabulated values calculated from equation c = 1.268 + 24.33 T + 0.082 T^3 mJ $mole^{-1}$ deg^{-1}; molecular weight = 54.86.
2	64	Zoller, P., et al.	1969		1.7-4.2	AISI type 304L s.s.	Bal.	19.7	1.38	0.82	0.101	8.94	0.023	0.015 S; specimen from the U.S. Steel, tabulated values calculated from equation c = 2.674 + 21.70 T + 0.104 T^3 mJ $mole^{-1}$ deg^{-1}; molecular weight = 55.05.
3	51, 59	Feith, A.D., Hein, R.A., Johnstone, C.P., and Flagella, P.N.	1969		473-1623	AISI type 304L s.s.	Bal.	18.72			0.226	9.87		Commercial grade alloy machined to 1.22 cm diameter and 2.5 cm long specimen, C_p = $0.5153 \times 10^3 + 12.524 \times 10^{-2}$ T J Kg^{-1} C^{-1}.
4	60	Lyusternik, V.F.	1959		298-1073	1Kh18N9T		20	2	0.8		11		0.8 Ti; no details given.
5	63	Venuti, R. and Seibel, R.D.	1959		366-1366		Bal.	18.67	1.11	0.46	0.063	9.50	0.023	0.017 S; specimen in the milled condition from the Armco Steel.
6	62	Smith, R.H.	1964		295-333									Measurements using flash heating technique.
7	61	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962		533-1366	AISI type 304 s.s.								Nominal composition.

TABLE 2-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF AISI 304 STAINLESS STEEL

(Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1})

T	C_p
CURVE 1	
1.7	0.0019
2.0	0.0022
3.0	0.0033
4.2	0.0048
CURVE 2	
1.7	0.0017
2.0	0.0020
3.0	0.0031
4.2	0.0044
CURVE 3	
473	0.129
573	0.132
673	0.135
773	0.138
873	0.141
973	0.144
1073	0.147
1173	0.150
1273	0.153
1373	0.156
1473	0.159
1573	0.162
1623	0.163
CURVE 4	
298	0.110
323	0.113
373	0.118
423	0.121
473	0.123
523	0.125
573	0.128
623	0.130
673	0.131
723	0.133
773	0.134
823	0.136
873	0.137
923	0.140
973	0.142
1023	0.143
1073	0.142
CURVE 5	
366	0.090
422	0.091
477	0.091
533	0.092
589	0.093
644	0.094
700	0.095
755	0.096
811	0.098
866	0.101
922	0.104
977	0.106
1033	0.109
1089	0.111
1144	0.113
1200	0.114
1255	0.115
1311	0.116
1366	0.117
CURVE 6	
295	0.128
295	0.134
333	0.128
333	0.118
CURVE 7	
533	0.160
811	0.160
1089	0.160
1366	0.160

c. Heat of Fusion

No experimental data were located in the literature. However, a value of 60 ± 5 cal g^{-1} for the heat of fusion of iron reported by Hultgren, Desai, Hawkins, Gleiser, Kelley, and Wagman [19] may be used as a very rough estimate.

d. Thermal Linear Expansion

There are nine sets of experimental data available for thermal linear expansion of AISI 304 stainless steel. The information on the specimen characterization and measurement condition for each data set is given in Table 2-8. The experimental data are tabulated in Table 2-9 and shown partially in Figure 2-3.

Among these, three data sets (curves 1, 5, and 8) were measured at temperatures below room temperature and others cover the range 293 to 1667 K. The recommended values shown in Figure 2-3 and tabulated in Table 2-7 agree agree well with most of the measurements with the exception of the data of Conway and Flagella [65] (curve 9) which are about 8% higher above 800 K. The uncertainty of the values is about ± 5% below 1300 K and ± 10% above.

The melting range for this steel is 1670-1727 K. No experimental values for the density of this steel in the molten state are located in the literature. Since the melting point of this steel is considerably high, estimations of densities from the Kopp-Neumann mixing rule or any other techniques are highly uncertain and also not possible due to lack of experimental density data for constituent elements in that temperature range.

The values of the instantaneous coefficient of thermal linear expansion, α, are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about ± 10% below 1300 K and ± 15% above.

TABLE 2-7. RECOMMENDED THERMAL LINEAR EXPANSION OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$,%; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α
20	-0.339	9.8
25	-0.336	9.9
30	-0.331	10.0
40	-0.319	10.2
50	-0.308	10.4
60	-0.298	10.6
70	-0.287	10.8
80	-0.277	11.0
90	-0.265	11.2
100	-0.254	11.4
150	-0.195	12.4
200	-0.130	13.2
250	-0.061	14.1
273.15	-0.031	14.4
293	0.000	14.7
300	0.011	14.9
350	0.086	15.6
400	0.167	16.3
450	0.251	16.9
500	0.338	17.5
550	0.427	18.0
600	0.519	18.6
650	0.612	19.0
700	0.709	19.5
750	0.807	19.9
800	0.907	20.2
850	1.007	20.4
900	1.112	20.6
950	1.217	20.8
1000	1.323	21.1
1100	1.536	21.3
1200	1.748	21.4
1300	1.959	21.4
1400	2.171‡	21.4‡
1500	2.386‡	21.5‡
1600	2.601‡	21.6‡
1670	2.753‡	21.7‡

‡ Provisional value.

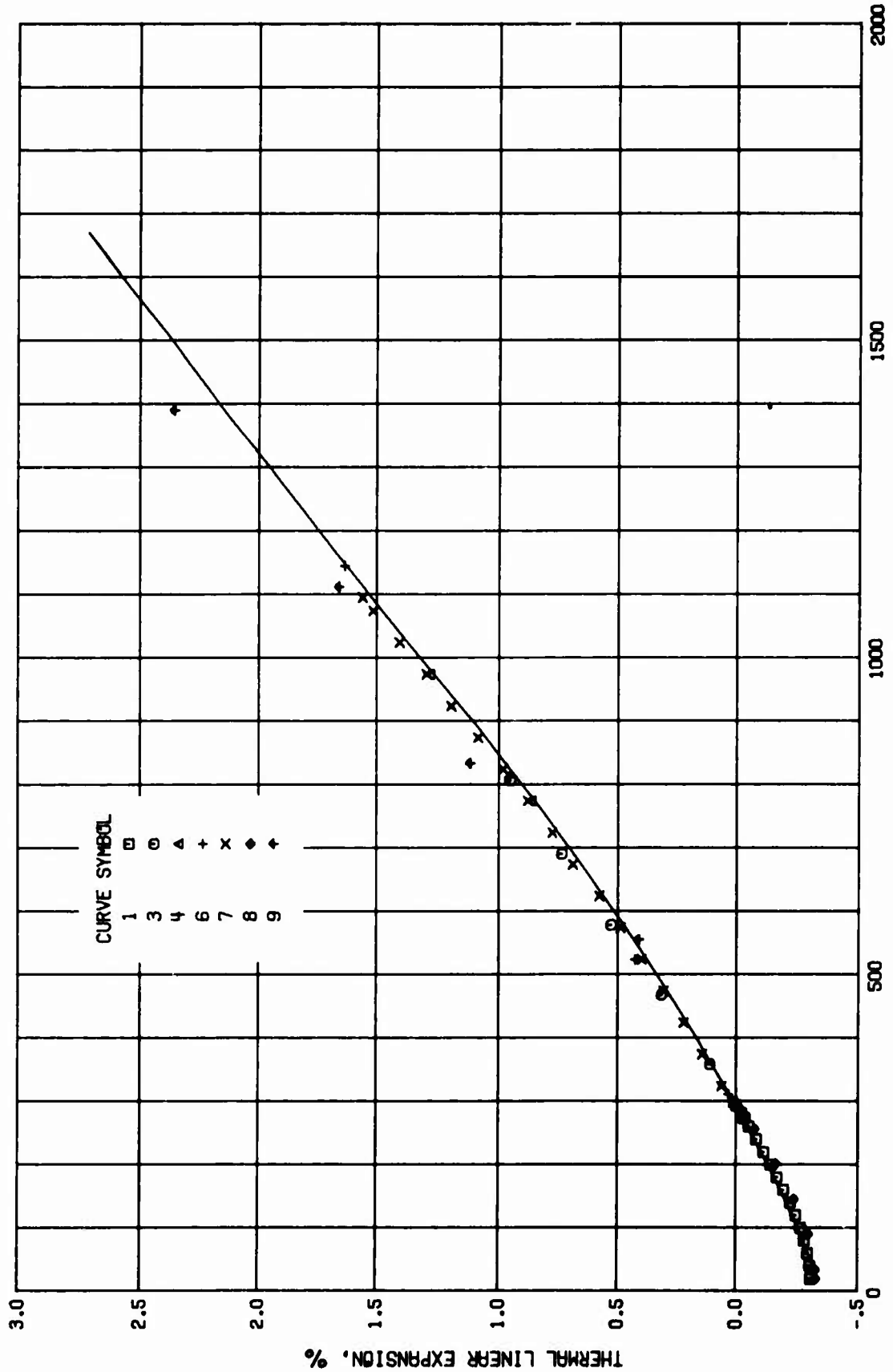

FIGURE 2-3. THERMAL LINEAR EXPANSION OF AISI 304 STAINLESS STEEL .

TABLE 2-8. MEASUREMENT INFORMATION ON THE LINEAR THERMAL EXPANSION OF AISI 304 STAINLESS STEEL

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Mn	Si	C	Ni	P	Composition (continued), Specifications, and Remarks
1	29	Arp, V., Wilson, J.H., Winrich, L., and Sikora, P.	1962	L	20-293	304 L	Bal.	18.4	1.4	0.6	0.02	9.7	0.02	0.01 S; hardness R_B 94; annealed specimen.
2*	66	Furman, D.E.	1950		89-810	304 ss	Bal.	19.19	0.65	0.53	0.068	8.49	0.024	0.007 S; 0.250 in. diameter by 4.0 in. long; prior to machining, the expansion specimen of commercial grade steel annealed at 1339 K for 30 min., then water quenched.
3	30	Valentich, J.	1965	L	293-806	304 ss								No details given.
4	67	Yaggee, F.L., Gilbert, E.R., and Styles, J.W.	1969	L	273-973	AISI Type 304 ss								Commercial grade alloy containing 950 ppm interstitiates, 6.4 mm O.D. rod.
5*	68	Beenakker, J.J.M. and Swenson, C.A.	1955	L	0-300									Technical grade alloy.
6	69	Martin, W.R. and Weir, J.R.	1961	L	310-1144									No details given.
7	70	Droege, J.W.	1972		293-1094									No details given.
8	34	Technology Utilization Div., NASA	1969	L	19-293	304 L CRES								Specimen prepared in accordance with Rocketdyne Materials and Processes Specifications or equivalent; annealed at 1950 F and water quenched.
9	65	Conway, J.B. and Flagella, P.N.	1968		298-1667	304 L								Data of Fieldhouse, et al.; zero-point correction is 0.008%.

* Not shown in figure.

TABLE 2-9. EXPERIMENTAL DATA ON THE LINEAR THERMAL EXPANSION OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1	
20	-0.306
40	-0.303
60	-0.294
80	-0.281
100	-0.265
120	-0.245
140	-0.222
160	-0.195
180	-0.168
200	-0.140
220	-0.113
240	-0.083
260	-0.052
273	-0.031
280	-0.021
293	0.000
CURVE 2*	
89	-0.271
94	-0.263
100	-0.257
105	-0.249
111	-0.243
117	-0.238
122	-0.231
128	-0.225
133	-0.217
139	-0.213
144	-0.206
150	-0.201
155	-0.192
161	-0.184
167	-0.177
172	-0.172
178	-0.168
183	-0.160
189	-0.152
194	-0.143
200	-0.140
205	-0.130
211	-0.126
217	-0.114
222	-0.104
228	-0.095
233	-0.089
239	-0.083
CURVE 2 (cont.)*	
244	-0.076
250	-0.071
255	-0.058
261	-0.046
267	-0.040
272	-0.029
278	-0.024
283	-0.013
289	-0.005
294	0.002
300	0.012
305	0.018
311	0.028
317	0.037
322	0.044
328	0.055
333	0.063
339	0.073
344	0.082
350	0.091
355	0.100
361	0.107
367	0.118
372	0.128
378	0.134
383	0.145
389	0.151
394	0.161
400	0.172
405	0.182
411	0.191
417	0.199
422	0.207
436	0.236
450	0.259
464	0.281
478	0.309
492	0.334
505	0.358
519	0.383
533	0.402
547	0.429
561	0.455
575	0.484
589	0.507
603	0.536
617	0.563
CURVE 2 (cont.)*	
630	0.588
644	0.614
658	0.636
672	0.667
686	0.695
700	0.724
714	0.741
728	0.768
742	0.809
755	0.831
769	0.858
783	0.887
797	0.917
810	0.945
CURVE 3	
293	0.000
358	0.109
468	0.314
578	0.527
690	0.737
806	0.954
CURVE 4	
273	-0.036
773	0.868
973	1.282
CURVE 5*	
0	-0.263
25	-0.263
50	-0.262
75	-0.252
100	-0.232
125	-0.205
150	-0.175
175	-0.142
200	-0.108
275	-0.038
300	0.042
CURVE 6	
310	0.031
CURVE 6 (cont.)	
523	0.427
811	0.958
1144	1.636
CURVE 7	
293	0.000
298	0.013
323	0.060
373	0.141
423	0.219
473	0.305
523	0.399
573	0.489
623	0.577
673	0.691
723	0.777
773	0.882
823	0.983
873	1.087
923	1.194
973	1.295
1023	1.405
1073	1.515
1094	1.561
CURVE 8	
19	-0.327
33	-0.325
89	-0.295
144	-0.237
200	-0.162
255	-0.075
287	-0.015
293	0.000
CURVE 9	
298	0.008
555	0.408
833	1.118
1111	1.658
1389	2.358
1667	3.008

* Not shown in figure.

e. Thermal Diffusivity

Ten sets of experimental data, all measured within the temperature range 290 to 1400 K, are available in the literature. These experimental data are tabulated in Table 2-12 and shown in Figure 2-4. The information on specimen characterization and measurement condition for the data sets is given in Table 2-11.

The recommended values for AISI 304 stainless steel with residual electrical resistivity of approximately 48.4 $\mu\Omega$ cm were calculated from the formula

$$\alpha = \frac{k}{C_p d}$$

where k is the thermal conductivity, C_p is the specific heat, and d is the density. The recommended thermal conductivity and specific heat values given in previous sections were used directly for the calculations and the recommended thermal linear expansion values were used to derive density values as a function of temperature. The recommended values tabulated in Table 2-10 and shown in Figure 2-4 agree to within ± 8% with the data of Feith et al. [52] (curves 5 and 6).

The uncertainty of the recommended values for the solid steel is estimated to be within ± 10%. The values for the molten steel are provisional with a probable uncertainty of ± 20%.

TABLE 2-10. RECOMMENDED THERMAL DIFFUSIVITY OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Thermal Diffusivity, α, $cm^2 s^{-1}$]

T	α
100	0.0417
150	0.0400
200	0.0389
250	0.0386
273.15	0.0386
293	0.0387
300	0.0388
350	0.0396
400	0.0403
450	0.0416
500	0.0426
550	0.0439
600	0.0450
650	0.0460
700	0.0473
750	0.0483
800	0.0497
850	0.0510
900	0.0520
950	0.0529
1000	0.0538
1100	0.0558
1200	0.0578
1300	0.0593
1400	0.0610
1500	0.0623
1600	0.0635
1670†	0.0639
1727†	0.0481
1800	0.0491
1900	0.0507
2000	0.0526

† Approximate melting range.

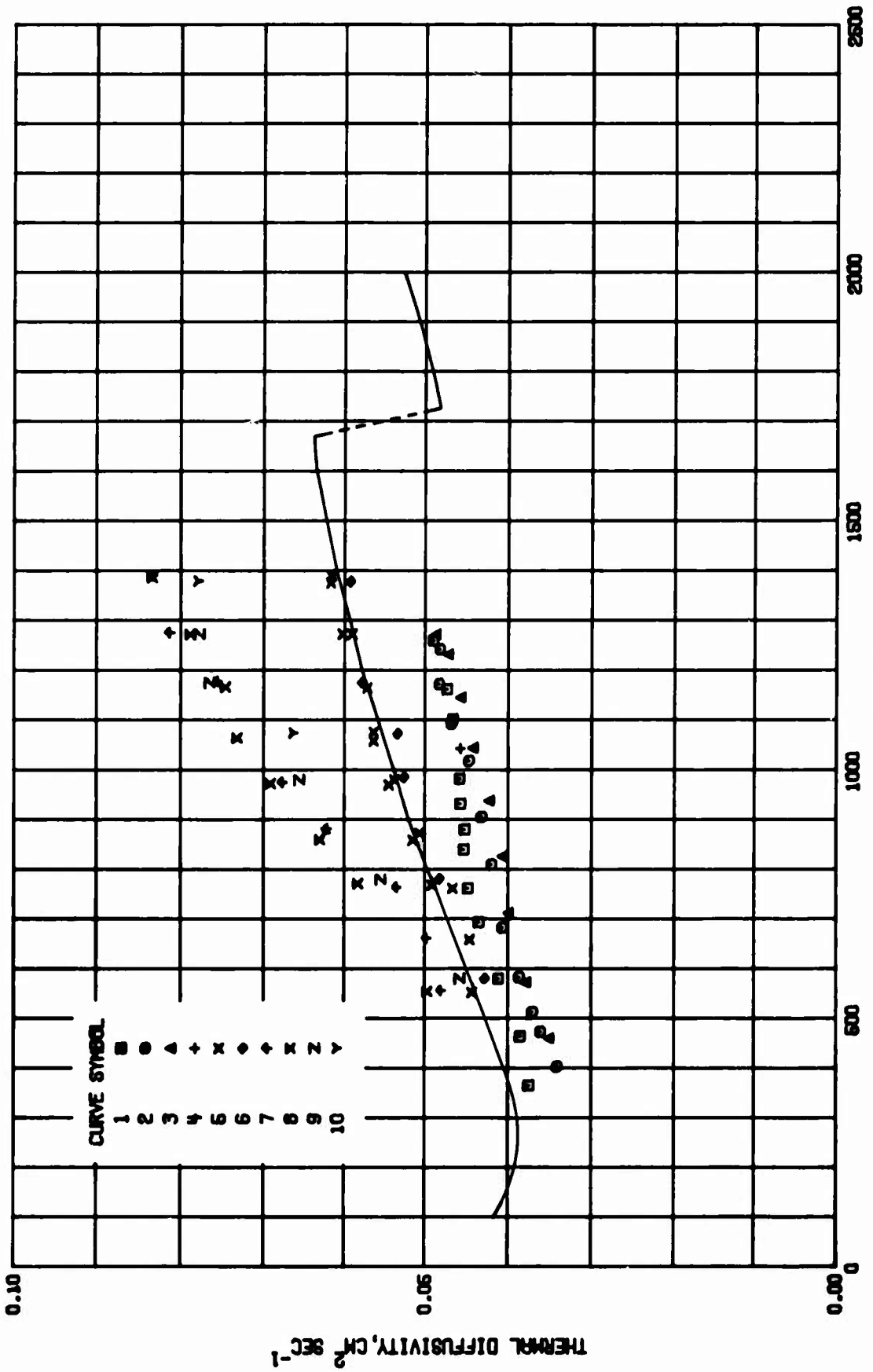

FIGURE 2-4. THERMAL DIFFUSIVITY OF AISI 304 STAINLESS STEEL.

TABLE 2-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF STAINLESS STEEL 304

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent) Fe	Cr	Ni	C	Mn	P	S	Si	Composition (continued), Specifications, and Remarks
1	71, 72, 73	Jenkins, R.J. and Westover, R.W.	1960	T	291-1261		→	18/ 20	8/ 12	0.08 max	2 max	0.045 max	0.03 max	1 max	64.845-70.845 Fe (by difference); nominal composition from Crucible Data Book, Crucible Steel Co. of America, as stated by authors; austenitic; cylindrical specimen 0.5 in. in diameter and 0.080 cm thick; provided by the Crucible Steel Co. of America; cut from No. 2 finish cold rolled sheet steel of thickness indicated, subjected to a minimum of working, and used without further surface preparation (surface very smooth but not a mirror finish); not subjected to any type of heating before the test runs; thermal pulses supplied by a xenon flash tube; diffusivity measured while specimen heated up during 1st cycle; reported error ±5%.
2	71, 72, 73	Jenkins, R.J. and Westover, R.W.	1960	T	403-1243										Same as the above specimen measured during cooling.
3	71, 72, 73	Jenkins, R.J. and Westover, R.W.	1960	T	460-1273										Same as the above specimen measured again during heating in the 2nd cycle.
4	71, 72, 73	Jenkins, R.J. and Westover, R.W.	1960	T	1043										Same as the above specimen measured during cooling.
5	51, 52	Feith, A.D., Hein, R.A., Johnstone, C.P., and Flagella, P.N.	1969	T	552-1390		→	18.37	9.89	0.024	1.31	0.041	0.012	0.70	69.513 Fe (by difference), 0.09 Mo, and 0.05 Cu; polished disk 0.635 cm in diameter and 0.152 cm thick; machined from a 5.08 cm in diameter by 46 cm long bar; annealed; measured by a ruby laser served as the source of a short duration pulse (<1 millisecond) of energy.
6	51, 52	Feith, A.D., et al.	1969	T	580-1379										Same as the above specimen except 0.127 cm thick.
7	74	Conway, J.B. and Flagella, P.N.	1968	T	556-1391			18.37	9.89	0.024	1.31	0.014	0.012	0.70	0.09 Mo and 0.05 Cu; 0.63 cm diameter by 0.152 cm thick; measured in argon; laser used as heat source.
8	74	Conway, J.B. and Flagella, P.N.	1968	T	554-1387										Same as the above specimen.
9	74	Conway, J.B. and Flagella, P.N.	1968	T	580-1273										Similar to the above specimen except 0.127 cm in thickness.
10	74	Conway, J.B. and Flagella, P.N.	1968	T	874-1380										Same as the above specimen measured at cooling.

TABLE 2-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF STAINLESS STEEL 304

[Temperature, T, K; Thermal Diffusivity, α, $cm^2 s^{-1}$]

T	α
CURVE 1	
291	0.0356
366	0.0376
465	0.0386
581	0.0412
695	0.0435
763	0.0448
841	0.0453
881	0.0452
933	0.0457
983	0.0458
1103	0.0466
1163	0.0473
1261	0.0490
CURVE 2	
403	0.0342
473	0.0362
513	0.0372
583	0.0387
683	0.0407
810	0.0420
906	0.0432
1018	0.0447
1093	0.0468
1173	0.0483
1243	0.0482
CURVE 3	
460	0.0352
573	0.0380
713	0.0400
827	0.0407
938	0.0423
1045	0.0442
1146	0.0457
1233	0.0472
1273	0.0487
CURVE 4	
1043	0.0457
CURVE 5	
552	0.0443
658	0.0446
762	0.0466
768	0.0492
859	0.0515
873	0.0507
970	0.0545
980	0.0538
1058	0.0564
1076	0.0564
1165	0.0572
1273	0.0591
1273	0.0603
1376	0.0618
1390	0.0617
CURVE 6	
580	0.0428
781	0.0482
986	0.0526
1073	0.0534
1176	0.0578
1379	0.0593
CURVE 7	
556	0.0480
662	0.0498
764	0.0535
882	0.0622
975	0.0678
1178	0.0756
1276	0.0813
1391	0.0833
CURVE 8	
554	0.0497
772	0.0583
860	0.0631
973	0.0692
1065	0.0732
1167	0.0746
1273	0.0789
1387	0.0833
CURVE 9	
580	0.0458
780	0.0555
980	0.0657
1176	0.0766
1273	0.0778
CURVE 10	
874	0.0624
1075	0.0664
1380	0.0779

3.3. Pyroceram (Corning 9606)

Pyroceram is a generic name for a group of microcrystalline glass-ceramic materials, which were developed by the Corning Glass Works, Corning, New York 14830.

Pyroceram brand glass-ceramic Code 9606 (Corning 9606) is a magnesia aluminosilicate glass-ceramic (composed of silicon dioxide, aluminum oxide, magnesium oxide, and a small amount of titanium dioxide). The ingredients are melted together at a temperature of the order of 1900 K using special techniques to insure uniform composition, constant density, freedom from bubbles and striations, and uniform electrical properties. Corning Pyroceram 9606 is non-porous, considerably harder than glass, opaque, and gray in color.

Corning Pyroceram 9606 is primarily used in military products and specifically as missile radomes since it has uniform electrical properties at elevated temperatures and the ability to pass R.F. signals. Other properties which make it useful for radome applications are good thermal shock and rain erosion characteristics.

According to Corning Pyroceram 9606 Data Sheets [75], its physical properties include softening point of 1623 K, density of 2.6 g cm^{-3}, porosity (void volume) of 0.00%, water absorption of 0.00%, and being impermeable to gass. Mechanical properties of Corning 9606 include strength to weight ratio (modulus of rupture to specific gravity) of 13.5 x 10^3 psi at 293 K, Young's modulus of 17.4 x 10^6 psi at 293 K, shear modulus of 6.9 x 10^6 psi at 293 K, Poisson's ratio of 0.245 at 293 K, modulus of rupture of 35 x 10^3 psi at 293 K, Knoop hardness of 619 kg mm^{-2} with a 500 gram load, and Knoop hardness of 698 kg mm^{-2} with a 100 gram load. Electrical properties include loss factor of 0.8% at 293 K and dielectric strength of 350 V rms mil^{-1} at 293 K and 60 cps.

a. Thermal Conductivity

Twelve sets of experimental data are available. Three of these are single points. No measurement was made between 4 and 100 K. The experimental data are tabulated in Table 3-3 and shown in Figure 3-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 3-2.

The recommended values tabulated in Table 3-1 and shown in Figure 3-1 are based on the data of Flynn [76] (curve 4) and Robinson and Flynn [77] (curves 7-9). According to Flynn, annealing has no effect on the thermal conductivity of Corning Pyroceram 9606. The uncertainty of the recommended values is within ± 10%.

TABLE 3-1. RECOMMENDED THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
100	0.0525
110	0.0549
120	0.0560
130	0.0556
150	0.0544
200	0.0478
250	0.0428
273.15	0.0413
293	0.0402
300	0.0398
350	0.0379
400	0.0364
450	0.0353
500	0.0343
550	0.0335
600	0.0328
650	0.0322
700	0.0317
750	0.0312
800	0.0308
850	0.0304
900	0.0300
950	0.0298
1000	0.0296
1100	0.0291
1200	0.0287
1300	0.0284
1400	0.0281
1500	0.0279
1600	0.0277

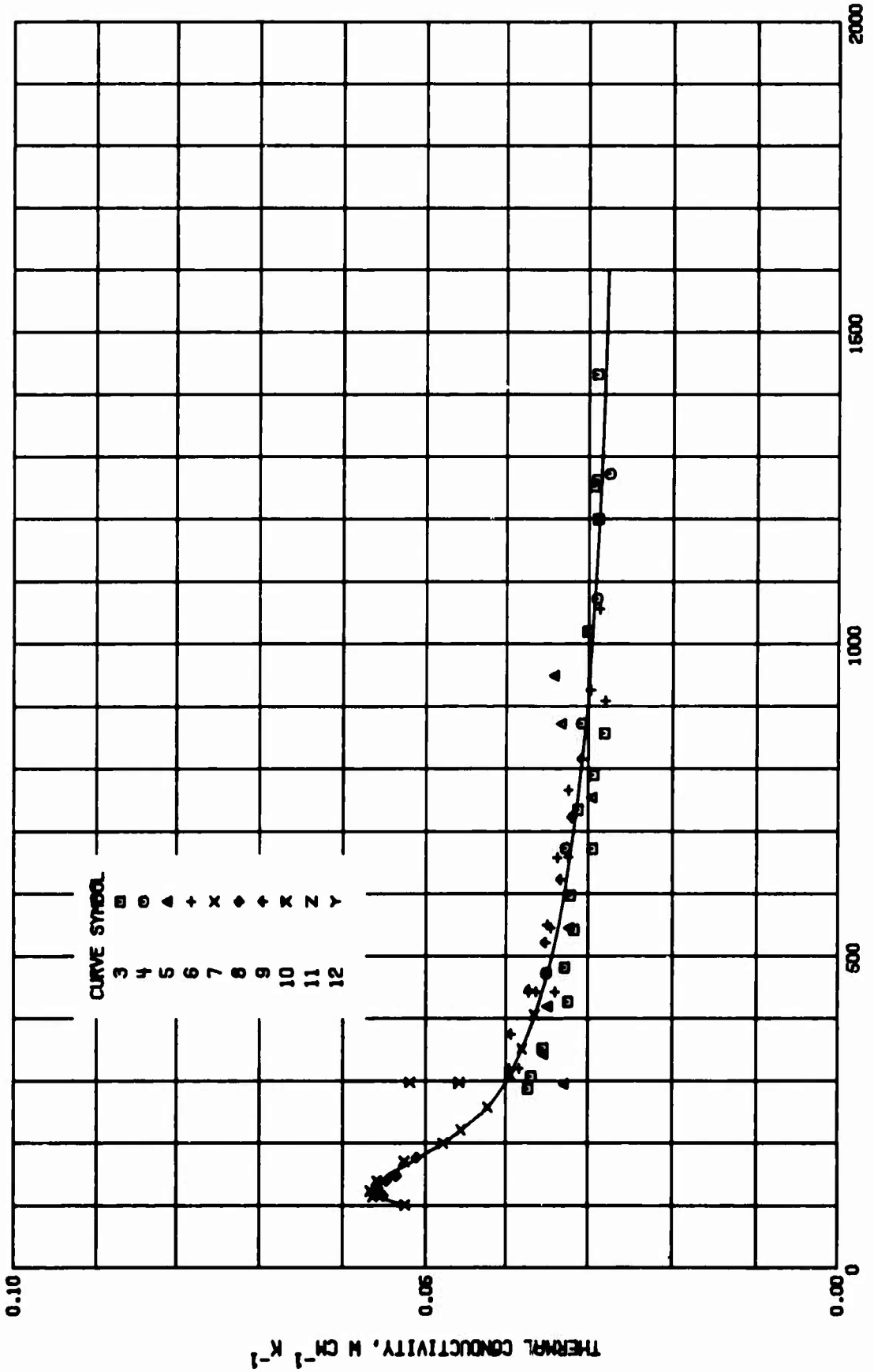

FIGURE 3-1. THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606).

TABLE 3-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	78	Chang, G.K. and Jones, R.E.	1962	L	2.7-3.9		From Corning Glass Works; specimen cross-section 0.034 cm x 1.666 cm.
2*	78	Chang, G.K. and Jones, R.E.	1962	L	1.6-3.9		From Corning Glass Works; specimen cross-section 0.130 cm x 1.607 cm.
3	79	Rudkin, R.L.	1963	P	288-1433		From Corning Glass Works; calculated from thermal diffusivity data.
4	76, 80	Flynn, D.R. and Robinson, H.E.	1962	L	473-1273		Pyroceram 9606 (a microcrystalline glass), product of Corning Glass Works; specimen 2.540 cm in diameter and 1.269 cm in length; density 2.601 g cm^{-3}; data obtained before and after the specimen held at 1000 C for about 275 hr agree with each other.
5	81	Braman, R.S.	1962	L	295-950		Specimen 2 in. long.
6	82, 83	Bienert, W.B., Trimmer, D.S., and Skrabek, E.A.	1966	L	320-1057		Cylindrical shape specimen between 1/4 and 1/2 in. diameter and up to 1/2 in. long.
7	77, 84	Flynn, D.R., Robinson, H.E., and Martz, I.L.	1964	L	101-474		4.4 cm diameter x 31 cm long; diatomaceous earth used as insulation material; data taken from smooth curve.
8	77, 84	Flynn, D.R., et al.	1964	L	101-177		The above specimen; opacified silica aerogel used as insulation material; data taken from smooth curve.
9	77, 84	Flynn, D.R., et al.	1964	L	375-927		The above specimen measured in a high temperature apparatus; data taken from smooth curve.
10	85	Peggs, I.D. and Mills, R.W.	1970	P	298		0.437 cm diameter x 0.025 cm thick.
11	85	Peggs, I.D. and Mills, R.W.	1970	P	298		0.472 cm diameter x 0.025 cm thick.
12	85	Peggs, I.D. and Mills, R.W.	1970	P	298		0.467 cm diameter x 0.057 cm thick

* Not shown in figure.

TABLE 3-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
CURVE 1*	
2.65	0.0027
2.74	0.0029
3.16	0.0041
3.56	0.0053
3.94	0.0068
CURVE 2*	
1.56	0.0012
1.59	0.0011
1.90	0.0017
2.10	0.0020
2.43	0.0029
2.67	0.0039
2.91	0.0045
3.18	0.0057
3.45	0.0067
3.70	0.0080
3.91	0.0090
CURVE 3	
288	0.0372
308	0.0368
353	0.0354
428	0.0324
483	0.0328
543	0.0317
598	0.0321
673	0.0295
735	0.0312
791	0.0294
858	0.0281
1021	0.0301
1201	0.0289
1253	0.0294
1263	0.0290
1433	0.0290
CURVE 4	
473	0.0350
673	0.0327
873	0.0308
1073	0.0290
1273	0.0275

T	k
CURVE 5	
295	0.0329
343	0.0354
420	0.0349
546	0.0323
755	0.0296
873	0.0333
950	0.0342
CURVE 6	
320	0.0396
320	0.0383
442	0.0371
443	0.0362
443	0.0340
546	0.0345
550	0.0349
658	0.0337
659	0.0323
766	0.0323
769	0.0324
909	0.0280
1057	0.0287
CURVE 7	
101	0.0526
114	0.0564
124	0.0567
140	0.0559
171	0.0527
200	0.0479
221	0.0457
258	0.0423
310	0.0394
351	0.0379
406	0.0364
474	0.0349
CURVE 8	
101	0.0526
116	0.0551
118	0.0557
128	0.0558
140	0.0547
148	0.0536
177	0.0512

T	k
CURVE 9	
375	0.0393
446	0.0370
522	0.0351
623	0.0333
723	0.0319
816	0.0307
927	0.0297
CURVE 10	
298	0.052
CURVE 11	
298	0.046
CURVE 12	
298	0.046

* Not shown in figure.

b. Specific Heat

There is only one data set available for the specific heat of Pyroceram 9606. The measurement was carried out at the Corning Glass Works [86] (curve 1). The information on the specimen characterization and measurement condition is given in Table 3-5. The experimental data are tabulated in Table 3-6 and shown in Figure 3-2.

The provisional values shown in Figure 3-2 and tabulated in Table 3-4 are derived from the above measurement. Above 1300 K the values are extrapolated. The uncertainty of the provisional values is about ± 7% below 1300 K and about ± 15% above that temperature.

TABLE 3-4. PROVISIONAL SPECIFIC HEAT OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
300	0.193
350	0.206
400	0.217
450	0.226
500	0.234
550	0.242
600	0.248
650	0.254
700	0.260
750	0.264
800	0.268
850	0.273
900	0.278
950	0.282
1000	0.286
1050	0.291
1100	0.294
1150	0.298
1200	0.302
1250	0.308
1300	0.316
1400	0.336
1500	0.358
1600	0.383

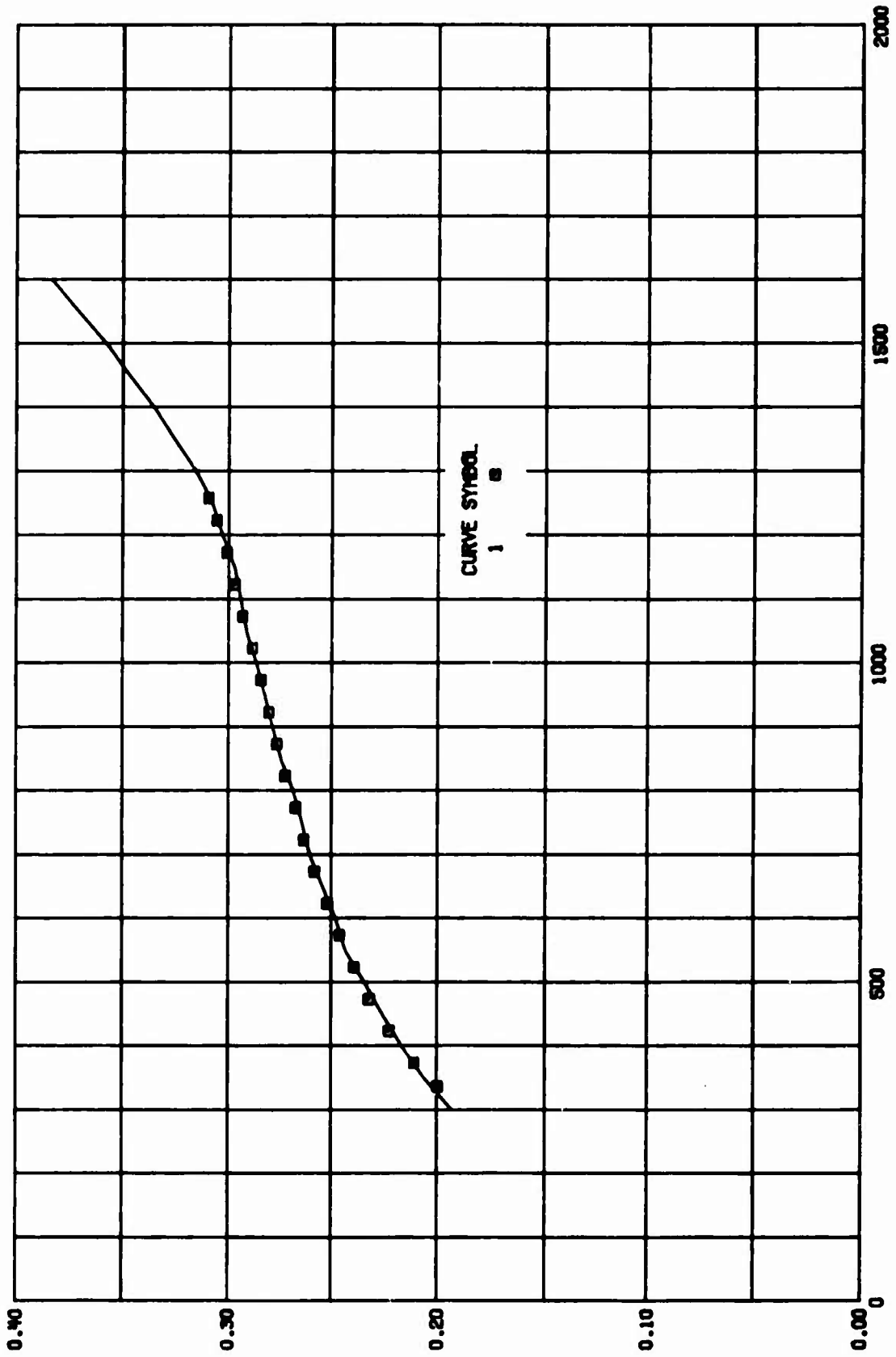

FIGURE 3-2. SPECIFIC HEAT OF PYROCERAM (CORNING 9606).

TABLE 3-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF PYROCERAM (CORNING 9606)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	86	Corning Glass Works	1958		336-1258		Hard, fine-grained crystalline material formed from special glasses; density 2.6 g cm^{-3}.

TABLE 3-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 1		CURVE 1 (cont.)	
336	0.200	1173	0.301
373	0.211	1223	0.306
423	0.223	1258	0.310
473	0.232		
523	0.239		
573	0.246		
623	0.252		
673	0.258		
723	0.263		
773	0.267		
823	0.272		
873	0.276		
923	0.280		
973	0.284		
1023	0.288		
1073	0.293		
1123	0.297		

c. Heat of Fusion

No experimental data for the heat of fusion of Pyroceram (Corning 9606) or any comparable material were located in the literature. Corning Glass Works [86] reported a value of 1623 K for the softening point of this material.

d. Thermal Linear Expansion

There is only one set of data available for thermal linear expansion of Pyroceram (Corning 9606). The measurement was carried out at the Corning Glass Works [86] (curve 1). The information on the specimen characterization and measurement condition is given in Table 3-8. The experimental data are tabulated in Table 3-9 and shown in Figure 3-3. The provisional values shown in Figure 3-3 and tabulated in Table 3-7 are derived from the above measurement. It is worth noting that Corning Glass Works [86] (curve 1) found an anomaly of an unexplainable nature near 300 K. Their specific heat and conductivity measurements on a similar material fail to show such anomaly. The uncertainty of the provisional vaues is ± 10%.

The values of the instantaneous coefficient of thermal linear expansion, α, are obtained both from the α values reported by the Corning Glass Works [86] and by differentiation of empirical equations which are used to fit the thermal linear expansion data. The values at and above 400 K are provisional and their uncertainty is ± 15%, and those below 400 K are typical values which are very uncertain.

TABLE 3-7 PROVISIONAL THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α
293	0.000	1.9‡
300	0.002	2.5‡
325	0.010	5.2‡
350	0.023	6.9‡
400	0.061	7.6
450	0.095	5.4
500	0.114	3.6
550	0.132	3.7
600	0.150	3.8
650	0.169	3.9
700	0.189	3.9
750	0.208	4.0
800	0.229	4.1
850	0.250	4.2
900	0.272	4.2
950	0.293	4.3
1000	0.314	4.4
1100	0.358	4.6
1200	0.401	4.7
1300	0.441	4.8

‡ Typical value.

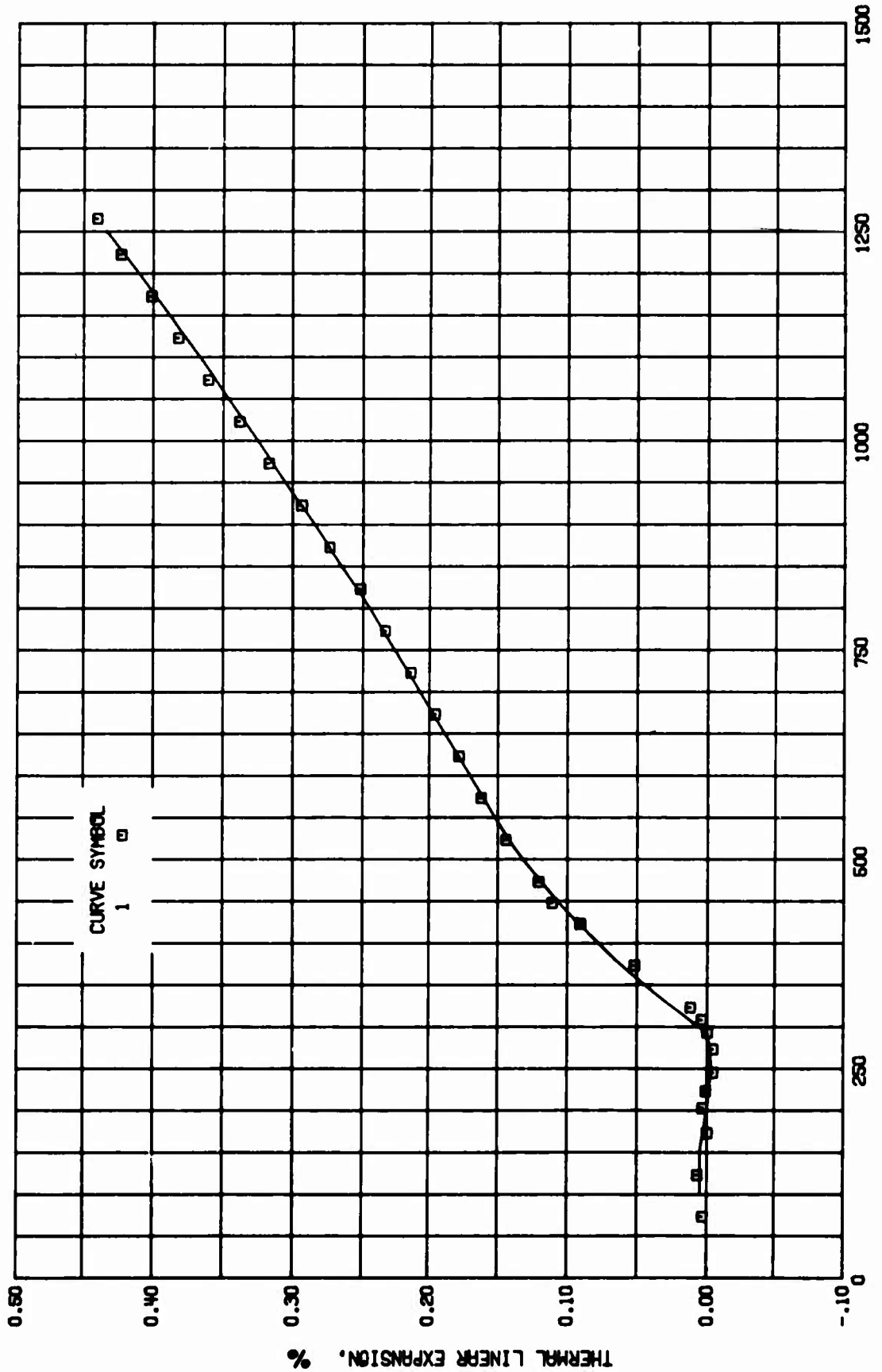

FIGURE 3-3. THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606).

TABLE 3-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	86	Corning Glass Works	1958		73-1266		Hard, fine-grained crystalline material formed from special glasses; density 2.6 g cm^{-3}.

TABLE 3-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 1		CURVE 1 (cont.)	
73	0.003	723	0.214
123	0.007	773	0.233
173	0.000	823	0.252
203	0.003	873	0.274
223	0.001	923	0.294
245	-0.004	973	0.317
273	-0.004	1023	0.338
293	0.000	1073	0.361
308	0.004	1123	0.382
323	0.012	1173	0.401
373	0.052	1223	0.423
423	0.091	1266	0.440
448	0.111		
473	0.121		
523	0.144		
573	0.162		
623	0.178		
673	0.195		

e. Thermal Diffusivity

Seven sets of experimental data are available in the literature. The data are tabulated in Table 3-12 and shown partially in Figure 3-4. The information on specimen characterization and measurement condition for the data sets is given in Table 3-11.

The recommended values are calculated from the equation

$$\alpha = \frac{k}{C_p d}$$

using the recommended thermal conductivity, specific heat, and thermal linear expansion. The values agree to within ± 10% with all the experimental data.

The recommended values are tabulated in Table 3-10 and shown in Figure 3-4. The uncertainty of the values is within ± 10%.

TABLE 3-10. RECOMMENDED THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Diffusivity, α, $cm^2\ s^{-1}$]

T	α
293	0.0194
300	0.0190
350	0.0170
400	0.0155
450	0.0143
500	0.0135
550	0.0128
600	0.0122
650	0.0117
700	0.0112
750	0.0108
800	0.0105
850	0.0102
900	0.0997
950	0.0975
1000	0.0955
1100	0.00921
1200	0.00893
1300	0.00872
1400	0.00858

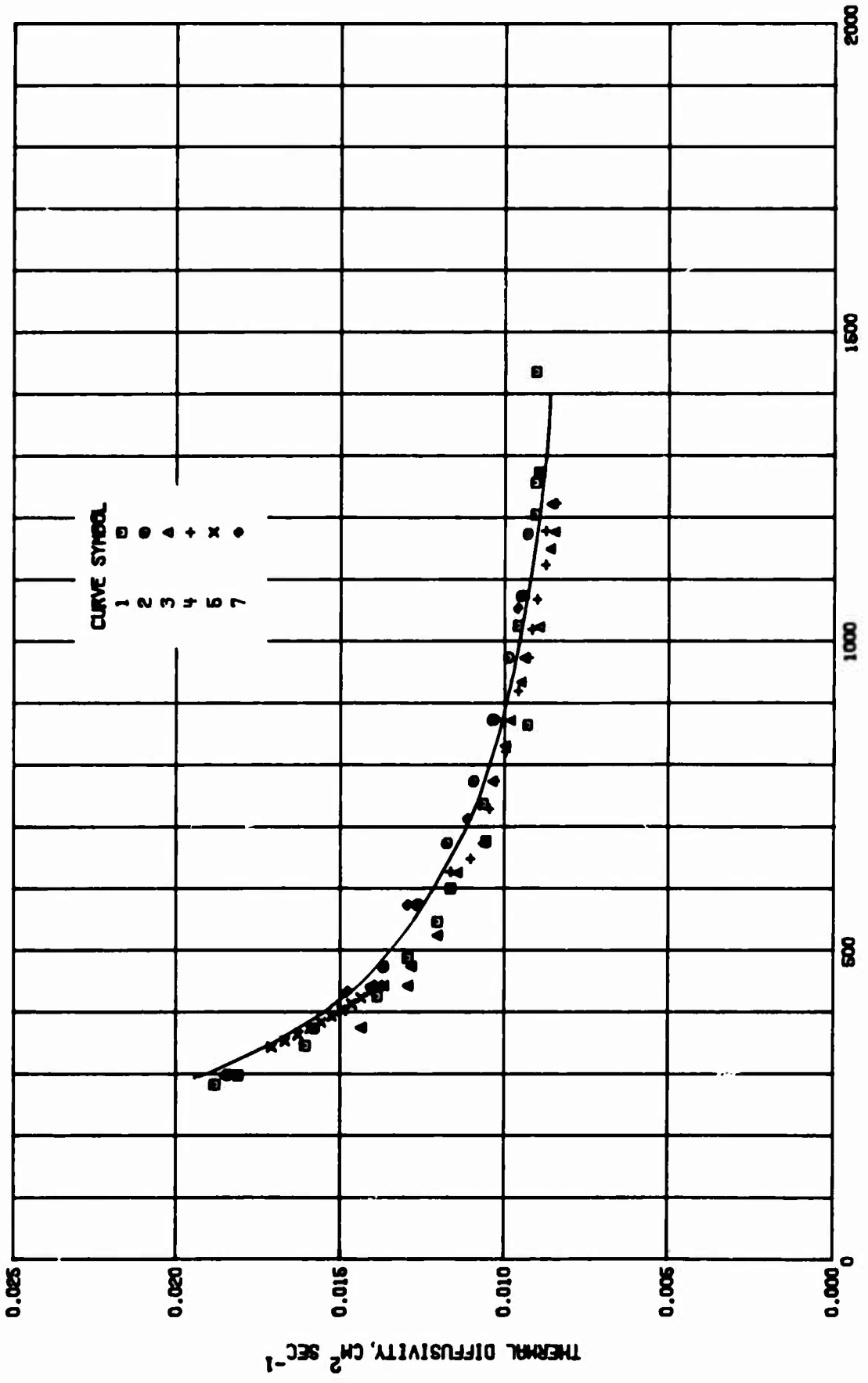

FIGURE 3-4. THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606).

TABLE 3-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	79, 87	Rudkin, R. L.	1963	T	283-1436		Glass-ceramic; disc specimen 0.75 in. in diameter and ~0.045 in. thick; developed at Corning Glass Works; coated on both sides with evaporated tungsten using electron beam techniques; short pulse of thermal energy from a xenon flash lamp absorbed at front surface of specimen; diffusivity determined from measured temperature-time function of the rear surface; measured in vacuum of $\sim 10^{-5}$ mm Hg; measurements below 873.2 K carried out in resistance furnace, measurements above 873.2 K made in vacuum induction furnace; reported error ±5 to ±10%.
2	88	Plummer, W. A., Campbell, D. E., and Comstock, A. A.	1962	T	298-1173		Specimen composed of three pieces: middle piece and two end pieces; middle piece separated from bottom piece by a 0.005 in. thick chromel sheet 7.6 x 18 cm forming the heat source, middle piece separated from upper piece by a 0.005 in. thick chromel sheet forming the heat sink; thicknesses on either side of the heater are the same; entire assembly constitutes a sandwich 12.7 cm long, 7.6 cm wide and at least 4 to 5 cm thick; diffusivity determined from measured ratio of the temperature rises of the heat source and sink; unidimensional heat flow; reported error ~15%.
3	89	Gibby, R. L.	1968	T	375-1272		Cylindrical specimen 0.63 cm in diameter and 0.0544 cm thick; laser beam used as the pulse energy source; diffusivity determined from measured temperature history of the rear surface; both surfaces coated with colloidal graphite suspension; all data corrected for finite-pulse-time effects and heat losses; reported error ±9%.
4	89	Gibby, R. L.	1968	T	626-1223		Same as the above specimen measured for diffusivity during cooling; other conditions same as above.
5	90	Flieger, H.W., Jr.	1963		343-973		Microcrystalline specimen, 2 in. in diameter and 14 in. long; diffusivity measured in series 1.
6*	90	Flieger, H.W., Jr.	1963		343-1273		Same as the above specimen; diffusivity measured in series 2.
7	91	Plummer, W.A.	1963		298-1053		Specimen 12.7 cm by 7.6 cm.

* Not shown in figure.

TABLE 3-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Diffusivity, α, $cm^2 s^{-1}$]

T	α
CURVE 1	
283	0.0188
298	0.0181
346	0.0161
426	0.0139
488	0.0130
546	0.0121
600	0.0117
676	0.0106
737	0.0107
795	0.0100
865	0.00930
1025	0.00960
1205	0.00905
1256	0.00905
1273	0.00895
1436	0.00903
CURVE 2	
298	0.0184
373	0.0158
473	0.0137
573	0.0127
673	0.0118
773	0.0110
873	0.0104
973	0.0099
1073	0.0095
1173	0.0093
CURVE 3	
375	0.0144
443	0.0137
443	0.0141
443	0.0130
474	0.0129
476	0.0126
524	0.0121
581	0.0122
625	0.0115
673	0.0107
773	0.0104
831	0.0100
872	0.00983
934	0.00950
973	0.00941
CURVE 3 (cont.)	
1023	0.00892
1075	0.00939
1149	0.00858
1177	0.00844
1222	0.00856
1272	0.00889
CURVE 4	
626	0.0117
647	0.0111
728	0.0105
773	0.0103
821	0.00998
919	0.00958
973	0.00924
1019	0.00916
1067	0.00898
1123	0.00872
1178	0.00872
1223	0.00840
CURVE 5	
343	0.01709
353	0.01669
363	0.01630
373	0.01594
383	0.01560
393	0.01527
403	0.01496
413	0.01467
423	0.01439
433	0.01412
443	0.01386
453	0.01391
463	0.01375
473	0.01359
483	0.01344
493	0.01329
503	0.01315
513	0.01301
523	0.01287
533	0.01274
543	0.01261
553	0.01249
563	0.01237
CURVE 5 (cont.)	
573	0.01225
583	0.01214
593	0.01203
603	0.01192
613	0.01182
623	0.01172
633	0.01163
643	0.01153
653	0.01144
663	0.01136
673	0.01127
683	0.01119
693	0.01111
703	0.01104
713	0.01096
723	0.01089
733	0.01082
743	0.01075
753	0.01069
763	0.01062
773	0.01056
783	0.01050
793	0.01044
803	0.01039
813	0.01033
823	0.01028
833	0.01023
843	0.01018
853	0.01013
863	0.01008
873	0.01004
883	0.00999
893	0.00995
903	0.00991
913	0.00986
923	0.00982
933	0.00978
943	0.00975
953	0.00971
963	0.00967
973	0.00964
CURVE 6*	
343	0.01663
353	0.01659
363	0.01622
CURVE 6 (cont.)*	
373	0.01587
383	0.01554
393	0.01522
403	0.01492
413	0.01464
423	0.01437
433	0.01411
443	0.01386
453	0.01381
463	0.01361
473	0.01342
483	0.01325
493	0.01308
503	0.01292
513	0.01277
523	0.01263
533	0.01249
543	0.01236
553	0.01223
563	0.01211
573	0.01200
583	0.01189
593	0.01178
603	0.01168
613	0.01158
623	0.01148
633	0.01139
643	0.01130
653	0.01121
663	0.01113
673	0.01105
683	0.01097
693	0.01089
703	0.01082
713	0.01074
723	0.01067
733	0.01060
743	0.01053
753	0.01047
763	0.01040
773	0.01034
783	0.01028
793	0.01022
803	0.01016
813	0.01011
823	0.01005
833	0.00999
CURVE 6 (cont.)*	
843	0.00994
853	0.00989
863	0.00984
873	0.00979
883	0.00974
893	0.00969
903	0.00964
913	0.00959
923	0.00955
933	0.00950
943	0.00946
953	0.00942
963	0.00937
973	0.00933
983	0.00929
993	0.00925
1003	0.00921
1013	0.00917
1023	0.00913
1033	0.00910
1043	0.00906
1053	0.00902
1063	0.00899
1073	0.00895
1083	0.00892
1093	0.00888
1103	0.00885
1113	0.00882
1123	0.00878
1133	0.00875
1143	0.00872
1153	0.00869
1163	0.00866
1173	0.00863
1183	0.00860
1193	0.00857
1203	0.00854
1213	0.00851
1223	0.00848
1233	0.00846
1243	0.00843
1253	0.00840
1263	0.00837
1273	0.00835
CURVE 7	
298	0.0185
433	0.0148
573	0.0130
713	0.0112
873	0.0103
1053	0.0096

* Not shown in figure.

3.4. Silicon Nitride (Si_3N_4)

Bulk silicon nitride is manufactured by reacting silicon powder with nitrogen at elevated temperatures (above 1573 K). It is used as a hard refractory material in high-temperature ceramic applications with a useful service temperature of about 1500 K. It dissociates at about 2200 K. It has been reported [92] that there are two types of crystal structure of silicon nitride, α-Si_3N_4 and β-Si_3N_4, both of which are hexagonal but with different lattice constants in the c-axis. It has also been reported [93] that silicon nitride has four types of crystal structure. Silicon nitride is a good electrical insulator with reported electrical resistivity of 10^{12} Ω cm at room temperature and 10^6 cm at 1300 K. It has a very low coefficient of thermal expansion; as a result, its thermal shock resistance is very good so that it can be used as a high-temperature radome material. Its theoretical room-temperature density is 3.16 g cm^{-3} [95].

Dense silicon nitride is produced by hot pressing and sintering silicon powder compact in a nitrogen atmosphere at high pressure and at a temperature near the melting point of silicon (1687 K). Using this technique, laboratory preparations have resulted in samples of 98% purity.

There is considerable increase of interest in silicon nitride thin films for microelectronic applications in the recent years. Silicon nitride films can be prepared by several different deposition techniques: direct nitridation, evaporation, glow discharge (dc and rf), sputtering (dc, rf, and reactive), and pyrolysis (chemical vapor deposition). The reactive sputtering and pyrolysis methods have been most frequently utilized. In each of these deposition methods, several parameters can be varied: temperature, flow rate, plasma density, pressure or degree of vacuum, ratio of reactants, and electric field. Prior to deposition, the substrates are usually given a mechanical lap followed by a mechanical or chemical polish. Heat treatment of the film is also utilized.

a. Thermal Conductivity

There are 36 sets of data available for the thermal conductivity of silicon nitride. Most of the measurements are on porous specimens with density ranging from approximately 2.0 g cm^{-3} to 2.8 g cm^{-3}, and only two sets (curves 3 and 24) are on nearly nonporous specimens (density $\approx$ 3.1 g cm^{-3}). The experimental data are tabulated in Table 4-3 and shown partially in Figure 4-1. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-2. The existing evidence seems to indicate that the thermal conductivity of silicon nitride depends not only on porosity and purity, but also on the relative abundance of the α and the β phases

and on the method of fabrication [95, 96]. For these reasons, only provisional values are given for the thermal conductivity. The values for a porous polycrystalline specimen of density 2.4 g cm^{-3} (approximate porosity 75%) are based on the data of Wells [96] at higher temperatures and of Godfrey and Lindley [95] at room temperature. The uncertainty of the provisional values is about ± 20%.

The thermal conductivity values for non-porous polycrystalline silicon nitride are estimated from those for the porous silicon nitride using the expression given by Koh and Fortini [156]:

$$\frac{k}{k_o} = \frac{1 - P}{1 + 11P^2}$$

where k and k_o are the thermal conductivities of the porous and the non-porous materials, respectively, and P is the porosity. The resulting values agree quite well with the data of Powell and Tye [94] (Curve 24) over the temperature range of their measurement, both in temperature dependence and in magnitude. Their uncertainty is estimated to be about ± 15% below 400 K and ± 25% at higher temperatures.

TABLE 4-1. PROVISIONAL THERMAL CONDUCTIVITY OF SILICON NITRIDE (Si_3N_4)

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	
	Density 2.4 g cm^{-3}	Density 3.16 g cm^{-3}
273.15	0.167	0.360
293	0.162	0.349
300	0.160	0.343
350	0.148	0.319
400	0.139	0.299
450	0.131	0.282
500	0.125	0.268
550	0.118	0.254
600	0.113	0.243
650	0.109	0.235
700	0.105	0.226
750	0.101	0.218
800	0.0988	0.213
850	0.0951	0.205
900	0.0924	0.199
950	0.0899	0.194
1000	0.0876	0.189
1100	0.0836	0.180
1200	0.0800	0.172
1300	0.0769	0.166
1400	0.0741	0.160
1500	0.0716	0.154
1600	0.0693	0.149
1700	0.0672	0.145
1800	0.0653	0.141
1900	0.0636	0.137
2000	0.0620	0.134

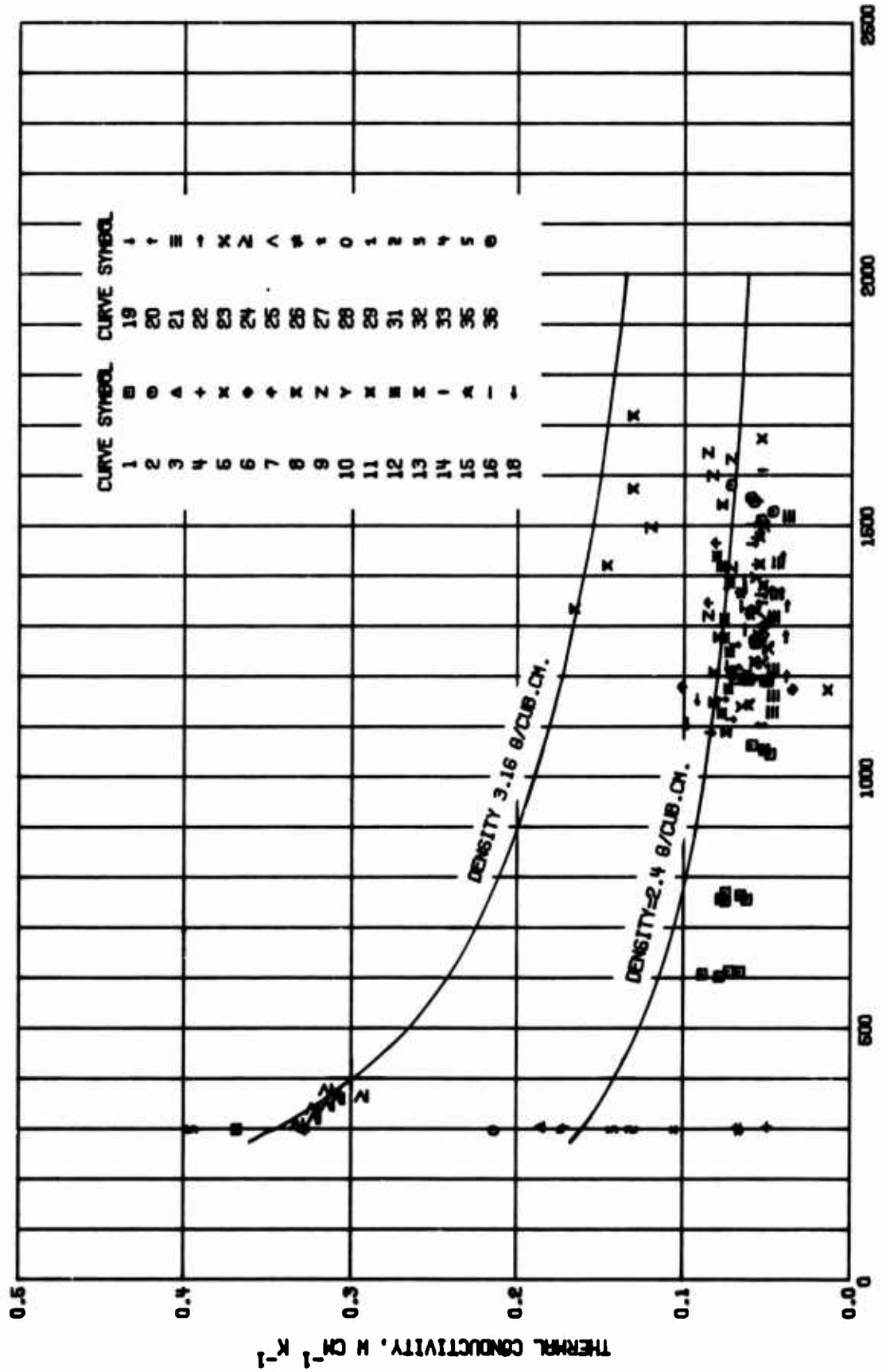

FIGURE 4-1. THERMAL CONDUCTIVITY OF POLYCRYSTALLINE SILICON NITRIDE.

TABLE 4-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF SILICON NITRIDE Si_3N_4

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	61, 98	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962	R	603-1195		Impurities 0.05 Ca, 0.01 Cu, 0.01 Mg, 0.3 Al, 1.5 Fe, 0.01 Ti, and trace Be, Na, and Mn; cast; specimen 3/4 in. O.D. 1/4 in. I.D. 3/4 in. long; density 2.38 g cm^{-3}; reported error 2.5%.
2	61, 98	Neel, D.S., et al.	1962	R	1267-2061		Second run of the above specimen; melted during run.
3	99, 100	Powell, R.W. and Tye, R.P.	1962	C	303		Density 3.16 g cm^{-3}; data read from ca[illegible]tion of a direct-reading thermal comparator.
4	99, 100	Powell, R.W. and Tye, R.P.	1962	C	303		Data for specimen of density 2.34 g cm^{-3}.
5	101	Swarts, E.L. and Crandall, W.B.	1955	P	1173, 1673		Porosity 70%; thermal conductivity calculated from measured thermal diffusivity, density, and specific heat.
6	101	Swarts, E.L. and Crandall, W.B.	1955	P	1173.2		Similar to the above specimen but porosity 85%.
7	96	Wells, W.M.	1964	R	1178-1465	RD	1.25 in. O.D. x 0.25 in. I.D. x 1.25 in. long; density 2.33 g cm^{-3}.
8	96	Wells, W.M.	1964	R	1334-1719	LRL	Similar to the above specimen but density 2.5 g cm^{-3}.
9	96	Wells, W.M.	1964	R	1320-1644	EC	Similar to the above specimen but density 2.1 g cm^{-3}.
10	96	Wells, W.M.	1964	R	1139-1396	H-3-TS	Similar to the above specimen but density 2.21 g cm^{-3}.
11	96	Wells, W.M.	1964	R	1204-1477	H-2-TS	Similar to the above specimen but density 2.32 g cm^{-3}.
12	96	Wells, W.M.	1964	R	1126-1439	EC-1-TS	Similar to the above specimen.
13	96	Wells, W.M.	1964	R	1088-1542	EC-3-TS	Similar to the above specimen.
14	96	Wells, W.M.	1964	R	1178-1610	EC-7-TS	Similar to the above specimen but density 2.22 g cm^{-3}.
15	96	Wells, W.M.	1964	R	1143-1366	EC-2-TS	Similar to the above specimen but density 2.34 g cm^{-3}.
16	96	Wells, W.M.	1964	R	1186-1391	N-10-TS	Similar to the above specimen but density 2.38 g cm^{-3}.
17*	96	Wells, W.M.	1964	R	1180-1384	N-1-TS	Similar to the above specimen.
18	96	Wells, W.M.	1964	R	1106-1436	N-5-TS	Similar to the above specimen but density 2.33 g cm^{-3}.
19	96	Wells, W.M.	1964	R	1087-1501	N-6-TS	Similar to the above specimen but density 2.32 g cm^{-3}.
20	96	Wells, W.M.	1964	R	1103-1471	CS-1-TS	Similar to the above specimen but density 2.01 g cm^{-3}.
21	96	Wells, W.M.	1964	R	1128-1519	CS-2-TS	Similar to the above specimen but density 2.15 g cm^{-3}.
22	96	Wells, W.M.	1964	R	1199-1436	CS-3-TS	Similar to the above specimen but density 2.07 g cm^{-3}.
23	96	Wells, W.M.	1964	R	1143-1499	CS-4-TS	Similar to the above specimen but density 2.17 g cm^{-3}.
24	94	Powell, R.W. and Tye, R.P.	1969	C	309-377		High purity; specimen square section area 0.000091 m^2; supplied by Messrs. Plessey, U.K. Ltd.; density 3.1 g cm^{-3}.
25	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1471	Flame sprayed; density 2.84 g cm^{-3}; thermal conductivity value calculated from measured thermal diffusivity using the literature data of specific heat.
26	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1473	Density 1.99 g cm^{-3}.

* Not shown in figure.

TABLE 4-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF SILICON NITRIDE Si_3N_4 (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
27	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1474	Density 2.00 g cm^{-3}.
28	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1475	Density 2.34 g cm^{-3}.
29	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1478	Density 2.43 g cm^{-3}.
30*	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1482	Density 2.63 g cm^{-3}.
31	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AME	Density 2.52 g cm^{-3}.
32	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	BSA	Density 2.47 g cm^{-3}.
33	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	Lucas	Flame sprayed; density 2.58 g cm^{-3}.
34*	95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	Lucas	Hot-pressed; density 3.07 g cm^{-3}.
35	102	Lange, F.F.	1972	L	298		0.5 x 0.25 x 0.25 in.; hot-pressed; heat flow perpendicular to pressing direction; reported error 2%.
36	102	Lange, F.F.	1972	L	298		Similar to the above specimen but heat flow parallel to pressing direction.

* Not shown in figure.

TABLE 4-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF SILICON NITRIDE Si_3N_4

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
CURVE 1	
603.2	0.0786
607.1	0.0887
611.5	0.0663
613.2	0.0727
753.2	0.0750
755.4	0.0623
757.1	0.0779
763.7	0.0779
764.3	0.0661
769.3	0.0750
1045.4	0.0490
1054.3	0.0525
1063.2	0.0596
1064.3	0.0594
1190.4	0.0503
1192.6	0.0522
1193.7	0.0617
1194.3	0.0636
1194.8	0.0698
CURVE 2	
1266.5	0.0575
1272.1	0.0584
1294.3	0.0591
1511.0	0.0548
1527.6	0.0476
1547.1	0.0584
1555.4	0.0606
1580.6	0.0721
2044.3	0.0715
2047.1	0.0600
2061.0	0.0734
CURVE 3	
303	0.185
CURVE 4	
303	0.050
CURVE 5	
1173.2	0.0146
1673.2	0.0544
CURVE 6	
1173.2	0.00360
CURVE 7	
1178	0.101
1346	0.0857
1465	0.0812
CURVE 8	
1334	0.165
1420	0.145
1573	0.130
1719	0.130
CURVE 9	
1320	0.0861
1416	0.0721
1496	0.120
1599	0.0835
1632	0.0724
1644	0.0865
CURVE 10	
1139	0.0662
1281	0.0564
1396	0.0580
CURVE 11	
1204	0.0627
1229	0.0584
1261	0.0560
1291	0.0587
1332	0.0577
1381	0.0534
1423	0.0555
1477	0.0555
CURVE 12	
1126	0.0776
1175	0.0737
1206	0.0718
CURVE 12 (cont.)	
1248	0.0730
1276	0.0763
1314	0.0763
1386	0.0731
1418	0.0785
1439	0.0808
CURVE 13	
1088	0.0750
1149	0.0822
1208	0.0822
1278	0.0798
1347	0.0770
1471	0.0828
1542	0.0776
CURVE 14	
1178	0.0610
1246	0.0711
1362	0.0554
1421	0.0573
1475	0.0577
1511	0.0555
1548	0.0564
1610	0.0539
CURVE 15	
1143	0.0619
1194	0.0637
1234	0.0593
1266	0.0548
1323	0.0613
1366	0.0669
CURVE 16	
1186	0.0626
1219	0.0629
1267	0.0607
1293	0.0642
1340	0.0665
1376	0.0636
1391	0.0646
CURVE 17*	
1180	0.101
1268	0.0763
1332	0.0763
1384	0.0741
CURVE 18	
1106	0.0982
1154	0.0924
1220	0.0746
1294	0.0770
1379	0.0753
1436	0.0724
CURVE 19	
1087	0.0847
1114	0.0721
1154	0.0769
1219	0.0692
1263	0.0697
1301	0.0643
1334	0.0630
1408	0.0561
1463	0.0599
1501	0.0601
CURVE 20	
1103	0.0544
1196	0.0558
1289	0.0570
1346	0.0542
1386	0.0554
1471	0.0577
CURVE 21	
1128	0.0480
1161	0.0474
1214	0.0474
1268	0.0552
1319	0.0472
1364	0.0460
1426	0.0447
1519	0.0384
CURVE 22	
1199	0.0394
1278	0.0401
1339	0.0392
1364	0.0425
1436	0.0417
CURVE 23	
1143	0.0603
1189	0.0562
1227	0.0541
1256	0.0508
1292	0.0536
1312	0.0516
1367	0.0506
1424	0.0567
1499	0.0532
CURVE 24	
308.5	0.330
320.7	0.320
339.9	0.321
347.1	0.312
358.7	0.306
364.8	0.292
370.0	0.308
377.2	0.313
CURVE 25	
298	0.330
CURVE 26	
298	0.067
CURVE 27	
298	0.105
CURVE 28	
298	0.214
CURVE 29	
298	0.328
CURVE 30*	
298	0.214
CURVE 31	
298	0.130
CURVE 32	
298	0.141
CURVE 33	
298	0.178
CURVE 34*	
298	0.328
CURVE 35	
298	0.395
CURVE 36	
298	0.368

* Not shown in figure.

b. Specific Heat

There are six sets of experimental data available for the specific heat of silicon nitride. The information on the specimen characterization and measurement conditions for each data set is given in Table 4-5. The experimental data are tabulated in Table 4-6 and shown in Figure 4-2.

These experimental data sets cover the temperature range 273-2200 K. The recommended values shown in Figure 4-2 and tabulated in Table 4-4 are derived primarily from the measurements of Kelley [103] (curve 2), Satoh [104] (curve 4), and McLean, Fisher, and Bratton [105] (curve 6). The specific heat data of Neel, Pears, and Oglesby [61] (curve 3) are about 7-15% higher than the recommended values above 1400 K. The mixing rule calculations of Pehlke and Elliott [106] (curve 1) yield values which are up to 35% higher below 800 K and 15% lower above that temperature. The uncertainty of the recommended values is $\pm 5\%$ below 1000 K and $\pm 10\%$ above that temperature.

TABLE 4-4. RECOMMENDED SPECIFIC HEAT OF SILICON NITRIDE (Si_3N_4)

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
200	0.138
250	0.152
273.15	0.158
293	0.163
300	0.165
350	0.176
400	0.186
450	0.197
500	0.206
550	0.215
600	0.224
650	0.233
700	0.242
750	0.248
800	0.254
850	0.260
900	0.266
950	0.271
1000	0.276
1100	0.285
1200	0.293
1300	0.301
1400	0.307
1500	0.312
1600	0.316
1700	0.320
1800	0.324
1900	0.327
2000	0.329

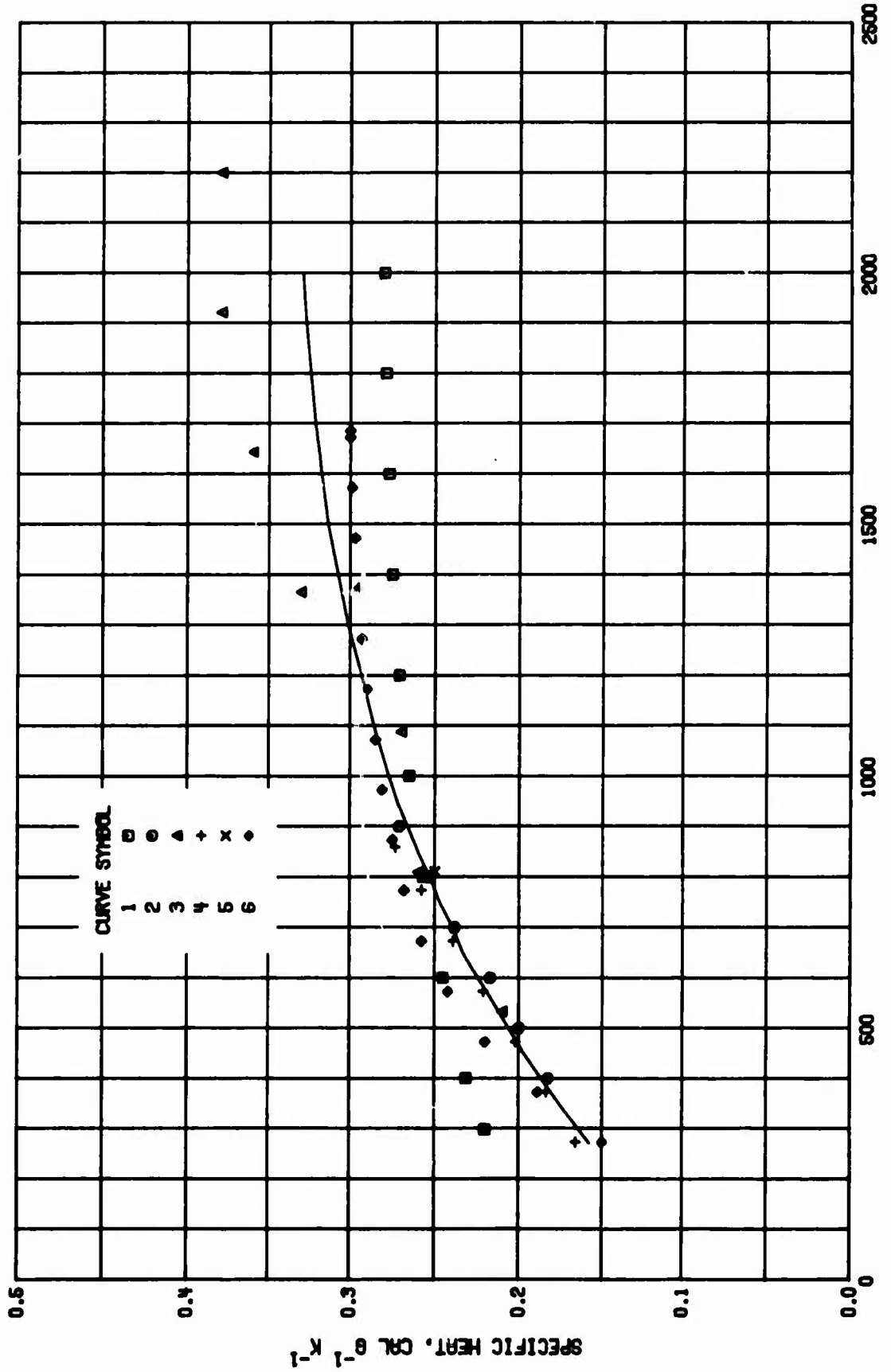

FIGURE 4-2. SPECIFIC HEAT OF SILICON NITRIDE .

TABLE 4-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF SILICON NITRIDE Si_3N_4

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	106	Pehlke, R.D. and Elliott, J.F.	1959		298-2000		Values calculated from $C_p(Si_3N_4) = 2.5 + 3C_p^o(Si) + 2C_p^o(N_2)$ cal deg^{-1} mole^{-1}; molecular weight 140.286 was assumed.
2	103	Kelley, K.K.	1949		400-900		NBS compilation, $C_p = 16.83 + 23.6 \times 10^{-3}$ T cal deg^{-1} mole^{-1}; molecular weight 140.286 was assumed.
3	61	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962		533-2200		98.12 Si_3N_4, 1.5 Fe, 0.3 Al, 0.05 Ca, 0.01 each Cu, Mg, Ti, and traces of Ba, Mn, and Na; supplied by the Carborundum Co.; density 2.37 g cm^{-3}; C_p values calculated from the heat content measurements.
4	104	Satoh, S.	1938		273-858		Specimen prepared by reacting $SiCl_4$ with NH_3 to form $Si(NH_2)_4$ which was heated stepwise to 1473 K to obtain the final product; values calculated from the equation $C_p = 0.1656 + 1.847 \times 10^{-4}$ t $- 4.5 \times 10^{-7}$ t^2 (t in °C).
5	107	Washburn, M.E.	1967		810		No details given.
6	105	McLean, A.F., Fisher, E.A., and Bratton, R.J.	1973	I	273-1673		Reaction sintered; injection molded specimen having nitrided density 2.23 g cm^{-3}.

TABLE 4-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF SILICON NITRIDE Si_3N_4

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
CURVE 1	
298.5	0.220
400	0.231
600	0.245
800	0.257
1000	0.265
1200	0.271
1400	0.275
1600	0.277
1800	0.279
2000	0.280
CURVE 2	
400	0.183
500	0.200
600	0.217
700	0.238
800	0.254
900	0.271
CURVE 3	
533	0.21
810	0.26
1088	0.27
1366	0.33
1644	0.36
1922	0.38
2200	0.38
CURVE 4	
273	0.166
373	0.184
473	0.202
573	0.221
673	0.239
773	0.258
858	0.273
CURVE 5	
810	0.25
CURVE 6	
273	0.150
373	0.189
473	0.220
573	0.242
673	0.258
773	0.268
873	0.275
973	0.281
1073	0.285
1173	0.290
1273	0.293
1373	0.295
1473	0.297
CURVE 6 (cont.)	
1573	0.299
1673	0.300
1686	0.300

c. Heat of Fusion

Silicon nitride decomposes at 2200 K. The standard heat of formation, ΔHf°_{298}, of silicon nitride for the reaction in which decomposition pressure of nitrogen reaches one atmosphere is 1270 ± 50 cal g^{-1} according to Stull and Prophet [108].

d. Thermal Linear Expansion

Silicon nitride occurs in two crystalline forms having nearly the same densities and crystallographic structures (c.p.h.). α-Si_3N_4 is formed at lower temperature and β-Si_3N_4 at higher ($\approx$ 1800 K) temperature. β-Si_3N_4 can be obtained by an irreversible reaction by heating α-Si_3N_4 at high temperature in the presence of nitrogen. The temperature at which the nitride is formed is an important factor in determining the phase. The thermal expansion data for each of the two forms of Si_3N_4 are treated separately.

There are 33 sets of experimental data available for the thermal linear expansion of Si_3N_4. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-8. The experimental data are tabulated in Table 4-9 and partially shown in Figures 4-3A thru 4-3E. The temperature range covered by these data sets is 273-2100 K.

$\underline{\alpha\text{-}Si_3N_4}$

There are 4 sets of experimental data (curves 18, 20, 22, and 24) for measurements parallel to a-axis. These are shown in Figure 4-3A. There are 4 sets of experimental data (curves 19, 21, 23, and 25) for measurements parallel to c-axis. These are shown in Figure 4-3B. The experimental data for polycrystalline material (curves 1-15) are partially shown in Figure 4-3C. For an anisotropic material like Si_3N_4, it is customary to select the most probable values for thermal linear expansion parallel to and perpendicular to the c-axis, and from these to calculate the values for a randomly oriented polycrystalline material. However, this procedure can not be applied here due to the lack of reliable data for the single crystal.

The provisional values for polycrystalline α-Si_3N_4 shown in Figure 4-3C and tabulated in Table 4-7A are derived primarily from the measurements of Tokuyama et al. [109] (curve 1), Burkhardt and Marvel [110] (curve 14), Gregor [111] (curve 15), Steel et al. [112] (curve 2), and of Wells [96] (curves 3-6). The data reported by Neel et al. [61] (curves 8-12) are inconsistent; moreover, they seemed to have problem with their specimen (curve 13). The uncertainty of the provisional values is about $\pm$ 15%.

The values of the instantaneous coefficient of thermal linear expansion, α, are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about $\pm$ 20%.

The provisional values for directions parallel to the a-axis (perpendicular to the c-axis) and parallel to the c-axis reported in Table 4-7A and shown in Figures 4-3A and 4-3B are based on the provisional values for polycrystalline material and on the trends of the data reported by Thompson and Pratt [113] (curves 18 and 19) and by Iwai and Yasunaga [114] (curves 24 and 25).

The specimens used by Thompson and Pratt [113] (curves 20-23) seemed to have been contaminated by free silicon and oxygen giving anomolous results around 700-1150 K. Their results above 1150 K are too low. The data of Iwai and Yasunaga [114] are also too low. The uncertainty of the provisional values is about ± 15%.

β-Si_3N_4

No experimental data for the thermal linear expansion for polycrystalline β-Si_3N_4 were located in the literature. The provisional values reported in Table 4-7B and shown in Figures 4-3D and 4-3E are based on the data of Thompson and Pratt [113] (curves 16 and 17) and of Iwai and Yasunaga [114] (curves 26 and 27). The phase formed at higher temperature generally has lower thermal expansion values than the phase formed at lower temperature. In generating the provisional values for the a-axis (perpendicular to the c-axis) and the c-axis, the shape of the thermal linear expansion curves for α-Si_3N_4 were also taken into account.

The provisional values for polycrystalline β-Si_3N_4 tabulated in Table 4-7B and shown in Figure 4-3C were calculated from the provisional values for a-axis and c-axis. These values are considered accurate to within ± 15%. The values of the instantaneous coefficient of thermal linear expansion, α, are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion data, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty in these values is about ± 15%.

TABLE 4-7A. PROVISIONAL THERMAL LINEAR EXPANSION OF ALPHA SILICON NITRIDE (α-Si_3N_4)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	⊥ c-axis	// c-axis	Polycrystalline	
	$\Delta L/L_0$	$\Delta L/L_0$	$\Delta L/L_0$	α
293	0.000	0.000	0.000	1.2
310	0.0003	0.002	0.001	1.4
320	0.001	0.003	0.002	1.4
340	0.004	0.008	0.005	1.6
350	0.005	0.010	0.007	1.6
360	0.006	0.012	0.008	1.7
380	0.007	0.016	0.010	1.8
400	0.010	0.020	0.013	1.9
420	0.014	0.026	0.018	2.0
450	0.020	0.035	0.025	2.2
500	0.029	0.051	0.036	2.4
550	0.041	0.066	0.049	2.6
600	0.054	0.080	0.063	2.8
650	0.069	0.096	0.078	3.0
700	0.083	0.112	0.093	3.1
750	0.098	0.129	0.108	3.2
800	0.114	0.145	0.124	3.3
850	0.130	0.163	0.141	3.3
900	0.147	0.179	0.158	3.4
950	0.163	0.197	0.174	3.4
1000	0.180	0.215	0.192	3.5
1100	0.213	0.253	0.226	3.5
1200	0.249	0.290	0.263	3.6
1300	0.285	0.329	0.300	3.7
1400	0.322	0.367	0.337	3.8
1500	0.360	0.405	0.375	3.9
1600	0.400	0.443	0.414	3.9
1700	0.440	0.482	0.454	4.0
1800	0.480	0.520	0.493	4.0
1900	0.520	0.558	0.533	4.1
2000	0.560	0.596	0.572	4.1

TABLE 4-7B. PROVISIONAL THERMAL LINEAR EXPANSION OF BETA SILICON NITRIDE (β-Si_3N_4)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	$\perp$ c-axis	// c-axis	Polycrystalline	
	$\Delta L/L_0$	$\Delta L/L_0$	$\Delta L/L_0$	α
293	0.000	0.000	0.000	1.0
310	0.001	0.002	0.001	1.2
320	0.001	0.003	0.002	1.2
340	0.002	0.006	0.003	1.4
350	0.002	0.007	0.004	1.4
360	0.003	0.009	0.005	1.5
380	0.005	0.011	0.007	1.6
400	0.009	0.013	0.010	1.7
420	0.010	0.016	0.012	1.9
450	0.019	0.022	0.020	2.0
500	0.032	0.032	0.032	2.3
550	0.044	0.045	0.044	2.5
600	0.057	0.058	0.057	2.7
650	0.071	0.073	0.072	2.8
700	0.086	0.088	0.087	3.0
750	0.100	0.105	0.102	3.1
800	0.114	0.122	0.117	3.2
850	0.129	0.140	0.133	3.3
900	0.144	0.159	0.149	3.3
950	0.159	0.179	0.166	3.4
1000	0.174	0.198	0.182	3.4
1100	0.205	0.239	0.216	3.5
1200	0.237	0.282	0.252	3.6
1300	0.271	0.325	0.289	3.6
1400	0.303	0.369	0.325	3.7
1500	0.337	0.414	0.362	3.7
1600	0.370	0.461	0.399	3.8
1700	0.404	0.507	0.438	3.9
1800	0.438	0.554	0.477	3.9
1900	0.474	0.601	0.516	4.0
2000	0.511	0.649	0.557	4.0

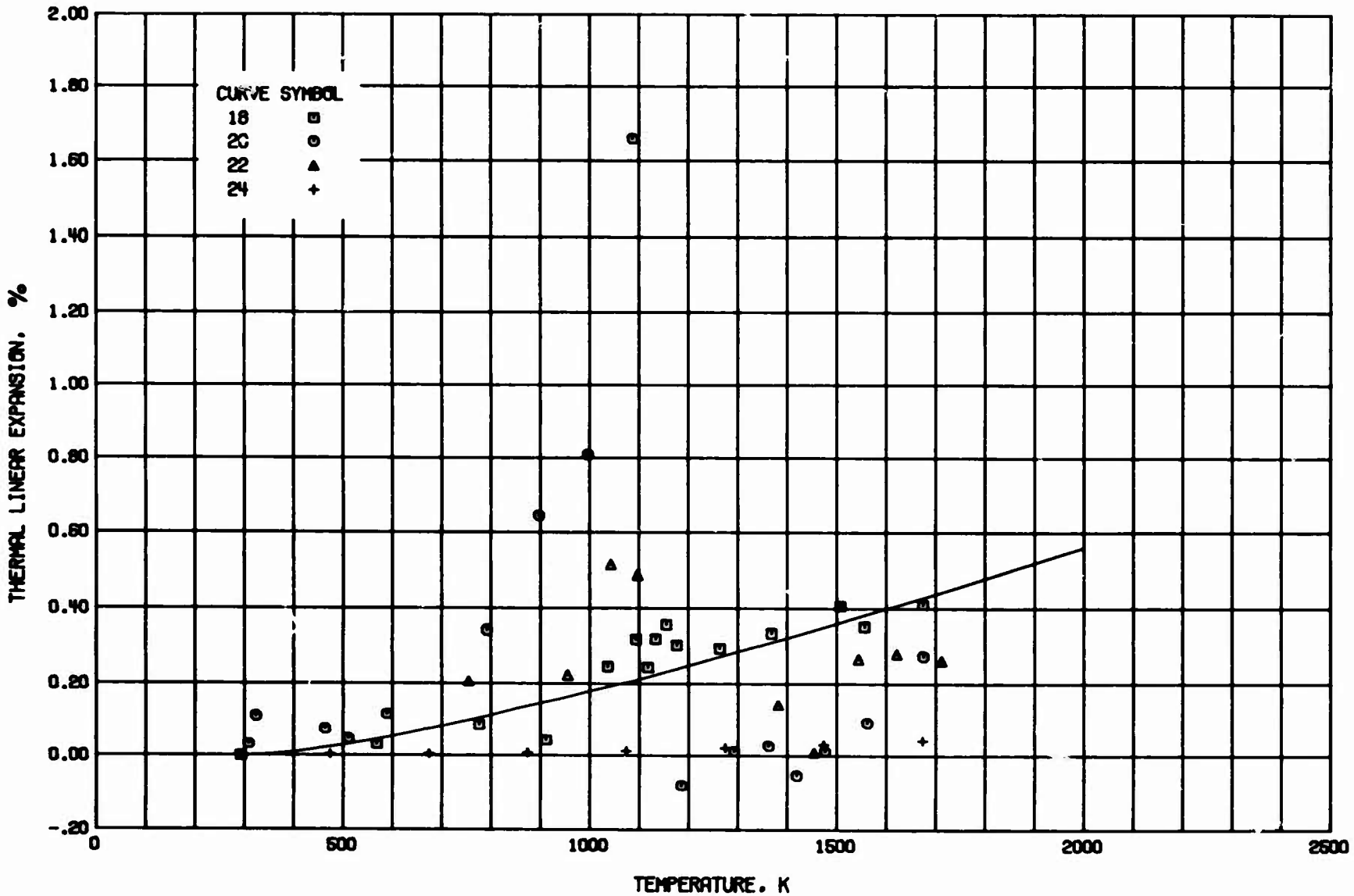

FIGURE 4-3A. THERMAL LINEAR EXPANSION OF ALPHA-SILICON NITRIDE PARALLEL TO A-AXIS .

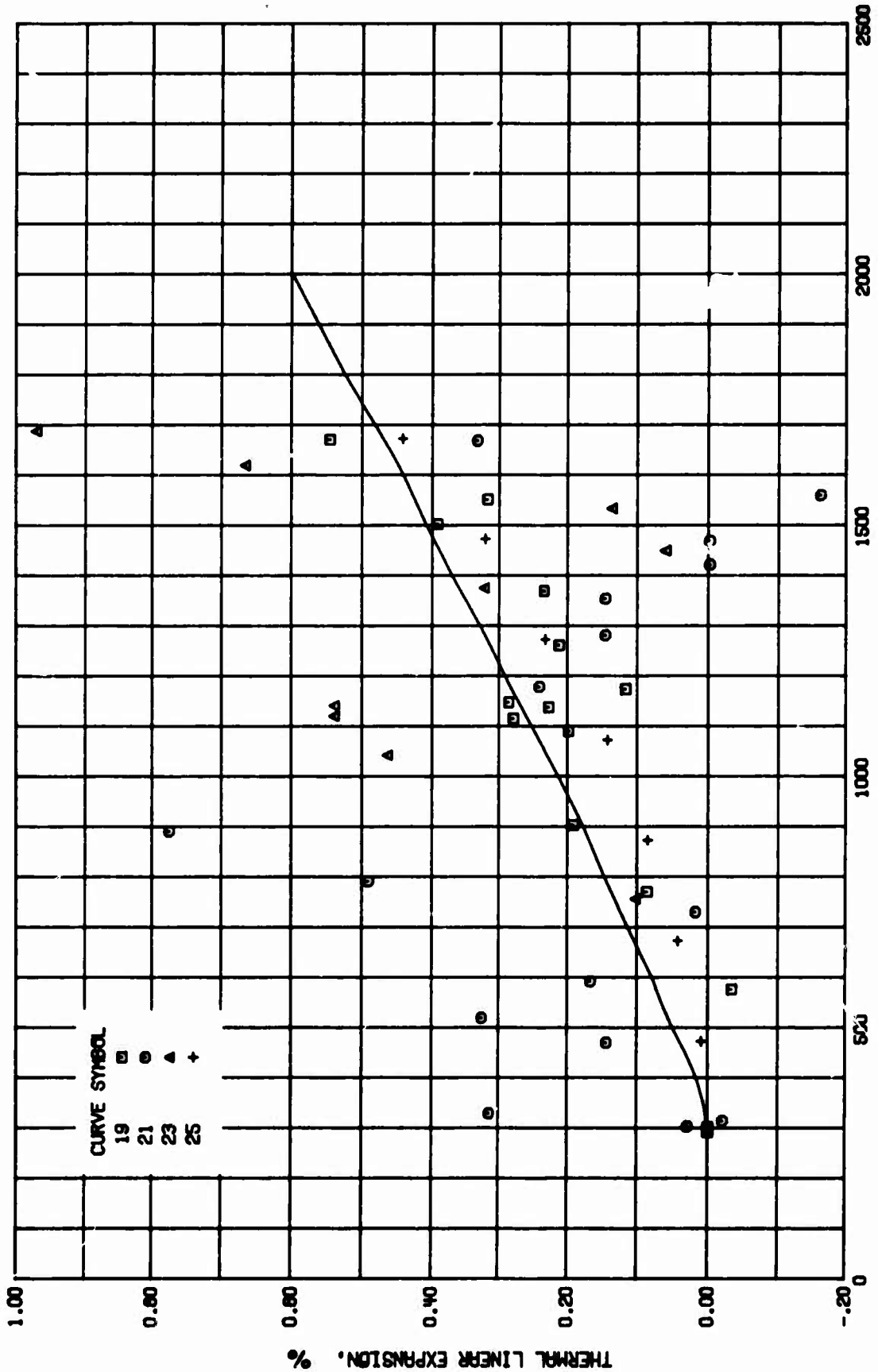

FIGURE 4-38. THERMAL LINEAR EXPANSION OF ALPHA-SILICON NITRIDE PARALLEL TO C-AXIS .

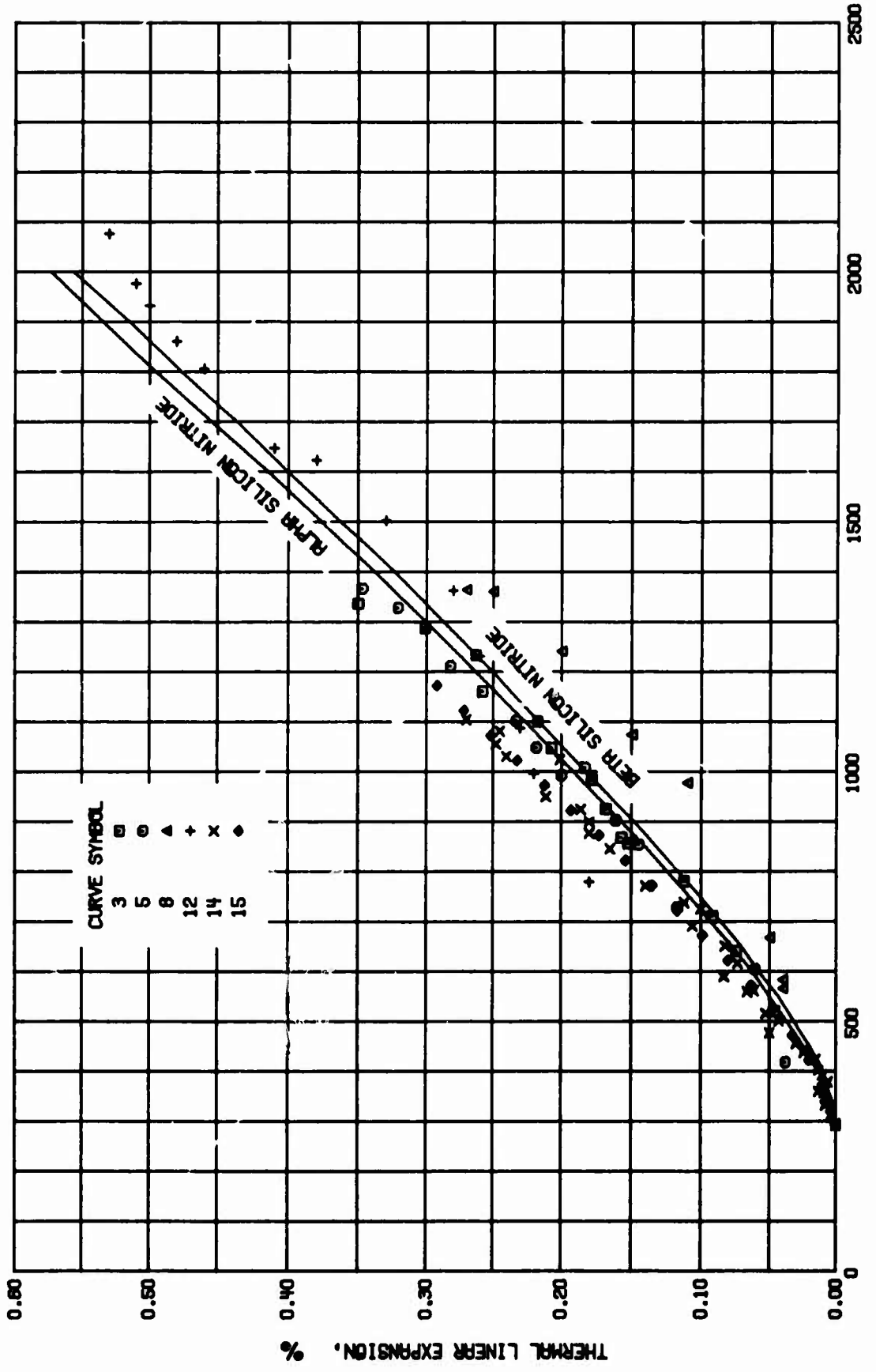

FIGURE 4-3C. THERMAL LINEAR EXPANSION OF POLYCRYSTALLINE SILICON NITRIDE .

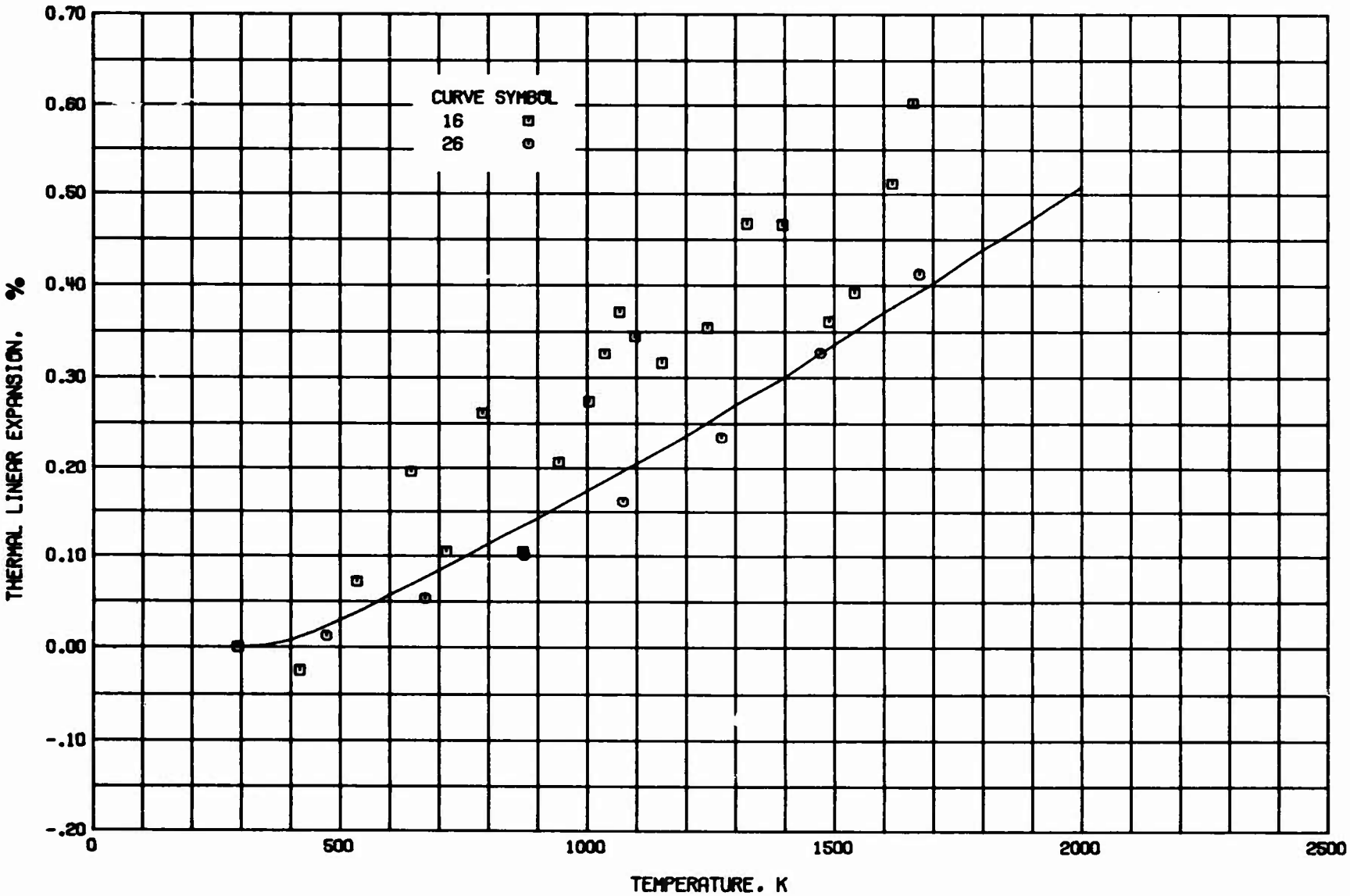

FIGURE 4-30. THERMAL LINEAR EXPANSION OF BETA-SILICON NITRIDE PARALLEL TO A-AXIS .

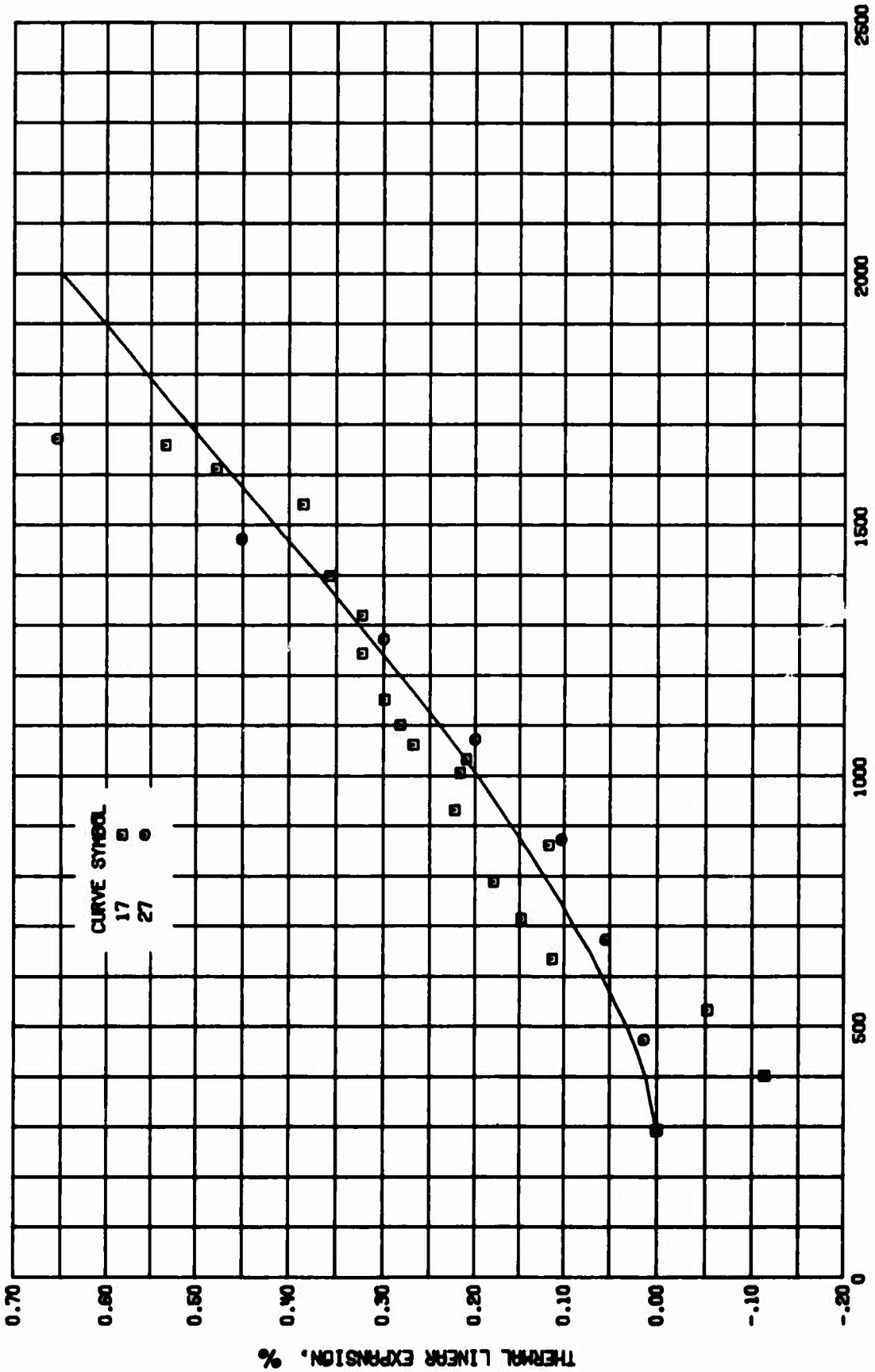

FIGURE 4-3E. THERMAL LINEAR EXPANSION OF BETA-SILICON NITRIDE PARALLEL TO C-AXIS .

TABLE 4-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	109	Tokuyama, T., Fujii, Y., Sugita, Y., and Kishino, S.	1967	X	1073, 1273		Film deposited through chemical reaction of SiH_4 and NH_3 at 1073 K on surface of the silicon substrate of the (111) surface cut along [110] direction to the dimension of 20 x 5 mm; oxidized in steam at 1073 K and 1273 K respectively; thermal expansion coefficient of films using coefficient of substrates; $\Delta L/L_0$ = 0.252 at 1073 K was assumed.
2*	112	Steele, S.R., Pappis, J., Schilling, H., and Hagan, L.	1967		273-1273		Specimen deposited from vapor at 1323-1573 K.
3	96	Wells, W.M.	1964		521-1337		Specimen 4 in. x 0.5 in. x 0.5 in.; density 2.3 g cm^{-3}; first run.
4*	96	Wells, W.M.	1964		531-1345		The above specimen; second run.
5	96	Wells, W.M.	1964		419-1367		The above specimen; third run.
6*	96	Wells, W.M.	1964		1048-1359		The above specimen; fourth run.
7*	96	Wells, W.M.	1964		863-1763		Similar to the above specimen; data taken using less precise apparatus.
8	61	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962	L	294-1365		Calculated composition before exposure 60.08 Si and 39.91 N, Carborundum Co.; initial length 7.58 cm; elements found by semi-quantitative emission spectrography, 0.7 Fe, 0.6 Ca, 0.03 Al, 0.1 each Mn, Mg, Cr, Zr, and traces of Ti; after exposure 0.49 C; formed by A casting; density before exposure 2.5 g cm^{-3} at 298 K; measurements in helium atm.
9*	61	Neel, D.S., et al.	1962	L	1365-796		Cooling the above specimen to 796 K.
10*	61	Neel, D.S., et al.	1962	L	796-1376		Reheating the above specimen to 1375 K.
11*	61	Neel, D.S., et al.	1962	L	1375-780		Recooling the above specimen to 780 K.
12	61	Neel, D.S., et al.	1962	L	780-2078		Final heating the above specimen.
13*	61	Neel, D.S., et al.	1962	L	2078-294		Final cooling the above specimen; specimen found broken on post inspection.
14	110	Burkhardt, P.J. and Marvel, R.F.	1969		293-1105		98.0 Si_3N_4 with impurities of Mo, Cl, O, Ca, and Al detected by electron microprobe; sample film prepared by sputtering 1-2 μ thick onto strip of annealed molybdenum metal of 0.5 in. wide, 3 in. long, and 0.003 in. thick, and then rolled over edge to provide lateral curvature; cathetometer used to measure distance between two reference marks as function of temperature on freely suspended strip of film.
15	111	Gregor, L.V.	1968	T	293-1104		Film specimen obtained by sputtering particles onto surface and stripping film off; specimen 7.62 cm x 1.27 cm x 1.5 μ thick; film suspended vertically for measurements.
16	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1660	β-Si_3N_4	No information on the specimen reported, measured along a-axis; lattice parameter reported at 293 K is 7.5968 Å.
17	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1659	β-Si_3N_4	Measured along c-axis; lattice parameter reported at 293 K is 2.9087 Å.

* Not shown in figure.

TABLE 4-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4 (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1674	α-Si_3N_4	No information on the specimen reported, measured along a-axis L/8 3% Si; lattice parameter reported at 293 K is 7.7534 Å; observed peak may be due to diffused oxygen atoms forming bonds with Si atoms.
19	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1671	α-Si_3N_4	The above specimen except measured along c-axis; lattice parameter reported at 293 K is 5.6046 Å.
20	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1669	α-Si_3N_4	The above specimen except L/6 5% Si; measured along a-axis; lattice parameter reported at 293 K is 7.7508 Å.
21	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1669	α-Si_3N_4	The above specimen except measured along c-axis; lattice parameter reported at 293 K is 5.6004 Å.
22	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1712	α-Si_3N_4	The above specimen except L/3 1% Si; measured along a-axis; lattice parameter reported at 293 K is 7.7508 Å.
23	113	Thompson, D.S. and Pratt, P.L.	1965	X	293-1688	α-Si_3N_4	The above specimen except L/3 1% Si; measured along c-axis; lattice parameter reported at 293 K is 5.5956 Å.
24	114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	α-Si_3N_4	Specimen prepared by heating pure Si and nitrogen at 1673 K; measured along a-axis; lattice parameter reported at 293 K is 7.7500 Å.
25	114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	α-Si_3N_4	The above specimen; measured along c-axis; lattice parameter reported at 293 K is 5.6146 Å.
26	114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	β-Si_3N_4	Specimen prepared by heating pure Si and nitrogen at 1673 K; measured along a-axis; lattice parameter reported at 293 K is 7.6048 Å.
27	114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	β-Si_3N_4	The above specimen; measured along c-axis; lattice parameter reported at 293 K is 2.9042 Å.
28*	115	Carr, E.M. and Bartlett, R.W.	1968		293-1273		Duplex silicon nitride; three 1.875 O.D. ring specimen; 2.55, 2.54, and 2.51 g cm^{-3} densities which were cut from an isostatically pressed cylinder and were fired for 20 hr at 1523 K, then 8 hr at 1723 K before the measurements of change in diameter; during test each specimens underwent two complete thermal cycles between 293 and 1273 K.
29*	105	McLean, A.F., Fisher, E.A., and Bratton, R.J.	1973	L	293-1714	B2, 1:A9	Hot pressed specimen; expansion for sample 2, billet 1 in the direction parallel to hot press direction is same as for sample 9 in the direction perpendicular to hot press direction.
30*	105	McLean, A.F., et al.	1973	L	293-1716	A10	Similar to the above specimen; expansion for sample 10 in the direction perpendicular to hot press direction.
31*	105	McLean, A.F., et al.	1973	L	293-1714	B10	The above specimen; expansion in the direction parallel to hot press direction.
32*	105	McLean, A.F., et al.	1973	L	293-1720	B9	Similar to the above specimen; expansion for sample 9 in the direction parallel to hot press direction.
33*	105	McLean, A.F., et al.	1973	L	293-1705	A2, 1	Similar to the above specimen; expansion for sample 2, billet 1 in the direction perpendicular to hot press direction.

* Not shown in figure.

TABLE 4-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1*	
1073	0.252
1273	0.329
CURVE 2*	
273	-0.012
1273	0.588
CURVE 3	
521	0.046
642	0.075
711	0.092
781	0.112
857	0.152
869	0.157
926	0.168
984	0.178
1009	0.183
1048	0.207
1101	0.217
1161	0.258
1234	0.263
1289	0.301
1337	0.350
CURVE 4*	
531	0.039
724	0.093
795	0.122
993	0.192
1070	0.218
1113	0.224
1173	0.255
1217	0.262
1250	0.267
1310	0.296
1345	0.320
CURVE 5	
419	0.038
605	0.061
729	0.117
854	0.145
903	0.161

T	$\Delta L/L_0$
CURVE 5 (cont.)	
993	0.200
1049	0.218
1103	0.233
1212	0.282
1329	0.321
1367	0.347
CURVE 6*	
1049	0.187
1143	0.233
1262	0.278
1302	0.299
1328	0.317
1359	0.321
CURVE 7*	
863	0.158
1144	0.279
1366	0.331
1423	0.360
1481	0.405
1536	0.447
1650	0.513
1763	0.536
CURVE 8	
294	0.00
567	0.04
585	0.04
668	0.05
978	0.11
1075	0.15
1242	0.20
1362	0.25
1365	0.27
CURVE 9*	
1365	0.27
796	0.16
CURVE 10*	
796	0.16

T	$\Delta L/L_0$
CURVE 10 (cont.)*	
1087	0.21
1235	0.25
1374	0.27
CURVE 11*	
1374	0.27
1180	0.25
1121	0.23
1074	0.22
1033	0.21
845	0.18
831	0.18
780	0.18
294	0.00
CURVE 12	
780	0.18
997	0.22
1088	0.23
1232	0.26
1363	0.28
1503	0.33
1624	0.38
1648	0.41
1807	0.46
1862	0.48
1933	0.50
1977	0.51
2077	0.53
CURVE 13*	
2077	0.53
294	0.20
CURVE 14	
293	0.000
312	0.004
333	0.008
346	0.008
358	0.009
360	0.013
366	0.008
379	0.006

T	$\Delta L/L_0$
CURVE 14 (cont.)	
393	0.010
403	0.013
425	0.015
438	0.024
446	0.023
456	0.030
477	0.050
502	0.043
516	0.053
560	0.067
562	0.062
590	0.084
617	0.074
651	0.083
691	0.106
726	0.100
738	0.112
772	0.140
846	0.165
877	0.180
900	0.180
925	0.186
950	0.211
1025	0.201
1031	0.240
1056	0.248
1082	0.245
1105	0.270
CURVE 15	
293	0.000
336	0.004
373	0.010
423	0.020
473	0.033
523	0.048
573	0.064
623	0.081
673	0.099
723	0.117
773	0.135
823	0.154
873	0.173
923	0.193
973	0.212
1023	0.232

T	$\Delta L/L_0$
CURVE 15 (cont.)	
1073	0.252
1123	0.272
1173	0.292
CURVE 16	
293	0.000
419	-0.024
534	0.072
644	0.196
715	0.105
788	0.261
870	0.105
943	0.207
1004	0.274
1036	0.326
1066	0.371
1097	0.345
1152	0.316
1244	0.354
1324	0.467
1396	0.466
1490	0.361
1542	0.392
1618	0.512
1660	0.603
CURVE 17	
293	0.000
401	-0.114
532	-0.052
634	0.113
714	0.148
788	0.179
861	0.117
931	0.223
1006	0.217
1033	0.210
1062	0.268
1101	0.282
1152	0.299
1244	0.323
1320	0.323
1399	0.357
1541	0.385
1612	0.478
1659	0.533

T	$\Delta L/L_0$
CURVE 18	
293	0.000
568	0.032
776	0.086
911	0.044
1036	0.246
1093	0.317
1117	0.244
1133	0.319
1155	0.356
1176	0.303
1263	0.294
1368	0.334
1507	0.407
1556	0.352
1674	0.411
CURVE 19	
293	0.000
303	0.000
577	-0.034
771	0.086
904	0.191
1018	0.121
1091	0.198
1116	0.278
1139	0.227
1148	0.285
1175	0.116
1262	0.212
1370	0.234
1503	0.392
1552	0.317
1671	0.546
CURVE 20	
293	0.000
308	0.033
323	0.110
463	0.075
510	0.048
588	0.115
791	0.341
896	0.644
996	0.809
1086	1.659

* Not shown in figure.

TABLE 4-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4 (continued)

T	$\Delta L/L_0$
CURVE 20 (cont.)	
1184	-0.081
1291	0.013
1361	0.028
1418	-0.053
1476	0.013
1561	0.093
1675	0.274
CURVE 21	
293	0.000
303	0.029
314	-0.021
329	0.314
470	0.143
519	0.325
592	0.166
730	0.018
792	0.491
891	0.775
998	1.123
1089	1.514
1179	0.241
1281	0.145
1354	0.145
1422	-0.002
1469	-0.002
1560	-0.162
1669	0.332
CURVE 22	
293	0.000
754	0.206
955	0.224
1043	0.515
1097	0.489
1382	0.142
1454	0.010
1544	0.267
1621	0.280
1712	0.262
CURVE 23	
293	0.000
303	0.000
757	0.102
1043	0.465
1121	0.540
1142	0.540
1376	0.322
1450	0.061
1534	0.136
1620	0.665
1688	0.972
CURVE 24	
273	0.000
293	0.000
473	0.003
673	0.004
873	0.008
1073	0.013
1273	0.022
1473	0.032
1673	0.044
CURVE 25	
273	-0.009
293	0.000
473	0.009
673	0.043
873	0.085
1073	0.142
1273	0.232
1473	0.321
1673	0.443
CURVE 26	
273	-0.003
293	0.000
473	0.013
673	0.054
873	0.101
1073	0.162
1273	0.235
1473	0.327
1673	0.412
CURVE 27	
273	0.000
293	0.000
473	0.014
673	0.055
873	0.103
1073	0.200
1273	0.300
1473	0.451
1673	0.654
CURVE 28*	
293	0.000
1273	0.441
CURVE 29*	
293	0.000
373	0.017
473	0.040
573	0.064
673	0.091
773	0.118
873	0.149
973	0.182
1073	0.214
1173	0.247
1273	0.282
1373	0.324
1473	0.368
1573	0.412
1673	0.460
1714	0.481
CURVE 30*	
293	0.000
373	0.014
473	0.028
573	0.050
673	0.075
773	0.103
873	0.131
973	0.162
1073	0.194
1173	0.229
1273	0.267
1373	0.308
1473	0.350
1573	0.395
1673	0.441
1716	0.464
CURVE 31*	
293	0.000
373	0.014
473	0.033
573	0.058
673	0.085
773	0.111
873	0.139
973	0.171
1073	0.203
1173	0.240
1273	0.275
1373	0.316
1473	0.360
1573	0.404
1673	0.451
1714	0.472
CURVE 32*	
293	0.000
373	0.011
473	0.027
573	0.045
673	0.068
773	0.093
873	0.120
973	0.150
1073	0.182
1173	0.214
1273	0.250
1373	0.292
1473	0.336
1573	0.383
1673	0.433
1720	0.457
CURVE 33*	
293	0.000
373	0.015
473	0.034
573	0.058
673	0.085
773	0.114
873	0.145
973	0.178
1073	0.212
1173	0.250
1273	0.289
1373	0.331
1473	0.376
1573	0.425
1673	0.476
1705	0.494

* Not shown in figure.

e. Thermal Diffusivity

There are twelve sets of data available for the thermal diffusivity of porous silicon nitride, ten of which consist of a single data point each at room temperature. The experimental data are tabulated in Table 4-12. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-11. The porosity of the various specimens reported varies between 17% and 85%. The available information is not adequate for analysis. Hence the thermal diffusivity values are calculated from the equation:

$$\alpha = \frac{k}{C_p d}$$

using the values of thermal conductivity, specific heat, and thermal linear expansion reported in earlier sections. The resulting values are tabulated in Table 4-10 and shown in Figure 4-4 and are for polycrystalline samples with densities 2.4 g cm^{-3} and 3.16 g cm^{-3}. Since the values are very uncertain, they are considered merely as typical values.

TABLE 4-10. TYPICAL THERMAL DIFFUSIVITY OF SILICON NITRIDE (Si_3N_4)

[Temperature, T, K; Thermal Diffusivity, α, $cm^2\ s^{-1}$]

T	α	
	Density 2.4 g cm^{-3}	Density 3.16 g cm^{-3}
293	0.0989	0.162
300	0.0963	0.157
350	0.0835	0.137
400	0.0742	0.121
450	0.0662	0.108
500	0.0598	0.0984
550	0.0545	0.0894
600	0.0503	0.0822
650	0.0467	0.0764
700	0.0433	0.0708
750	0.0406	0.0667
800	0.0387	0.0636
850	0.0365	0.0599
900	0.0347	0.0570
950	0.0330	0.0540
1000	0.0317	0.0520
1100	0.0293	0.0480
1200	0.0273	0.0447
1300	0.0258	0.0420
1400	0.0245	0.0397
1500	0.0232	0.0377
1600	0.0222	0.0360
1700	0.0213	0.0347
1800	0.0205	0.0333
1900	0.0196	0.0322
2000	0.0190	0.0318

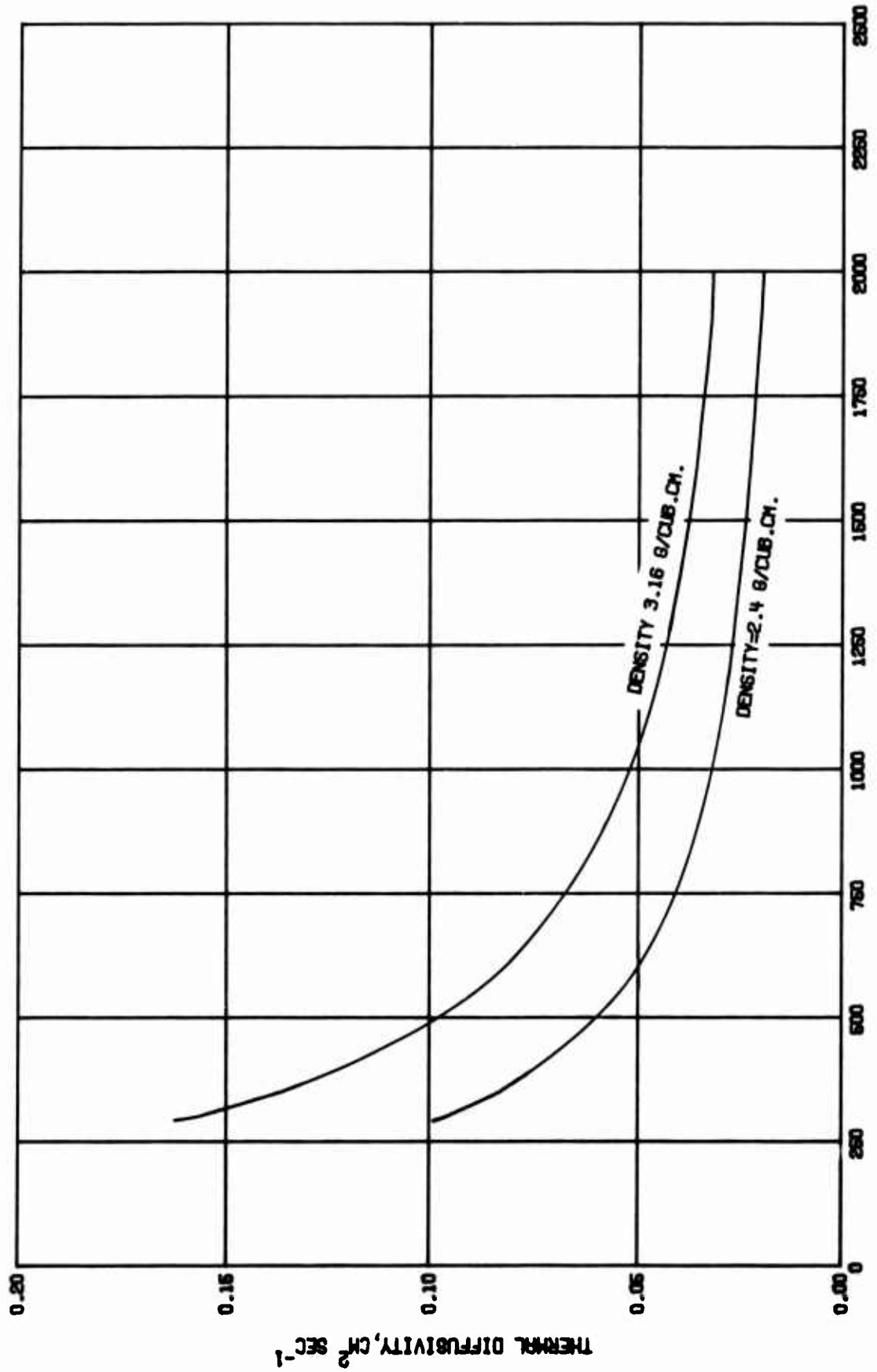

FIGURE 4-4. THERMAL DIFFUSIVITY OF POLYCRYSTALLINE SILICON NITRIDE.

TABLE 4-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF SILICON NITRIDE Si_3N_4

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	101	Swarts, E. L. and Crandall, W. B.	1951		1173, 1673		Porosity 70%.
2*	101	Swarts, E. L. and Crandall, W. B.	1951		1173		Porosity 85%.
3*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1471	Flame-sprayed; density 2.84 g cm^{-3}.
4*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1473	Density 1.99 g cm^{-3}.
5*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1474	Density 2.00 g cm^{-3}.
6*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1475	Density 2.34 g cm^{-3}.
7*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1478	Density 2.43 g cm^{-3}.
8*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AML 1482	Density 2.63 g cm^{-3}.
9*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	AME	Density 2.52 g cm^{-3}.
10*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	BSA	Density 2.47 g cm^{-3}.
11*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	Lucas	Flame-sprayed; density 2.58 g cm^{-3}.
12*	95	Godfrey, D.J. and Lindley, M.W.	1972		298	Lucas	Hot-pressed; density 3.07 g cm^{-3}.

TABLE 4-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF SILICON NITRIDE Si_3N_4

[Temperature, T, K; Thermal Diffusivity, α, $cm^2\ s^{-1}$]

T	α
CURVE 1*	
1173	0.0110
1673	0.0055
CURVE 2*	
1173	0.0063
CURVE 3*	
298	0.191
CURVE 4*	
298	0.056
CURVE 5*	
298	0.090
CURVE 6*	
298	0.150
CURVE 7*	
298	0.220
CURVE 8*	
298	0.145
CURVE 9*	
298	0.083
CURVE 10*	
298	0.086
CURVE 11*	
298	0.124
CURVE 12*	
298	0.155

* Not shown in figure.

3.5. Boron Fiber Epoxy Composite

This composite material consists usually of continuous boron filaments surrounded by a matrix of epoxy resin. It is usually produced in tape form so that it can be used in further fabrication of specialized materials.

The boron filaments, as currently produced, are formed by vapor deposition of boron on a fine tungsten wire substrate within a reactor. Exposure of the tungsten substrate to the high-temperature boron trichloride reactor environment results in a filament consisting of a boron sheath on a tungsten boride core. Other means of producing boron filaments are currently being investigated which would eliminate the tungsten substrate.

The organic matrix resins most commonly used with boron filaments are modified epoxy resins, available as commercial formulations developed specifically for this purpose. Other organic resins used include polyamides and phenolics. However, the state of the art with these resins is less advanced than for the epoxy resins.

The normal service temperature range of the boron fiber epoxy composite is dependent on the type of epoxy resin being used as a matrix. This range is from about 220 K, below which the epoxy becomes very brittle, to 450 K. Epoxy resin decomposes around 590 K.

a. Thermal Conductivity

There are three sets of data available for the thermal conductivity of boron fiber epoxy composite. The experimental data are tabulated in Table 5-3 and shown in Figure 5-1. The information on specimen characterization and measurement condition is given in Table 5-2. The data reported by Gille [116] (curve 1) is for a composite with epoxy content of 32.5%. Hertz et al. [117] (curves 2 and 3) did not report the composition of their specimens for thermal conductivity measurements; however, most of their specimens for other tests (e.g. mechanical strength) are for composites with approximate epoxy content of 33%. It is therefore assumed that their thermal conductivity measurements are for specimens with the same epoxy content, i.e. 33%.

The provisional values tabulated in Table 5-1 and shown in Figure 5-1 are based on the investigations of Gille (curve 1) for heat flow in the direction parallel to the boron fibers, and on those of Hertz et al. (curve 2) for heat flow in the direction perpendicular to the boron fibers. The data of Hertz et al. (curve 3) for heat flow in the

parallel direction are ignored because their data show a wild temperature dependence at around 350 K. The tabulated values are for a composite with epoxy content of about 30%. Their uncertainty is estimated to be ± 25%.

TABLE 5-1. PROVISIONAL THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	
	30 volume percent epoxy	
	a	b
40	0.0151	0.0029
60	0.0184	0.0031
80	0.0201	0.0034
100	0.0210	0.0037
120	0.0215	0.0039
150	0.0219	0.0043
200	0.0223	0.0049
250	0.0226	0.0054
293	0.0228	0.0058
300	0.0229	0.0059
350	0.0230	0.0061
400	0.0228	0.0060
450	0.0224	0.0051

a Heat flow parallel to fiber direction.
b Heat flow perpendicular to fiber direction.

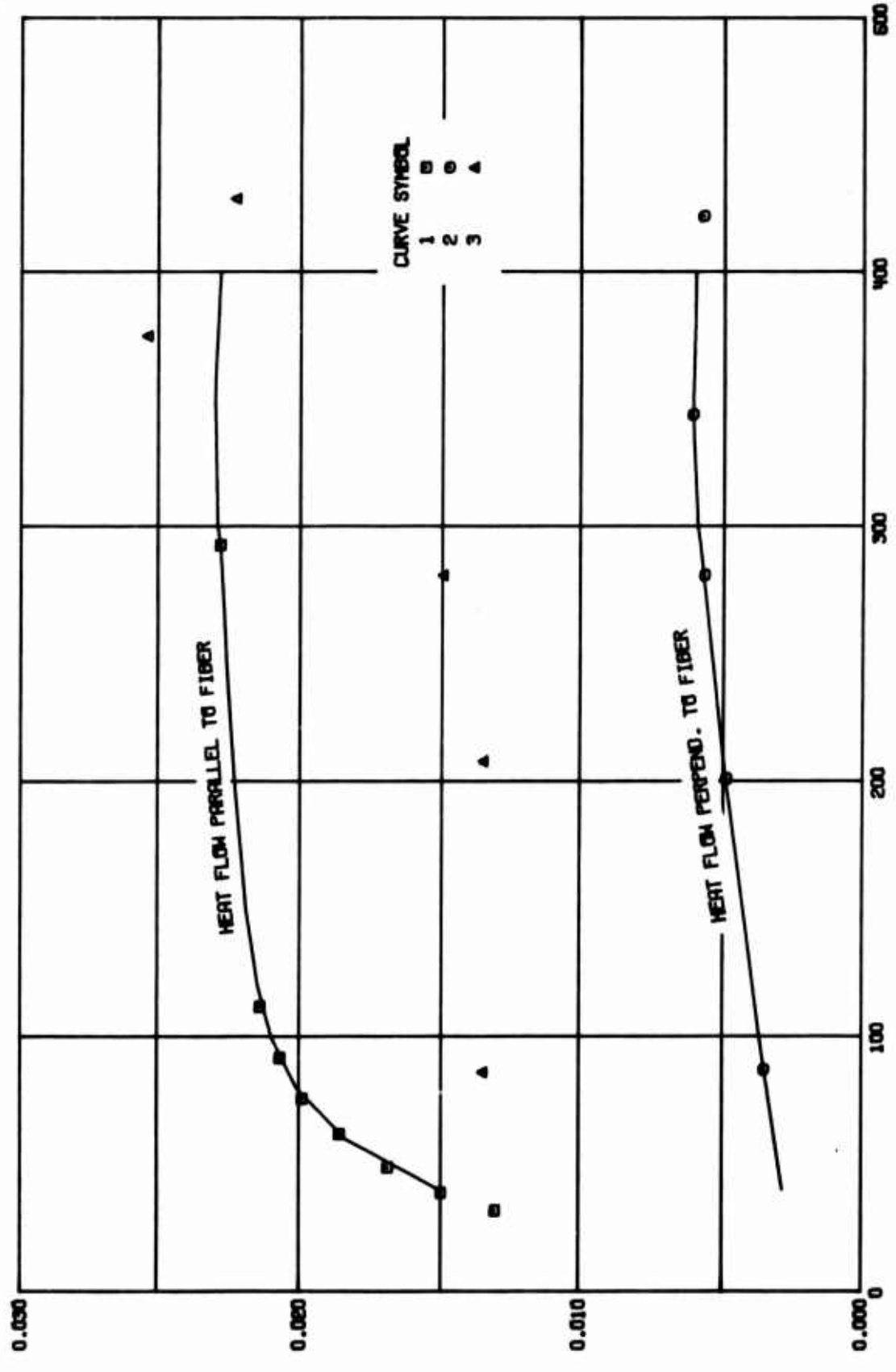

FIGURE 5-1. THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITES.

TABLE 5-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	116	Gille, J.P.	1969	L	32-293	4	67.5% 0.004 in. boron fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.005 in. I.D., 1.143 in. O.D., and 0.540 in. in effective length; density 2.08 g cm^{-3}; heat flow parallel to fibers; data taken from smooth curve.
2	117	Hertz, J., Christian, J.L., and Varias, M.	1972	L	87-422	SP-272	8 x 8 x 0.5 in. unidirection panel; heat flow perpendicular to fibers.
3	117	Hertz, J., et al.	1972	L	85-429	SP-272	Similar to the above specimen but heat flow parallel to fibers.

TABLE 5-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	T	k
CURVE 1		CURVE 3	
32	0.0130	86	0.0135
39	0.0150	208	0.0135
49	0.0169	281	0.0150
62	0.0186	375	0.0254
76	0.0199	429	0.0223
92	0.0207		
112	0.0214		
293	0.0228		
CURVE 2			
87	0.00355		
201	0.00489		
281	0.00567		
344	0.00609		
422	0.00573		

b. Specific Heat

There are 3 sets of experimental data available for the specific heat of boron fiber epoxy composite. The information on the specimen characterization and measurement conditions for each of the data sets are given in Table 5-5. The experimental data are tabulated in Table 5-6 and shown in Figure 5-2.

The provisional values tabulated in Table 5-4 and shown in Figure 5-2 are based on the measurements of Kim [118] (curve 1). The uncertainty of the values is about ± 7%. Hertz, Christian and Varlas [117] (curves 2 and 3) did not report the composition of their specimen, and therefore their results were not analyzed.

TABLE 5-4. PROVISIONAL SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
	27 percent Epoxy
100	0.087
150	0.134
200	0.181
250	0.225
273.15	0.245
293	0.262
300	0.268
350	0.307
400	0.342
450	0.370

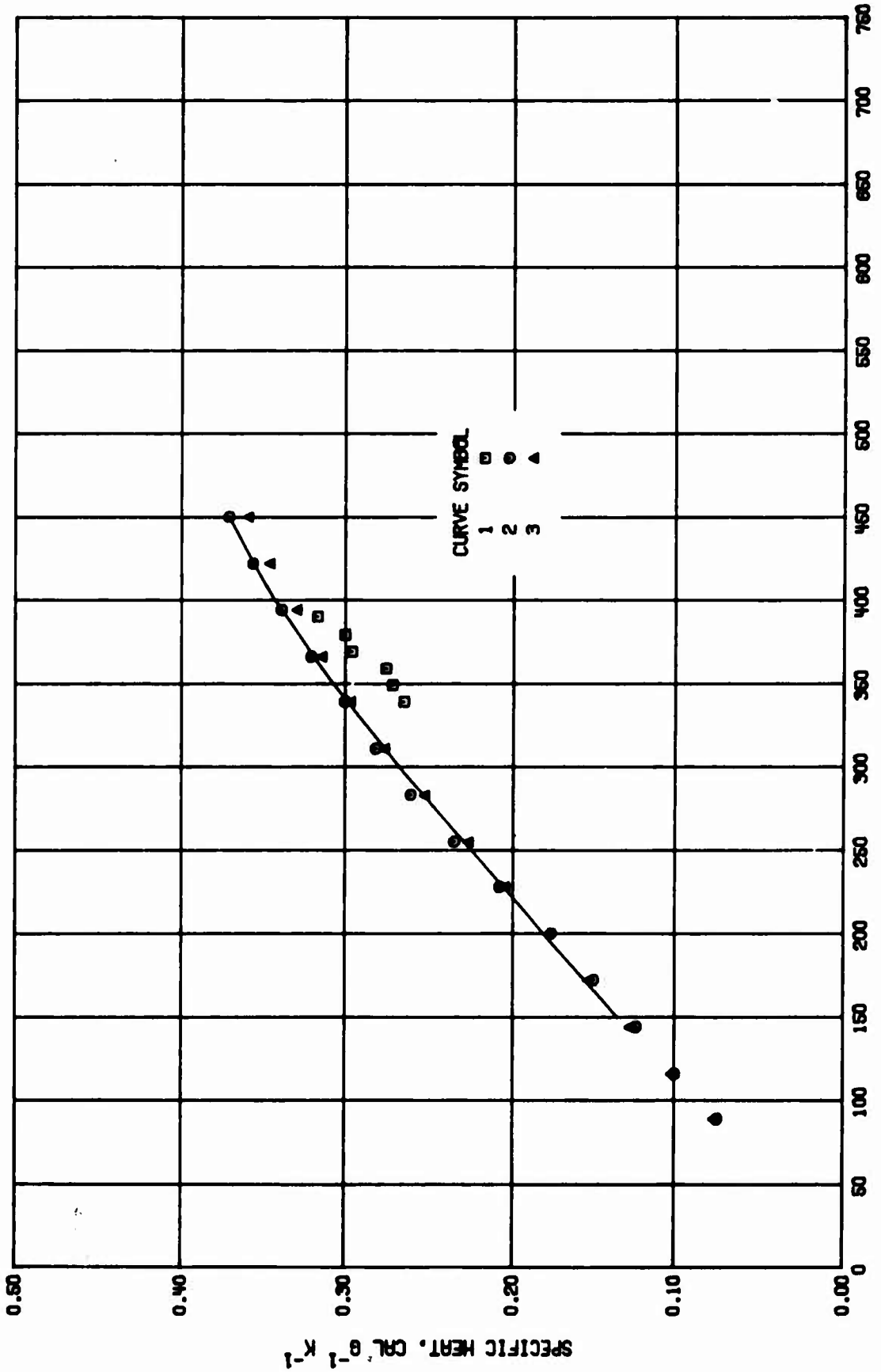

FIGURE S-2. SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITES .

TABLE 5-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	118	Kim, D. H.	1972	DSC	339-390	Specimen No. 11	Composite laminate consisted of SP272 epoxy and boron fibers; resin content 27.1 weight percent; density 1.890 g cm^{-3}; thickness 0.10 in.
2	117	Hertz, J., Christian, J. L., Varias, M.	1972		89-450	Panel 361-4	3 M's SP-272 panel.
3	117	Hertz, J., et al.	1972		89-450		Similar to the above specimen except water boiled for 24 hr.

TABLE 5-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
CURVE 1	
339	0.265
349	0.272
359	0.276
369	0.296
379	0.300
390	0.316
CURVE 2	
89	0.075
116	0.100
144	0.123
172	0.149
200	0.176
228	0.206
255	0.235
283	0.261
311	0.282
CURVE 2 (cont.)	
339	0.300
366	0.320
394	0.338
422	0.355
450	0.370
CURVE 3	
89	0.077
116	0.102
144	0.127
172	0.153
200	0.178
228	0.205
255	0.227
283	0.253
311	0.277
339	0.297
CURVE 3 (cont.)	
366	0.314
394	0.329
422	0.345
450	0.358

c. Heat of Fusion

No experimental data for the heat of fusion of boron fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific epoxy resin, curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost and the specific properties desired in the cured resin. The softening point of cured resin is near 450 K. No experimental data for the heat of fusion/softening of cured epoxy resin were located in the literature. The melting point of boron is about 2300 K and its heat of fusion is 1110 ± 40 cal g^{-1}.

d. Thermal Linear Expansion

There are 23 sets of experimental data available for the thermal linear expansion of boron fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets are given in Table 5-8. The experimental data are tabulated in Table 5-9 and shown partially in Figures 5-3A and 5-3B.

Nakamura and Larsen [119] (curves 1-3) reported the longitudinal and transverse thermal linear expansion data for Boron/Avco 5505 composite. Hertz et al. [117] (curves 4-23) reported data for SP-272 boron epoxy composites under various laminate orientations and experimental conditions. However, Hertz et al. [117] did not report the compositions of the specimens. Therefore, the provisional values tabulated in Table 5-7 and shown in Figures 5-3A and 5-3B are based on the data of Nakamura and Larsen [119] (curves 1 and 2), and are applicable to cured Boron/Avco 5505 composite with a density of 2 g cm^{-3} and a fiber content of about 50 volume percent. No experimental data for this Boron/Avco 5505 composite below 293 K were located in the literature. The low-temperature values were obtained by extrapolating the high-temperature values according to the general trend of the data for other composites. The uncertainty of the provisional values is about $\pm 10\%$.

The values of the instantaneous coefficient of thermal linear expansion, α, are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is within $\pm 20\%$.

TABLE 5-7. PROVISIONAL THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

T	a		b	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α
75	-0.041	1.0	-0.309	7
100	-0.038	1.3	-0.286	9
150	-0.031	1.6	-0.233	12
200	-0.022	2.0	-0.166	14
250	-0.011	2.5	-0.085	18
273.15	-0.005	2.7	-0.042	20
293	0.000	3.0	0.000	23
300	0.002	3.0	0.017	24
350	0.019	3.6	0.154	31
400	0.038	4.1	0.325	37
450	0.058	4.4	0.522	42

a Longitudinal thermal linear expansion.
b Transverse thermal linear expansion.

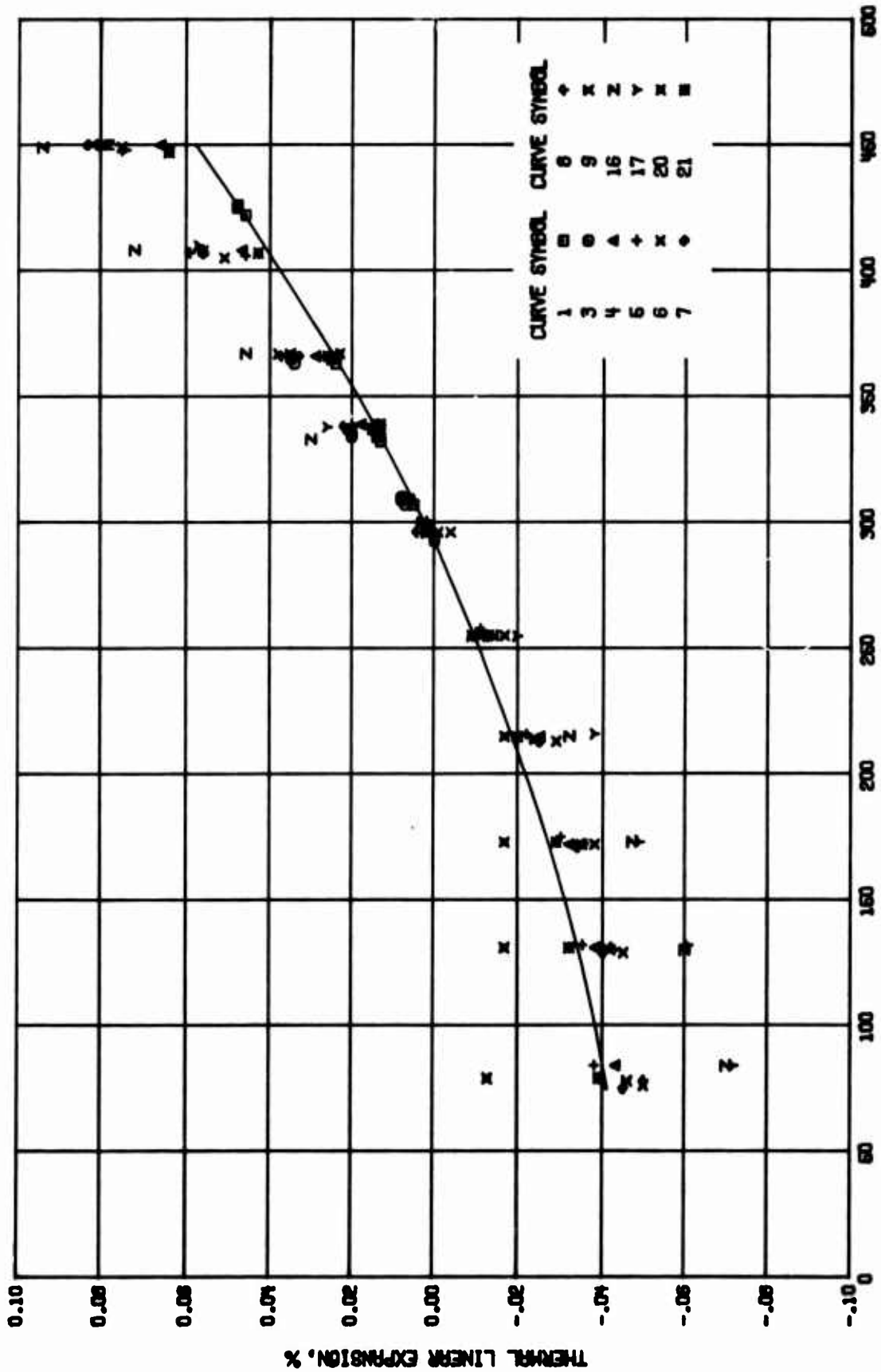

FIGURE 5-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES.

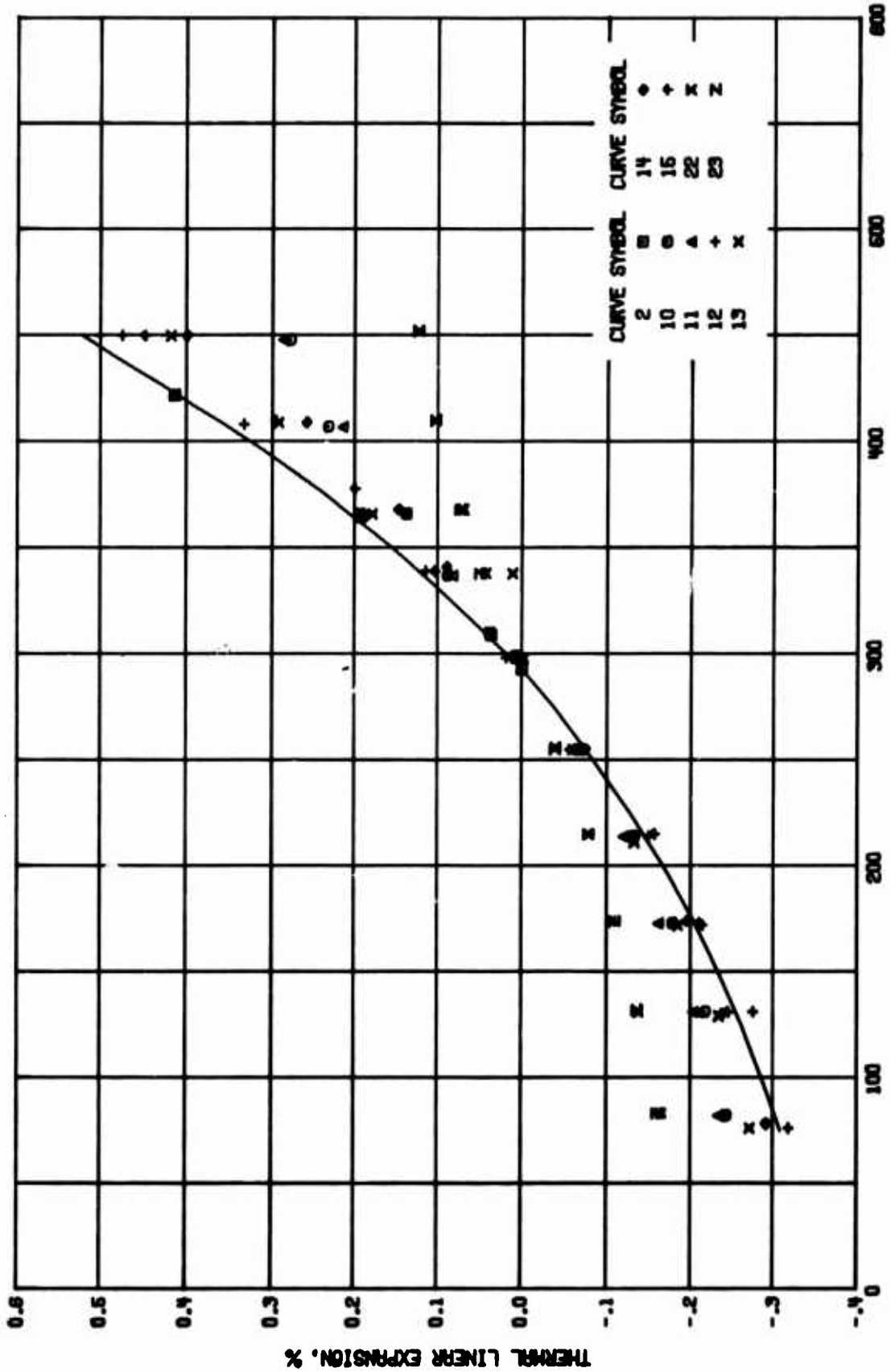

FIGURE 5-38. TRANSVERSE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES.

TABLE 5-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percen., Specifications, and Remarks
1	119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-426	Boron/ Avco 5505	Boron/epoxy system of density 2 g cm^{-3}; fiber tensile modulus 60 x 10^6 psi; six ply of 0 deg (longitudinal) orientation; three specimens tested for each material orientation, reinforced epoxy laminates consisted of 5-7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; expansion in the specimen length direction measured for single 0.5 x 2 in. laminate roughly 0.050 in. thick; specimens cycled twice in air from ambient room temperature to 450 K; values based on second cycle, stable behavior.
2	119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-422	Boron/ Avco 5505	The above specimen except specimen eight ply of 90 deg (transverse) orientation; values based on second cycle, stable behavior.
3	119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-366	Boron/ Avco 5505	The above specimen except nine ply of balanced symmetric unidirectional-angle ply orientation designated [0/45/135/0/90]s; plies stacked in directions (0/+45/-45/0/90/-45/+45/0); individual ply thickness 5.8 mils; values based on second cycle, stable behavior.
4	117	Hertz, J., Christian, J.L., and Varlas, M.	1972	L	84-450	NO558	SP-272 boron epoxy composite; panel B/EP-361-5; expansion for unidirectional laminate in 0 deg direction; zero-point correction 0.002%.
5	117	Hertz, J., et al.	1972	L	84-450	NO559	Similar to the above specimen and conditions; zero-point correction 0.003%.
6	117	Hertz, J., et al.	1972	L	76-450	Specimen No. 670	Similar to the above specimen and conditions; panel B/EP-410-2; zero-point correction 0.002%.
7	117	Hertz, J., et al.	1972	L	75-450	Specimen No. 667	Similar to the above specimen; last stable cycle; zero-point correction 0.007%.
8	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 723	Similar to the above specimen; water boiled for 24 hr; zero-point correction 0.002%.
9	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 719	Similar to the above specimen; specimen water boiled for 24 hr; zero-point correction 0.002%.
10	117	Hertz, J., et al.	1972	L	82-448	NO560	Similar to the above specimen; panel B/EP-361-5; expansion for unidirectional laminate in 90 deg direction; zero-point correction 0.008%.
11	117	Hertz, J., et al.	1972	L	82-448	NO561	Similar to the above specimen and conditions.
12	117	Hertz, J., et al.	1972	L	76-450	Specimen No. 668	Similar to the above specimen and conditions; zero-point correction 0.015%.
13	117	Hertz, J., et al.	1972	L	76-450	Specimen No. 669	Similar to the above specimen; panel B/EP-410-2; expansion for unidirectional lay up in 90 deg direction; last stable cycle; zero-point correction 0.025%.
14	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 721	Similar to the above specimen and conditions; specimen water boiled for 24 hr.
15	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 722	Similar to the above specimen and conditions; zero-point correction 0.001%.
16	117	Hertz, J., et al.	1972	L	84-449	NO546	Similar to the above specimen; panel B/EP-361-5; expansion for [±45°] laminate in 0 deg direction; zero-point correction 0.004%.
17	117	Hertz, J., et al.	1972	L	84-448	NO562	Similar to the above specimen and conditions; zero-point correction 0.004%.

TABLE 5-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18*	117	Hertz, J., Christian, J. L., and Varias, M.	1972	L	84-450	NO564	Similar to the above specimen; expansion for [$\pm 45^\circ$] laminate in 45 deg direction; zero-point correction 0.005%.
19*	117	Hertz, J., et al.	1972	L	84-449	NO547	Similar to the above specimen and conditions; zero-point correction 0.004%.
20	117	Hertz, J., et al.	1972	L	79-447	NO582	Similar to the above specimen; expansion for [$0_2^\circ/\pm 45^\circ$] laminate in 0 deg direction; zero-point correction 0.002%.
21	117	Hertz, J., et al.	1972	L	79-447	NO583	Similar to the above specimen and conditions; zero-point correction 0.002%.
22	117	Hertz, J., et al.	1972	L	83-452	NO584	Similar to the above specimen; expansion for [$0_2^\circ/\pm 45^\circ$]s in 90 deg direction; zero-point correction 0.007%.
23	117	Hertz, J., et al.	1972	L	83-452	NO585	Similar to the above specimen and conditions; zero-point correction 0.003%.

* Not shown in figure.

TABLE 5-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1	
293	0.000
307	0.005
309	0.006
332	0.013
334	0.014
337	0.015
363	0.024
365	0.025
365	0.025
422	0.046
425	0.048
426	0.048
CURVE 2	
293	0.000
309	0.036
309	0.036
310	0.038
365	0.192
365	0.192
366	0.195
422	0.414
422	0.414
422	0.414
CURVE 3	
293	0.000
307	0.007
309	0.008
310	0.008
334	0.020
335	0.020
337	0.021
363	0.034
365	0.035
366	0.035
CURVE 4	
84	-0.043
131	-0.038
172	-0.032
215	-0.025
255	-0.013
298	0.002
CURVE 4 (cont.)	
339	0.018
366	0.029
408	0.047
450	0.066
CURVE 5	
84	-0.038
132	-0.035
175	-0.030
216	-0.022
258	-0.011
300	0.003
339	0.017
366	0.028
406	0.046
450	0.065
CURVE 6	
76	-0.050
129	-0.045
172	-0.038
213	-0.029
255	-0.017
296	-0.004
296	-0.001
337	0.013
366	0.026
405	0.051
449	0.075
450	0.078
CURVE 7	
75	-0.045
129	-0.040
171	-0.034
213	-0.025
255	-0.013
298	0.002
338	0.020
366	0.033
407	0.056
450	0.083
CURVE 8	
78	-0.0502
130	-0.0429
172	-0.0355
213	-0.0253
255	-0.0127
296	0.0020
296	0.0043
338	0.0220
366	0.0373
407	0.0591
450	0.0808
CURVE 9	
78	-0.046
131	-0.041
172	-0.035
214	-0.024
255	-0.011
296	0.002
337	0.020
367	0.035
408	0.056
450	0.079
CURVE 10	
82	-0.243
131	-0.217
173	-0.177
214	-0.130
255	-0.070
299	0.008
337	0.088
366	0.138
407	0.233
448	0.279
CURVE 11	
82	-0.234
131	-0.203
173	-0.160
214	-0.119
255	-0.057
299	0.008
337	0.082
CURVE 11 (cont.)	
366	0.138
407	0.215
448	0.287
CURVE 12	
76	-0.319
131	-0.276
172	-0.214
214	-0.149
255	-0.071
298	0.007
298	0.018
339	0.115
366	0.191
408	0.333
450	0.474
450	0.501
CURVE 13	
76	-0.272
129	-0.234
172	-0.184
211	-0.132
255	-0.060
298	-0.002
338	0.107
366	0.179
409	0.293
450	0.418
CURVE 14	
78	-0.292
130	-0.238
174	-0.195
214	-0.133
255	-0.074
297	0.004
341	0.089
368	0.147
409	0.259
450	0.399
CURVE 15	
78	-0.292
131	-0.246
173	-0.211
215	-0.156
255	-0.073
298	0.010
339	0.103
378	0.199
410	0.296
450	0.447
CURVE 16	
84	-0.070
130	-0.060
173	-0.047
215	-0.032
255	-0.014
300	0.003
333	0.030
367	0.046
408	0.072
449	0.094
CURVE 17	
84	-0.072
132	-0.061
173	-0.049
216	-0.038
255	-0.020
300	0.003
338	0.026
367	0.038
410	0.057
448	0.074
CURVE 18*	
84	-0.070
130	-0.059
175	-0.048
216	-0.035
257	-0.017
299	0.005
339	0.025
366	0.041
CURVE 18 (cont.)*	
409	0.062
450	0.084
CURVE 19*	
84	-0.068
133	-0.059
173	-0.047
213	-0.034
257	-0.016
299	0.005
334	0.023
366	0.044
409	0.065
449	0.091
CURVE 20	
79	-0.013
131	-0.017
173	-0.017
215	-0.017
255	-0.009
299	0.002
339	0.013
367	0.023
407	0.043
447	0.064
CURVE 21	
79	-0.039
131	-0.032
173	-0.029
215	-0.020
255	-0.009
299	0.002
339	0.014
366	0.025
407	0.043
447	0.064
CURVE 22	
83	-0.164
131	-0.137
174	-0.105

* Not shown in figure.

TABLE 5-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 22 (cont.)	
215	-0.078
256	-0.040
299	0.006
338	0.042
368	0.069
410	0.103
452	0.123
CURVE 23	
83	-0.159
132	-0.135
174	-0.109
215	-0.078
255	-0.039
336	0.043
368	0.073
410	0.103
452	0.124

e. Thermal Diffusivity

There are no experimental data available for the thermal diffusivity of boron fiber epoxy composites. The calculation of the thermal diffusivity from the thermal conductivity, specific heat, and density values has not been carried out, because of the lack of uniformity in specimens for which other thermal properties are available. Furthermore, the thermal diffusivity of a composite is not a well-defined quantity.

3.6. Glass Fiber Epoxy Composite

The glass fiber epoxy composite consists usually of fine glass fibers surrounded by a matrix of epoxy resin. The other alternative form commonly used is the glass fabric reinforced plastics with epoxy surfacer.

Modified epoxy resins developed specifically for use in composites with glass fibers are available commercially. These are thermosetting resins used for low pressure laminating and normally cannot be used in continuous service above about 450 K, although intermittent service at a higher temperature up to 490 K is possible. Many of the various epoxy resins used as matrix constituents of composites are proprietory formulations, the exact chemical compositions of which are not available.

a. Thermal Conductivity

There are 93 sets of experimental data available for glass fibers and fabrics bonded by epoxy resins, mostly for temperatures ranging from about 100 K to somewhat above the softening temperature of about 450 K; one set of data (curve 30), not shown in the figure, is for a plate specimen measured at temperatures up to 1315 K.

The experimental data are tabulated in Table 6-3 and shown partially in Figure 6-1. The types of glass fibers and epoxy resins constituting the test specimens are:

YM-31-A glass/DER 332 (curves 1-8, 17-23),
E-glass/NICC 1174/3 (curves 28, 29),
E-glass/DER 332 (curves 13-16, 24-27, 30-32),
E-glass/DEN 438 (curves 33-38),
E-glass/ERSB-0111 (curves 40, 41),
S-glass/DEN 438 (curves 42, 43),
S-glass/E-787 (curves 44-67),
S-glass/DER 332 (curves 68, 69),
S-glass/DER 332/DEH 50 (curves 70-84), and
S-glass/Polaris ((curves 90-93).

Further information on specimen characterization and measurement conditions is given in Table 6-2.

Since the thermal conductivity of these composites depends on the type of glass and resin, the relative amounts of each and the direction of heat flow, no single set of recommended or provisional values can be given. The typical values tabulated in Table

6-1 and shown in Figure 6-1 are presented for a 35% ERSB on epoxy resin reinforced by parallelly laminated E-glass 181 fabric, density 1.87 g cm^{-3}, for heat flow perpendicular to the fabric. These values are based primarily on the measurements of Lewis [128] (curves 40 and 41).

TABLE 6-1. TYPICAL THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITES

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
100	0.0027
150	0.0032
200	0.0036
250	0.0040
273.15	0.0041
293	0.0042
300	0.0043
350	0.0045
400	0.0046
450	0.0044

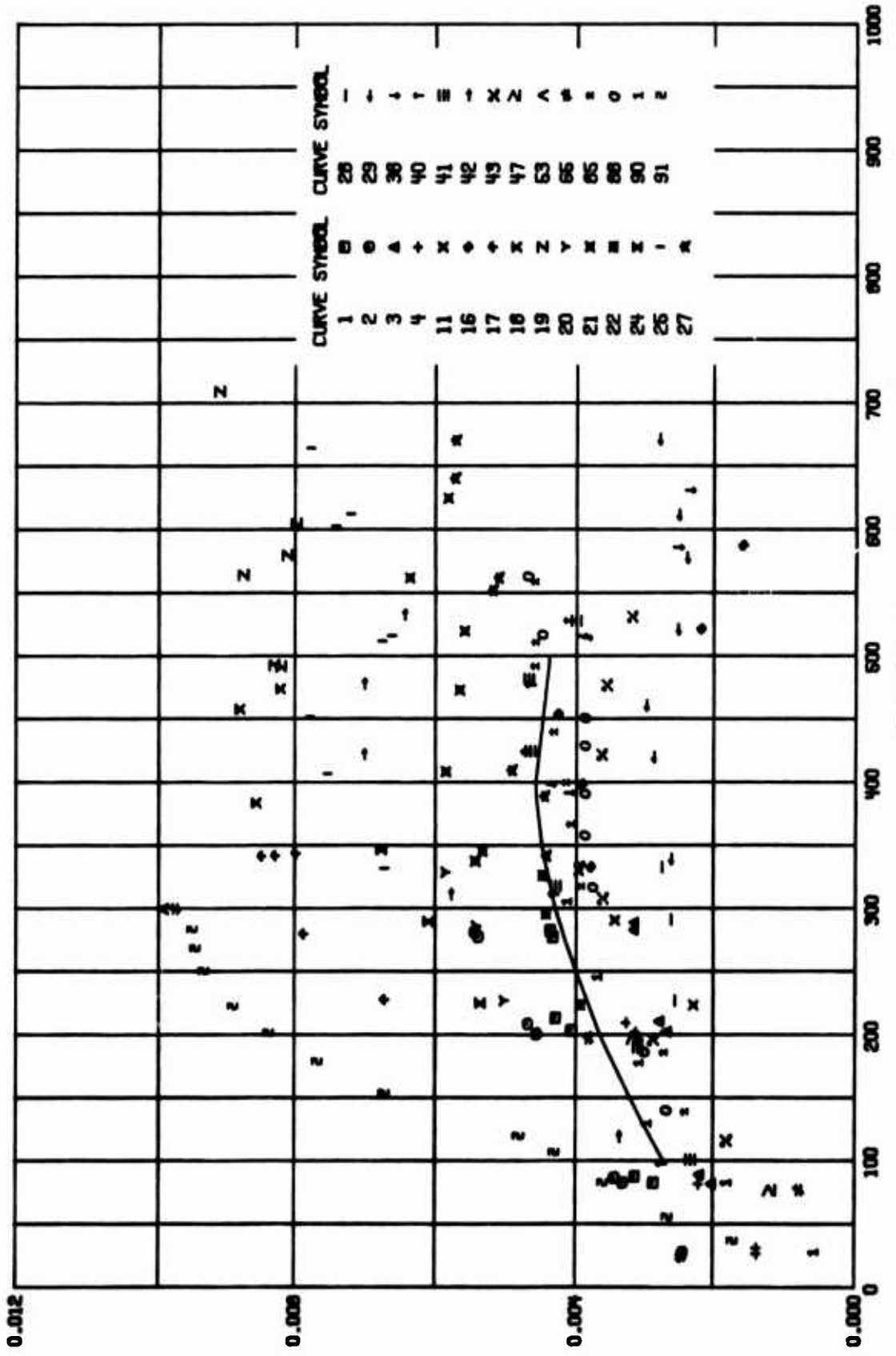

FIGURE 6-1. THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITES.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	120, 121	Campbell, M.D., Haskins, J.F., O'Barr, G.L., and Hertz, J.	1964	L	83-283	D	80 Owens-Corning high modulus YM-31-A glass fiber roving containing an HTS finish and 20 Dow Chemical DER-332 epoxy resin with the fibers unidirectional and parallel; 7 x 7 x 0.5 in.; heat flow parallel to fiber direction; measured in nitrogen atm.
2	120, 121	Campbell, M.D., et al.	1964	L	25-282	D	Same as the above specimen except measured in helium atm.
3	121, 122	Campbell, M.D., et al.	1963	L	82-289	D	Same as the above specimen except sawed into 7 x 0.5 x 0.5 in. strips and reassembled with epoxy adhesive such that heat flow perpendicular to the fibers; measured in nitrogen atm.
4	121, 122	Campbell, M.D., et al.	1963	L	27-210	D	Same as the above specimen except measured in helium atm.
5*	120, 121	Campbell, M.D., et al.	1964	L	84-282	E	80 Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish and 20 Dow Chemical DER-332 epoxy resin cured with an acid anhydride; 7 x 7 x 0.5 in.; alternate layers of the simulated helical filament-wound fiber roving cross-plied at angles of 57° and 303° from the horizontal axis; heat-flow parallel to the thickness with the fiber; measured in nitrogen atm.
6*	120, 121	Campbell, M.D., et al.	1964	L	26-282	E	Same as the above specimen except measured in helium atm.
7*	121, 122	Campbell, M.D., et al.	1963	L	83-281	E	Same as the above specimen except sawed into 7 x 0.5 x 0.5 in. strips and reassembled with epoxy adhesive such that heat flow perpendicular to the thickness; measured in nitrogen atm.
8*	121, 122	Campbell, M.D., et al.	1963	L	26-285	E	Same as the above specimen except measured in helium atm.
9*	58	Careaga, J.A., Mayer, E.R., and Del Castillo, L.	1970	L	81-216		No details reported.
10*	123	Baltakis, F.P., Hurd, D.E., and Holmes, R.F.	1960	L	298	A2(XSP-2A-1)	35% epoxy resin reinforced by 15% glass fiber and filled by 50% ceramic; 1 x 1 x 0.125 in.; density 2.110 g cm^{-3}; reported error 3-5%.
11	124	Engelke, W.T., Pears, C.D., and Ogelsby, S., Jr.	1963	L	224-330	d-1	30% NRC 1174/3 epoxy resin reinforced by 70% randomly oriented Owens-Corning "E" glass flakes 2 μm thick and 200 to 2000 μm in diameter; 0.2339 in. thick plate specimen; supplied by Narmco Research and Development; molded under 10 psi at 450 K for 3 min; cured under 800 psi at 450 K for 2 hr; density 1.97 g cm^{-3}.
12*	124	Engelke, W.T., et al.	1963	L	223-332	d-2	25% NRC 1174/3 epoxy resin reinforced by 75% Owens-Corning "E" glass flakes 2 μm thick and 200 to 2000 μm in diameter; 0.2408 in. thick plate specimen; supplied by Narmco Research and Development; cured under 1500 psi at 450 K for 2 hr; density 1.97 g cm^{-3}.
13*	125, 126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1963	L	222-334	c-2	30% Dow Chemical DER 332 epoxy resin reinforced by 70% "E" glass fiber roving in 40 layers of parallel orientation; 0.2404 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 394 K for 2 hr; density 1.85 g cm^{-3}.
14*	125, 126	Pears, C.D., et al.	1963	L	349-615	c-2	Same as the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
15*	125, 126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1963	L	225-332	d-1	The specimen for curve No. 11 remeasured.
16	125, 126	Pears, C.D., et al.	1963	L	334-588	d-1	Same as the above specimen.
17	125, 126	Pears, C.D., et al.	1963	L	228-344	c-1	40% Dow Chemical DER 332 epoxy resin reinforced by 60% unidirectional parallel high modulus YM 31 A glass fiber roving with HTS finish; 0.2213 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.91 g cm^{-3}; heat flow parallel to reinforcement glass roving in a-direction.
18	125, 126	Pears, C.D., et al.	1963	L	384-474	c-1	Same as the above specimen.
19	125, 126	Pears, C.D., et al.	1963	L	492-710	c-1	Same as the above specimen.
20	125, 126	Pears, C.D., et al.	1963	L	227-329	c-1	Similar to the above specimen except thickness 0.2365 in.; heat flow perpendicular to reinforcement glass roving in b-direction.
21	125, 126	Pears, C.D., et al.	1963	L	338-672	c-1	Same as the above specimen.
22	125, 126	Pears, C.D., et al.	1963	L	224-332	c-1	Similar to the above specimen except thickness 0.2491 in.; heat flow in the thickness of the specimen in c-direction.
23*	125, 126	Pears, C.D., et al.	1963	L	335-669	c-1	Same as the above specimen.
24	125, 126	Pears, C.D., et al.	1963	L	226-347	c-2	30% Dow Chemical DER 332 epoxy resin reinforced by 70% parallel "E" glass fiber roving with HTS finish in 40 layers; 0.2412 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.85 g cm^{-3}; heat flow parallel to reinforcement roving in a-direction.
25	125, 126	Pears, C.D., et al.	1963	L	332-665	c-2	Same as the above specimen.
26*	125, 126	Pears, C.D., et al.	1963	L	229-324	c-2	Similar to the above specimen except thickness 0.2042 in.; heat flow perpendicular to reinforcement roving in b-direction.
27	125, 126	Pears, C.D., et al.	1963	L	342-671	c-2	Same as the above specimen.
28	125, 126	Pears, C.D., et al.	1963	L	227-333	c-3	40% Dow Chemical DER 332 epoxy resin reinforced by 60% high modulus YM 31 A glass fiber roving with HTS finish in 40 layers cross plied parallel to and 66° from horizontal axis; 0.2302 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.94 g cm^{-3}; heat flow through thickness of the specimen in c-direction.
29	125, 126	Pears, C.D., et al.	1963	L	339-672	c-3	Same as the above specimen.
30*	125, 126	Pears, C.D., et al.	1963	L	225-332	c-4	20% Dow Chemical DER 332 epoxy resin reinforced by 80% "E" glass fiber roving with HTS finish in 40 cross plied layers; 0.2702 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 2.10 g cm^{-3}; heat flow through thickness of specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
31*	125, 126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1963	L	356-479	c-4	Same as the above specimen.
32*	125, 126	Pears, C.D., et al.	1963	L	336-624	c-4	Same as the above specimen.
33*	125, 126	Pears, C.D., et al.	1963	L	229-333	c-5	20% Dow Chemical DEN 438 epoxy resin reinforced by 80% "E" glass fiber roving 20 ends with HTS finish in 40 unidirectional parallel layers; 0.2466 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 2.06 g cm^{-3}; heat flow through thickness of specimen in c-direction.
34*	125, 126	Pears, C.D., et al.	1963	L	338-674	c-5	Same as the above specimen.
35*	125, 126	Pears, C.D., et al.	1963	L	221-332	d-1	Similar to the specimen for curve No. 11 except thickness 0.2107 in.; heat flow parallel to the flake orientation.
36*	125, 126	Pears, C.D., et al.	1963	L	340-616	d-1	Same as the above specimen.
37*	125, 126	Pears, C.D., et al.	1963	L	223-333	d-2	Similar to the specimen for curve No. 12 except thickness 0.2408 in.; heat flow through thickness of specimen in c-direction.
38	125, 126	Pears, C.D., et al.	1963	L	336-631	d-2	Same as the above specimen.
39*	127	Gray, C.O.	1958	L	386-1315		Fiberglas monofilament roving bonded with 23% epoxy resin; plate specimen supplied by Goodyear Aircraft Corp.; density 1.90 g cm^{-3}; data taken from smooth curve.
40	128	Lewis, W.	1965	C	98-528	EP-E	36.0% ERSB-0111 epoxy resin reinforced by parallelly laminated "E" glass 181 fabric; 2.5 x 2.5 x 0.201 in.; density 1.92 g cm^{-3}; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
41	128	Lewis, W.	1965	C	101-528	EP-S	35.0% ERSB-0111 epoxy resin reinforced by parallelly laminated "E" glass 181 fabric; 2.5 x 2.5 x 0.231 in.; density 1.82 g cm^{-3}; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
42	128	Lewis, W.	1965	C	119-533	DEN-S-R	19.3% Dow Chemical DEN 438 epoxy Novalac resin reinforced by parallelly laminated "S" glass 181 fabric; 2.5 x 2.5 x 0.245 in.; density 1.99 g cm^{-3}; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
43	128	Lewis, W.	1965	C	116-531	DEN-S-L	32.0% Dow Chemical DEN 438 epoxy Novalac resin reinforced by parallelly laminated "S" glass 181 fabric; 2.5 x 2.5 x 0.277 in.; density 1.65 g cm^{-3}; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
44*	129, 130	Toth, L.W., Boller, T.J., Butcher, I.R., Kariotis, A.H., and Yoder, F.D.	1965	L	77-300	BFW-7A7B-23-1	E-787 epoxy resin reinforced by cross-plied "S" glass 901 roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
45*	129, 130	Toth, L.W., et al.	1965	L	20-300	BFW-7A7B-23-2	Similar to the above specimen.
46*	129, 130	Toth, L.W., et al.	1965	L	77-300	BFW-7A7B-23-3	Similar to the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
47	129, 130	Toth, L.W., Boller, T.J., Butcher, I.R., Kariotis, A.H., and Yoder, F.D.	1965	L	77-300	UFW-9A9B-23-1	E-787 epoxy resin reinforced by unidirectional "S" glass 901 roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
48*	130	Toth, L.W., et al.	1966	L	20-300	UFW-9A9B-23-2	Similar to the above specimen.
49*	130	Toth, L.W., et al.	1966	L	77-300	UFW-9A9B-23-3	Similar to the above specimen.
50*	129, 130	Toth, L.W., et al.	1965	L	77-300	1543-10A-23-1	E-787 epoxy resin reinforced by "S" glass 1543 cloth laminates; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
51*	129, 130	Toth, L.W., et al.	1966	L	20-300	1543-10A-23-2	Similar to the above specimen.
52*	129, 130	Toth, L.W., et al.	1966	L	77-300	1543-10A-23-3	Similar to the above specimen.
53	129, 130	Toth, L.W., et al.	1965	L	77-300	1581-9A9B-23-1	E-787 epoxy resin reinforced by "S" glass 1581 cloth laminates; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
54*	130	Toth, L.W., et al.	1966	L	20-300	1581-9A9B-23-2	Similar to the above specimen.
55*	130	Toth, L.W., et al.	1966	L	77-300	1581-9A9B-23-3	Similar to the above specimen.
56*	129, 130	Toth, L.W., et al.	1965	L	77-300	BFW-7A7B-31-1	Similar to the specimen for curve No. 44 except heat flow perpendicular to reinforcement.
57*	129, 130	Toth, L.W., et al.	1965	L	20-300	BFW-7A7B-31-2	Similar to the above specimen.
58*	130	Toth, L.W., et al.	1966	L	77-300	BFW-7A7B-31-3	Similar to the above specimen.
59*	130	Toth, L.W., et al.	1966	L	77-300	UFW-9A9B-31-1	Similar to the specimen for curve No. 47 except heat flow perpendicular to reinforcement.
60*	130	Toth, L.W., et al.	1966	L	20-300	UFW-9A9B-31-2	Similar to the above specimen.
61*	130	Toth, L.W., et al.	1966	L	77-300	UFW-9A9B-31-3	Similar to the above specimen.
62*	129, 130	Toth, L.W., et al.	1965	L	77-300	1543-10A-31-1	Similar to the specimen for curve No. 50 except heat flow perpendicular to reinforcement.
63*	130	Toth, L.W., et al.	1966	L	20-300	1543-10A-31-2	Similar to the above specimen.
64*	130	Toth, L.W., et al.	1966	L	77-300	1543-10A-31-3	Similar to the above specimen.
65	129, 130	Toth, L.W., et al.	1965	L	77-300	1581-9A9B-31-1	Similar to the specimen for curve No. 53 except heat flow perpendicular to reinforcement.
66*	130	Toth, L.W., et al.	1966	L	20-300	1581-9A9B-31-2	Similar to the above specimen.
67*	130	Toth, L.W., et al.	1966	L	77-300	1581-9A9B-31-3	Similar to the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
68*	130	Toth, L.W., Boller, T.J., Butcher, I.R., Kariotis, A.H., and Yoder, F.D.	1966	L	77,300	2006-4-1	DER 332/BF_3 epoxy resin reinforced by cross-plied "S" glass roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
69*	130	Toth, L.W., et al.	1966	L	77,300	2006-5-1	Similar to the above specimen except heat flow perpendicular to reinforcement.
70*	130	Toth, L.W., et al.	1966	L	77,300	3006-4-1	DER 332/DEH 50 epoxy resin reinforced by cross-plied "S" glass roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
71*	130	Toth, L.W., et al.	1966	L	77,300	3006-5-1	Similar to the above specimen except heat flow perpendicular to reinforcement.
72*	126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1964	L	231-328	c-3	Similar to the specimen for curve No. 28; heat flow in a-direction.
73*	126	Pears, C.D., et al.	1964	L	333-650	c-3	Same as the above specimen.
74*	126	Pears, C.D., et al.	1964	L	225,324	c-3	Similar to the above specimen except heat flow in b-direction.
75*	126	Pears, C.D., et al.	1964	L	329-702	c-3	Same as the above specimen.
76*	126	Pears, C.D., et al.	1964	L	223-326	c-4	Similar to the specimen for curve No. 30; heat flow in a-direction.
77*	126	Pears, C.D., et al.	1964	L	330-664	c-4	Same as the above specimen.
78*	126	Pears, C.D., et al.	1964	L	220-326	c-4	Similar to the above specimen except heat flow in b-direction.
79*	126	Pears, C.D., et al.	1964	L	358-655	c-4	Same as the above specimen.
80*	126	Pears, C.D., et al.	1964	L	234-328	c-5	Similar to the specimen for curve No. 33; heat flow in a-direction.
81*	126	Pears, C.D., et al.	1964	L	319-676	c-5	Same as the above specimen.
82*	126	Pears, C.D., et al.	1964	L	229-321	d-2	Similar to the specimen for curve No. 37; heat flow parallel to reinforcement.
83*	126	Pears, C.D., et al.	1964	L	294-609	d-2	Same as the above specimen.
84*	126	Pears, C.D., et al.	1964	L	325-674	d-2	Same as the above specimen.
85	131	Avco Corporation	1966	L	139-559		36 to 42% U.S. Polymeric epoxy novalac NMA resin reinforced by glass fabric 181; density 1.775 g cm^{-3}; heat flow perpendicular to reinforcing laminations.
86*	131	Avco Corporation	1966	L	142-573		Similar to the above specimen except density 1.828 g cm^{-3}.
87*	131	Avco Corporation	1966	L	138-578		Similar to the above specimen except density 1.829 g cm^{-3}.
88	131	Avco Corporation	1966	L	141-564		Similar to the above specimen except heat flow parallel to reinforcing laminations and density 1.772 g cm^{-3}.
89*	131	Avco Corporation	1966	L	319-451		Similar to the above specimen.
90	116	Gille, J.P.	1969	L	28-306	1	81.3 "S" glass fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.002 in. I.D., 1.140 in. O.D., and 0.503 in. in effective length; density 2.02 g cm^{-3}; heat flow perpendicular to fibers; data taken from smooth curve.
91	116	Gille, J.P.	1969	L	37-284	2	79.4 "S" glass fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.000 in. I.D., 1.132 in. O.D., and 0.500 in. in effective length; density 2.02 g cm^{-3}; heat flow parallel to fibers; data taken from smooth curve.
92*	116	Gille, J.P.	1969	L	56,279	3	Similar to the above specimen except 1.000 in. in effective length.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
93*	132	Ogawa, K. and Noguchi, Y.	1968	P	300-422	LE-61N	95 x 65 x 0.99 mm; density 1.76 g cm^{-3}; thermal conductivity values calculated from thermal diffusivity and specific heat measured by infrared radiation method.

* Not shown in figure.

TABLE 6-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
CURVE 1	
83	0.00285
88	0.00313
204	0.00407
214	0.00430
278	0.00434
283	0.00438
CURVE 2	
25	0.00245
28	0.00243
83	0.00331
87	0.00343
201	0.00458
209	0.00471
278	0.00541
282	0.00546
CURVE 3	
82.2	0.00203
89.4	0.00220
202.8	0.00267
211.1	0.00278
283.6	0.00316
289.3	0.00316
CURVE 4	
26.9	0.00140
31.3	0.00140
81.9	0.00221
196.4	0.00307
202.4	0.00313
209.7	0.00327
CURVE 5*	
84	0.00280
87	0.00271
202	0.00433
208	0.00443
216	0.00447
278	0.00483
282	0.00492

T	k
CURVE 6*	
26	0.00193
28	0.00195
83	0.00280
87	0.00291
200	0.00444
278	0.00487
282	0.00492
CURVE 7*	
83	0.00199
88	0.00276
202	0.00283
209	0.00288
277	0.00335
281	0.00330
CURVE 8*	
26	0.00133
30	0.00143
82	0.00213
87	0.00221
202	0.00303
212	0.00314
277	0.00329
281	0.00322
285	0.00339
CURVE 9*	
81.0	0.00297
86.1	0.00581
90.7	0.00785
115.2	0.0117
124.3	0.0146
130.5	0.0174
151.5	0.0224
164.2	0.0334
167.7	0.0329
171.0	0.0324
189.2	0.0635
215.8	0.0637

T	k
CURVE 10*	
298	0.00568
CURVE 11	
223.7	0.00228
291.1	0.00343
330.5	0.00397
CURVE 12*	
223.0	0.00313
292.3	0.00470
331.9	0.00444
CURVE 13*	
221.5	0.00388
289.0	0.00454
334.3	0.00466
CURVE 14*	
348.7	0.00440
356.6	0.00457
394.7	0.00463
451.3	0.00477
499.6	0.00493
554.3	0.00513
614.9	0.00369
CURVE 15*	
225.1	0.00345
292.6	0.00355
332.1	0.00366
CURVE 16	
333.5	0.00379
399.0	0.00392
454.3	0.00427
521.6	0.00218
587.7	0.00160

T	k
CURVE 17	
228.1	0.00671
280.3	0.00787
342.0	0.00849
342.2	0.00829
344.0	0.00799
CURVE 18	
384.1	0.00857
458.3	0.00881
474.3	0.00821
CURVE 19	
491.8	0.00821
492.9	0.00831
564.5	0.00877
579.9	0.00812
604.7	0.00799
709.5	0.00913
CURVE 20	
227.2	0.00503
286.1	0.00544
328.9	0.00586
CURVE 21	
338.0	0.00545
345.6	0.00535
408.7	0.00586
473.2	0.00567
519.9	0.00560
562.1	0.00636
625.0	0.00583
672.5	0.00593
CURVE 22	
224.0	0.00394
296.2	0.00444
326.3	0.00449
331.8	0.00466

T	k
CURVE 23*	
334.6	0.00460
397.7	0.00463
460.0	0.00486
520.1	0.00511
569.0	0.00548
624.3	0.00500
669.3	0.00503
CURVE 24	
225.5	0.00538
290.2	0.00610
347.0	0.00676
CURVE 25	
332.0	0.00672
407.0	0.00753
452.2	0.00779
512.2	0.00675
516.5	0.00662
603.1	0.00741
612.8	0.00720
664.7	0.00777
CURVE 26*	
228.9	0.00428
287.8	0.00464
324.0	0.00459
CURVE 27	
341.8	0.00444
388.9	0.00447
409.5	0.00493
552.0	0.00521
561.8	0.00512
640.4	0.00574
670.7	0.00573
CURVE 28	
227.0	0.00254

T	k
CURVE 28 (cont.)	
291.0	0.00260
332.7	0.00274
CURVE 29	
339.3	0.00261
420.1	0.00286
460.9	0.00297
521.1	0.00251
578.1	0.00238
611.8	0.00250
671.5	0.00278
CURVE 30*	
225.4	0.00381
282.3	0.00434
332.4	0.00466
CURVE 31*	
356.5	0.00440
378.7	0.00428
479.3	0.00550
CURVE 32*	
336.4	0.00493
398.2	0.00464
476.9	0.00547
519.0	0.00545
565.0	0.00528
624.0	0.00339
CURVE 33*	
229.0	0.00404
288.1	0.00431
333.1	0.00441
CURVE 34*	
337.9	0.00472
338.4	0.00467
397.4	0.00489
450.2	0.00526

* Not shown in figure.

TABLE 6-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

T	k
CURVE 34 (cont.)*	
499.6	0.00534
574.2	0.00524
610.5	0.00499
673.7	0.00470
CURVE 35*	
221.1	0.00436
290.0	0.00538
332.1	0.00561
CURVE 36*	
340.2	0.00598
388.6	0.00622
453.8	0.00692
503.4	0.00702
562.2	0.00689
615.8	0.00558
CURVE 37*	
222.9	0.00366
286.5	0.00402
332.6	0.00410
CURVE 38	
335.6	0.00395
391.8	0.00410
398.3	0.00437
514.3	0.00385
515.7	0.00391
585.8	0.00251
631.1	0.00234
CURVE 39*	
386	0.00803
582	0.00674
806	0.00569
831	0.00582
854	0.00619
879	0.00703
900	0.00812
924	0.00992
1051	0.0218
1067	0.0224

T	k
CURVE 39 (cont.)	
1086	0.0226
1315	0.0225
CURVE 40	
97.8	0.00274
200	0.00374
311	0.00433
424	0.00473
477	0.00467
528	0.00412
CURVE 41	
101	0.00232
190	0.00309
318	0.00430
425	0.00467
482	0.00469
528	0.00401
CURVE 42	
119	0.00336
201	0.00456
311	0.00578
422	0.00701
478	0.00700
533	0.00643
CURVE 43	
116	0.00182
196	0.00286
308	0.00361
422	0.00363
477	0.00356
531	0.00319
CURVE 44*	
77	0.00108
197	0.00347
300	0.00755
CURVE 45*	
20	0.00075

T	k
CURVE 45 (cont.)*	
77	0.00109
197	0.00320
300	0.00857
CURVE 46*	
77	0.00090
197	0.00201
300	0.00640
CURVE 47	
77	0.00116
197	0.00312
300	0.00893
CURVE 48*	
20	0.00115
77	0.00127
197	0.00211
300	0.00666
CURVE 49*	
77	0.00133
197	0.00253
300	0.00669
CURVE 50*	
77	0.00084
197	0.00268
300	0.00795
CURVE 51*	
20	0.00080
77	0.00100
197	0.00240
300	0.00650
CURVE 52*	
77	0.00123
197	0.00220
300	0.00629

T	k
CURVE 53	
77	0.00100
197	0.00314
300	0.00994
CURVE 54*	
20	0.00086
77	0.00100
197	0.00300
300	0.00853
CURVE 55*	
77	0.00102
197	0.00295
300	0.00816
CURVE 56*	
77	0.00092
197	0.00292
300	0.01050
CURVE 57*	
20	0.00108
77	0.00107
197	0.00317
300	0.01080
CURVE 58*	
77	0.00127
197	0.00337
300	0.01055
CURVE 59*	
77	0.00135
197	0.00360
300	0.00690
CURVE 60*	
20	0.00119
77	0.00132
197	0.00299
300	0.00679

T	k
CURVE 61*	
77	0.00130
197	0.00330
300	0.00780
CURVE 62*	
77	0.00090
197	0.00372
300	0.01100
CURVE 63*	
20	0.00105
77	0.00118
197	0.00334
300	0.01070
CURVE 64*	
77	0.00113
197	0.00215
300	0.01015
CURVE 65	
77	0.00079
197	0.00382
300	0.00977
CURVE 66*	
20	0.00117
77	0.00120
197	0.00375
300	0.00880
CURVE 67*	
77	0.00136
197	0.00272
300	0.00778
CURVE 68*	
77	0.00107
300	0.00650

T	k
CURVE 69*	
77	0.00115
300	0.00641
CURVE 70*	
77	0.00110
300	0.00620
CURVE 71*	
77	0.00100
300	0.00633
CURVE 72*	
231	0.00337
299	0.00505
328	0.00495
CURVE 73*	
333	0.00502
381	0.00509
450	0.00557
497	0.00570
579	0.00567
614	0.00567
650	0.00541
CURVE 74*	
225	0.00412
324	0.00487
CURVE 75*	
329	0.00482
353	0.00476
411	0.00489
468	0.00584
503	0.00567
561	0.00557
579	0.00513
611	0.00535
702	0.00541

* Not shown in figure.

TABLE 6-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

T	k
CURVE 76*	
223	0.00437
290	0.00568
326	0.00588
CURVE 77*	
330	0.00567
393	0.00570
463	0.00665
469	0.00650
499	0.00652
559	0.00678
621	0.00613
663	0.00588
664	0.00606
CURVE 78*	
220	0.00449
291	0.00547
326	0.00586
CURVE 79*	
358	0.00545
489	0.00603
533	0.00622
655	0.00570
CURVE 80*	
234	0.00453
293	0.00490
328	0.00560
CURVE 81*	
319	0.00599
352	0.00586
378	0.00586
441	0.00619
509	0.00637
568	0.00637
609	0.00623
676	0.00616
CURVE 82*	
229	0.00558
292	0.00617
321	0.00588
CURVE 83*	
294	0.00562
332	0.00596
457	0.00596
609	0.00637
CURVE 84*	
325	0.00607
392	0.00614
478	0.00640
526	0.00656
581	0.00659
674	0.00609
CURVE 85	
139	0.00239
186	0.00270
318	0.00393
367	0.00408
400	0.00415
440	0.00433
492	0.00460
511	0.00459
559	0.00460
CURVE 86*	
142	0.00279
193	0.00329
339	0.00414
381	0.00436
433	0.00466
485	0.00474
538	0.00474
573	0.00495
CURVE 87*	
138	0.00261
192	0.00312
343	0.00367
385	0.00357
434	0.00353
485	0.00379
539	0.00427
578	0.00447
CURVE 88	
141	0.00267
187	0.00299
318	0.00376
359	0.00388
392	0.00388
430	0.00388
452	0.00388
518	0.00450
564	0.00471
CURVE 89*	
319	0.00377
358	0.00389
392	0.00388
430	0.00388
451	0.00388
CURVE 90	
28	0.000588
83	0.00182
130	0.00296
178	0.00308
246	0.00369
306	0.00414
CURVE 91	
37	0.00173
56	0.00265
83	0.00360
107	0.00431
120	0.00483
154	0.00672
179	0.00767
202	0.00838
223	0.00891
251	0.00935
269	0.00948
284	0.00952
CURVE 92*	
56	0.00299
279	0.00928
CURVE 93*	
300	0.00325
334	0.00342
377	0.00320
422	0.00325

* Not shown in figure.

b. Specific Heat

There are 38 sets of experimental data available for the specific heat of glass fiber epoxy composites. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 6-5. The experimental data are tabulated in Table 6-6 and partially shown in Figures 6-2A through 6-2D. These data sets cover the following types of composites:

E-glass fibers/Narmco (curves 1-7, 37, 38),
E-glass fibers/Dupont P.I. (curve 8),
YM-31-A glass fibers/DER 332 (curves 10, 13, 26, 27, 32, 34),
"181" glass fabric/shell X-131 (curves 22, 23),
Glass fibers/Epon 828 (curves 11, 28-30),
E-glass fibers/DER 332 (curves 33, 35), and
Glass fibers/DEN 438 (curves 24, 25, 36).

The provisional values generated as discussed in the following sections are for well cured and thermally stable composites. The resin content of each composite is given together with the specific heat values.

E-Glass/DER 332 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2A are based on the measurements of Pears, Engelke, and Thornburgh [126] (curves 33 and 35). These values are considered accurate to about ± 10%. This composite begins to degrade near 550 K.

E-Glass/DEN 438 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2B are based on the measurements of Pears, Engelke, and Thornburgh [126] (curve 36). These values are considered accurate to about ± 10%. The investigations of Lagedrost et al. [133] (curves 24 and 25) yield considerably higher values for their composites containing chopped glass and microballoons.

E-Glass/Narmco Epoxy Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2C are based on the measurements of Kim [118] (curves 1-7). These values are considered accurate to within ± 10%. The specific heat values of Pears et al. [126] (curves 37 and 38) for

composites with Narmco NRC 1174/3 epoxy resin (molded from powder) are considerably higher below 350 K and lower above that temperature.

YM-31-A Glass/DER 332 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2D are based primarily on the data of Campbell et al. [134] (curve 26). The uncertainty of these values is about ± 10%. The specific heat values of Pears et al. [126] (curves 32 and 34) for composite containing 40 percent epoxy vary as much as 25% from the provisional values.

TABLE 6-4. PROVISIONAL SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITES

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	E-Glass Fibers					YM-31-A Glass Fibers
	DER-332 Epoxy	DEN-438 Epoxy	Narmco Epoxy			DER-332 Epoxy
	20 percent	20 percent	25 percent	38 percent	58 percent	20 percent
25						0.007
30						0.013
40						0.024
50						0.034
60						0.044
70						0.052
80						0.061
90						0.070
100						0.078
150						0.116
200	0.135	0.135				0.153
250	0.165	0.165				0.188
273.15	0.178	0.178				0.204
293	0.189	0.189				0.217
300	0.193	0.193	0.200	0.220	0.230	0.223
350	0.220	0.220	0.234	0.260	0.313	0.258
400	0.246	0.246	0.267	0.302	0.396	0.292
450	0.271	0.271				0.324
500	0.295	0.295				

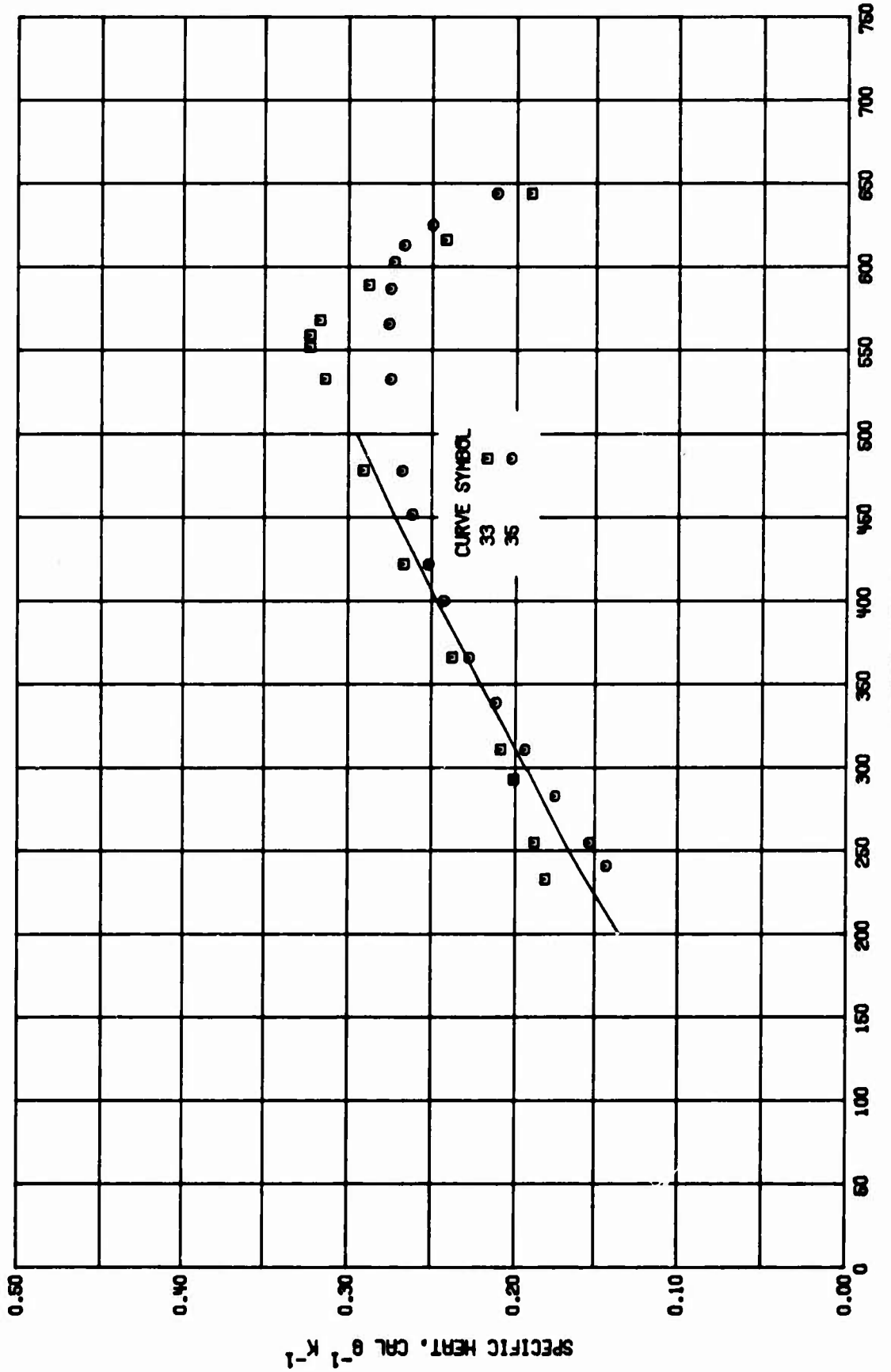

FIGURE 6-2A. SPECIFIC HEAT OF E-GLASS FIBER DER 332 EPOXY COMPOSITES .

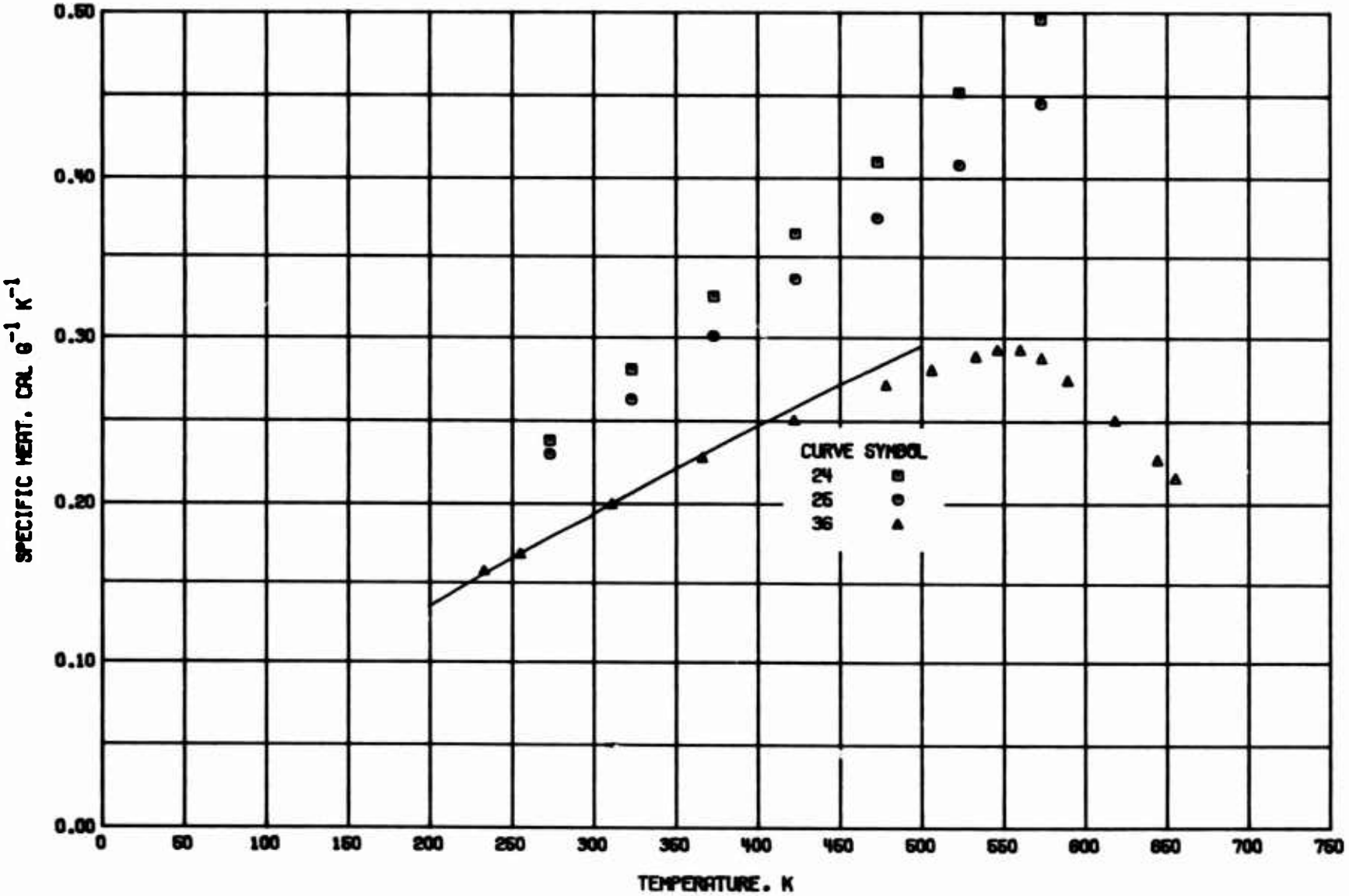

FIGURE 6-28. SPECIFIC HEAT OF E-GLASS FIBER DEN 438 EPOXY COMPOSITES .

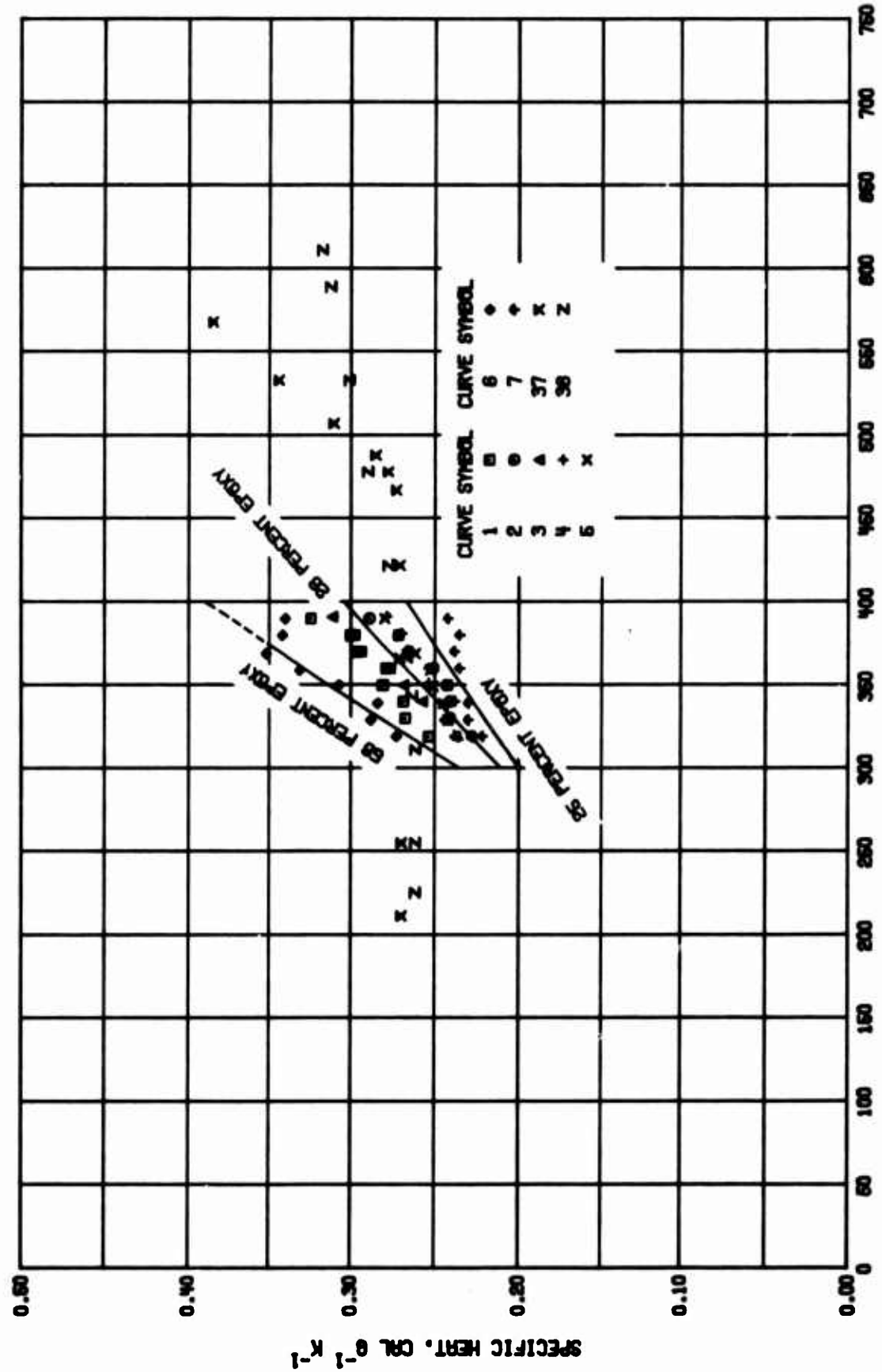

FIGURE 8-EC. SPECIFIC HEAT OF E-GLASS FIBER NARMCO EPOXY COMPOSITES.

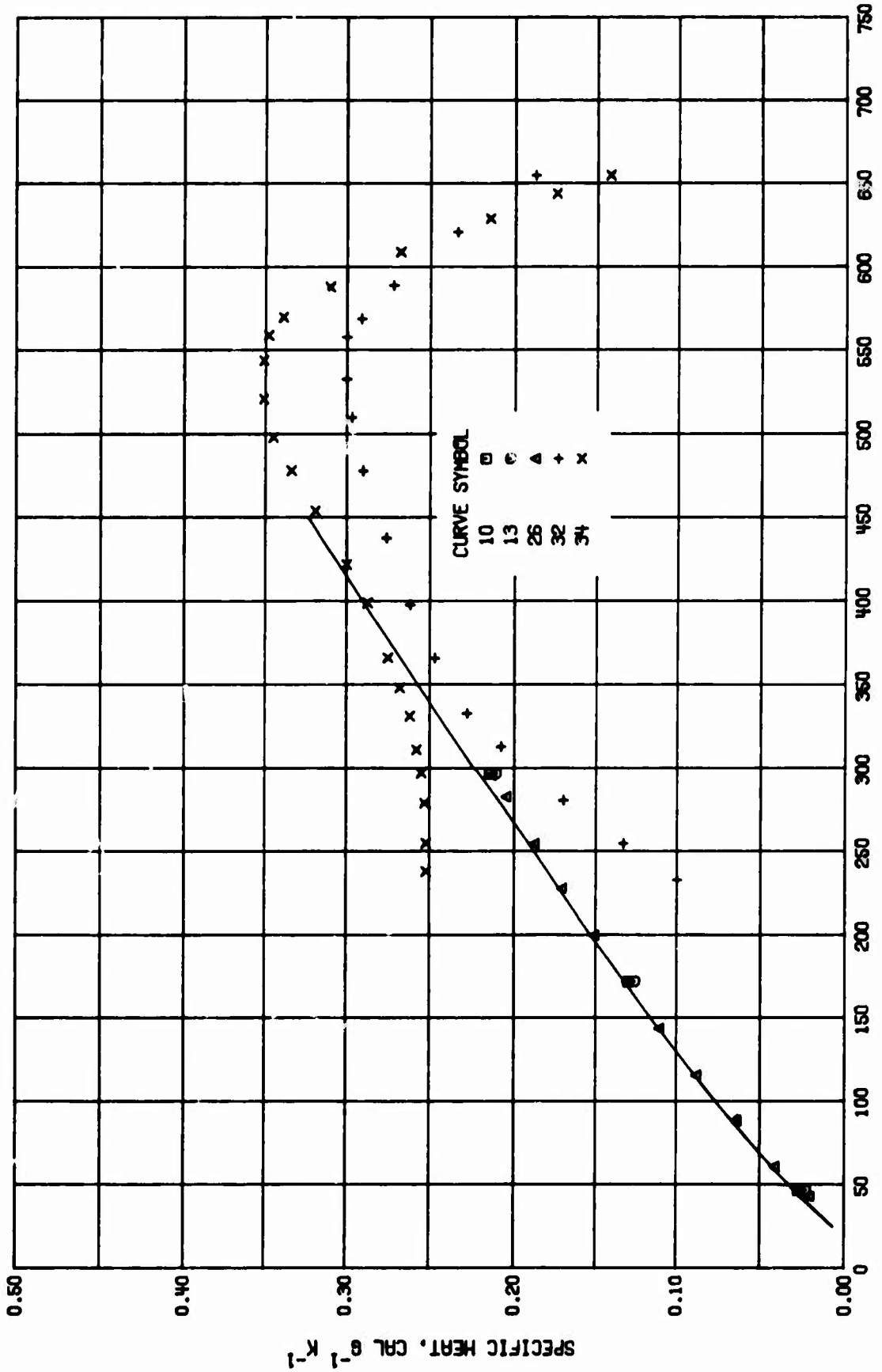

FIGURE 6-2D. SPECIFIC HEAT OF YM-31-A GLASS FIBER DER 332 EPOXY COMPOSITES .

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 1	Composite laminate consisted of Narmco epoxy and E-glass 120 fibers; resin content 46.6 weight % after cure; density 1.748 g cm^{-3}; thickness 0.50 in.
2	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 2	Composite laminate consisted of Narmco epoxy and E-glass 143 fibers; resin content 37.7 weight % after cure; density 1.868 g cm^{-3}; thickness 0.50 in.
3	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 3	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 38.6 weight % after cure; density 1.868 g cm^{-3}; thickness 0.52 in.
4	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 4	Composite laminate consisted of Narmco epoxy and E-glass 182 fibers; resin content 38 weight % after cure; density 1.924 g cm^{-3}; thickness 0.75 in.
5	118	Kim, D.H.	1972	DSC	320-390	Specimen No. 6	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 30 weight % (52.2 volume %) after cure; density 2.004 g cm^{-3}; thickness 0.62 in.
6	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 8	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 57.6 weight % (80.5 volume %) after cure; density 1.603 g cm^{-3}; thickness 0.43 in.
7	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 9	Composite laminate consisted of Narmco high-temperature cure epoxy and E-glass 181 fibers; resin content 26.3 weight % after cure; density 1.900 g cm^{-3}; thickness 0.20 in.
8*	118	Kim, D.H.	1972	DSC	319-390	Specimen No. 10	Composite laminate consisted of Dupont P.I. (polymide) and E-glass fibers; resin content 22.7 weight % after cure; density 1.764 g cm^{-3}.
9*	132	Ogawa, K. and Noguchi, Y.	1968		300-422	LE-61N	Epoxy resin reinforced by nonalkaline glass cloth; 95 x 65 x 1.08 mm; density 1.76 g cm^{-3}; infrared radiation method.
10	121	Campbell, M.D., Haskins, J.F., O'Barr, G.L., and Hertz, J.	1966		47-297	Specimen D	Glass fiber reinforced epoxy; unidirectional, parallel fiber, flat molding; 20 weight percent Dow DER-332 epoxy resin cured with an acid hydride and 80% Owens-Corning high modulus YM-31-A glass fiber roving containing an HTS finish; 0.0441 thickness.
11*	121	Campbell, M.D., et al.	1966		47-297	Specimen V	Glass micro-balloon filled epoxy; 525 weight percent Epon 828 epoxy resin and the remainder glass micro-balloons (filled with N_2).
12*	121	Campbell, M.D., et al.	1966		47-297	Specimen W	Similar to the above specimen except 35 weight percent resin.
13	121	Campbell, M.D., et al.	1966		47-297	Specimen E	Simulated helical filament-wound fiber reinforced epoxy 20 weight percent Dow Chemical DER-332 epoxy resin cured with an acid anhydride and Owens-Corning high modulus YM-31-A glass fiber roving with an HTS finish; alternate layers of roving cross plied at angles 57 and 303 deg from the horizontal axis.
14*	135, 136	Kirillov, V.N., Avrasin, Ya.D., Efimov, V.A., and Dobrokhotova, R.A.	1973		299-562	Stektotekstolits	Glass fabric laminates RJM based on epoxy-phenolic and TS-8/3-T_2 satin weave glass fabric, titanium composition glass using 652 size; compression molding of impregnated glass fabric; density 1.940 g cm^{-3}.
15*	135, 136	Kirillov, V.N., et al.	1973		313-567	Stektotekstolits	Similar to the above specimen except heat treated at 473 K for 24 hr; density 1.930 g cm^{-3}.
16*	135, 136	Kirillov, V.N., et al.	1973		313-573	Stektotekstolits	Similar to the above specimen except heat treated at 473 K for 100 hr.

* Not shown in figure.

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17*	135, 136	Kirillov, V.N., et al.	1973		298-564	Stektotekstolits	Glass fabric laminates RJM based on epoxy-phenolic and multi-ply fabric, bulky weave, type MTTS-1,6, titanium composition glass using 652 size; impregnation under vacuum or under pressure; density 2.020 g cm^{-3}.
18*	135, 136	Kirillov, V.N., et al.	1973		298-568		Similar to the above specimen except heat treated at 523 K for 24 hr; density 2.000 g cm^{-3}.
19*	135, 136	Kirillov, V.N., et al.	1973		298-569		Similar to the above specimen except heat treated at 523 K for 24 hr; density 1.960 g cm^{-3}.
20*	135, 136	Kirillov, V.N., et al.	1973		298-564		Glass fabric laminates RJM based on modified epoxy and TS-8/3 250 glass fabric aluminoborasilicate composition glass using paraffinic size; impregnation under vacuum or under pressure; density 1.83 g cm^{-3}.
21*	135, 136	Kirillov, V.N., et al.	1973		298-567		Similar to the above specimen except heat treated at 453 K for 2 hr; density 1.815 g cm^{-3}.
22*	137	Melonas, J.V., Covington, P.C., and Pears, C.D.	1958	A	311-589	X-131 laminates	Shell X-131 epoxy resin (41.7 weight percent); "181" glass fabric, fabricated by Brunswick-Balke-Collender Co.; curing process same as above; C_p values derived from heat content studies.
23*	137	Melonas, J.V., et al.	1958	A	311-589	X-131 Fluted core sandwich	Shell X-131 epoxy resin (43.4 weight percent); "181" glass fabric; fluted core thickness 0.025 in., flute size 0.30 in. wide, 0.350 in. thick; wall thickness 0.0075 in.; fabricated by Brunswick-Balke-Collender Co.; curing process same as above; C_p values derived from heat content studies.
24	133	Lagedrost, J.F., Fabish, T.J., Eldridge, E.A., Deem, H.W., Krause, H.H., and Vaughan, D.A.	1968	I	273-623		Composite consisted of anhydride cured (nadic methyl anhydride 38.7 weight percent) epoxy novolac (Dow Chemical Co., DEN-438, 45.6 weight percent) and chopped (0.03125 in. hammer-milled) 15 weight percent fiber glass; density 1.33 and 1.29 g cm^{-3} respectively at 293 and 573 K; measurements in argon atmosphere.
25	133	Lagedrost, J.F., et al.	1968	I	273-573		Composite consisted of anhydride cured (nadic methyl anhydride 45.6 weight percent) epoxy novolac (Dow Chemical Co. DEN-438, 53.6 weight percent) and microballoons; density 0.61 and 0.58 g cm^{-3} respectively at 293 and 573 K; measurements in argon atmosphere.
26	134	Campbell, M.D., Hertz, J., O'Barr, G.L., and Haskins, J.F.	1965		43-296	Specimen D	Unidirectional, parallel fiber, flat molding composed of 20 weight percent Dow Chemical DER-332 epoxy resin cured with an acid anhydride and 80 weight percent Owens-Corning high modulus YM-31-A glass fiber roving containing HTS finish; cooling curve method used.
27*	134	Campbell, M.D., et al.	1965		55-295	Specimen E	Similar to the above specimen except cross-plied, unidirectional glass roving, flat molding simulating a helical wound composite; alternate layers of roving cross-plied at angles of 57 and 303 deg from the horizontal axis.
28*	138	Campbell, M.D., O'Barr, G.L., Haskins, J.F., and Hertz, J.	1965		39-297	Specimen U	Composite from CTL, division of Studbaker; glass microballoons (Eccospheres), and Epon 828 epoxy resin (53-55 weight percent) from Shell Chemical Co.; random molding heated to 276 K and held for 1 hr; average of two runs on similar specimens.
29*	138	Campbell, M.D., et al.	1965		25-298	Specimen V	Similar to the above specimen except resin content 25 weight percent.
30*	138	Campbell, M.D., et al.	1965		30-298	Specimen W	Similar to the above specimen except resin content 35 weight percent.

* Not shown in figure.

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
31*	138	Campbell, M.D., O'Barr, G.L., Haskins, J.F., and Hertz, J.	1965		27-299	Specimen X	Composite from above source; S-994 glass roving; epoxy resin (30 weight percent) from U.S. Polymeric; unidirectional molding of HTS finish; glass roving and resin pressed; heated to 366 K and held for 0.5 hr; raised temperature to 427 K and held for 1.5 hr; average of runs on two similar specimens.
32	126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1964		233-655	Specimen C-1	Composite (density 1.91 g cm^{-3}, void content 5-10 volume percent) from Raytheon Corp. containing 40 weight percent (36-50 weight percent after cure) Dow Chemical DER-332 epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin, and DMP 30, 2 parts per 100 gr. of resin; Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish; unidirectional parallel to surface layup; cured at 200 psi; heated at 366 K for 2 hr and 394 K for 2 hr.
33	126	Pears, C.D., et al.	1964		233-661	Specimen C-2	Composite (density 1.85 g cm^{-3}, void content 5 volume percent) from Raytheon Corp. containing 30 weight percent (28.23 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol A; cured with nadic anhydride 80 parts in 100 gr. resin and DMP-30, 30 parts per 100 gr. of resin; Owens-Corning "E" glass fiber roving with HTS finish; 40 layers parallel to surface layup; cured at 200 psi; 2 hr at 366 K, 2 hr at 394 K.
34	126	Pears, C.D., et al.	1964		238-655	Specimen C-3	Composite (density 1.94 g cm^{-3}, void content 5-10 volume percent) from Raytheon Corp. containing 40 weight percent (32.15 weight percent after cure) Dow Chemical DER-322 epoxy bisphenol cured with methyl nadic anhydride, 80 parts per 100 gr. of resin and DMP 30, 2 parts per 100 gr. of resin; Owens-Corning high modulus YM-31-A glass fiber with HTS finish; 40 layers cross-plied parallel and 66 deg from the horizontal axis; cured at 200 psi; 2 hr at 366 K and 2 hr at 394 K.
35	126	Pears, C.D., et al.	1964		241-661	Specimen C-4	Composite (density 2.10 g cm^{-3}, void content 5 volume percent) from Raytheon Corp. containing 20 weight percent (17.7 weight percent after cure) Dow Chemical DER-332 (bisphenol) epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin and DMP-30, 2 parts per 100 gr. resin; Owens-Corning "E" glass fiber roving with HTS finish; layups parallel to surface, 40 layers cross-plied; cured at 200 psi; 2 hr each at 366 and 394 K.
36	126	Pears, C.D., et al.	1964		233-655	Specimen C-5	Composite (density 2.06 g cm^{-3}, void content 5 volume percent) from Raytheon Corp. containing Dow Chemical 20 percent DEN-438 epoxy cured as above; Owens-Corning "E" glass fiber roving 20 end with HTS finish; unidirectional 40 layers parallel to surface; cured as above.
37	126	Pears, C.D., et al.	1964		211-568	Specimen d-1	Composite (density 1.97 g cm^{-3}) from Narmco containing 30 weight percent (27.7 weight percent after cure) Narmco NRC 1174/3 epoxy resin (molded from epoxy powder); Owens-Corning "E" glass flakes, 2 μ thick and 200-2000 μ diameter; layups, plies and reinforcement random; cured at 800 psi; 450 K for 2 hr.
38	126	Pears, C.D., et al.	1964		225-611	Specimen d-2	Similar to the above specimen except resin content 23 weight percent (26.5 weight percent after cure); cured at 1500 psi; 450 K for 2 hr.

* Not shown in figure.

TABLE 6-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
CURVE 1	
319	0.254
330	0.268
340	0.269
350	0.281
360	0.279
370	0.296
380	0.300
390	0.324
CURVE 2	
319	0.228
330	0.241
340	0.241
350	0.243
360	0.251
370	0.266
380	0.272
390	0.289
CURVE 3	
319	0.238
329	0.244
340	0.258
350	0.269
360	0.277
370	0.294
380	0.298
391	0.311
CURVE 4	
319	0.228
330	0.243
340	0.238
351	0.254
360	0.254
371	0.267
381	0.270
391	0.279
CURVE 5	
320	0.236
329	0.242
339	0.245

T	C_p
CURVE 5 (cont.)	
349	0.251
359	0.253
369	0.262
380	0.272
390	0.280
CURVE 6	
319	0.273
329	0.288
339	0.284
350	0.307
359	0.331
369	0.352
380	0.342
390	0.340
CURVE 7	
319	0.221
329	0.230
339	0.230
350	0.240
360	0.235
370	0.238
380	0.235
390	0.242
CURVE 8*	
319	0.210
329	0.216
340	0.210
350	0.213
360	0.213
370	0.216
380	0.216
390	0.221
CURVE 9*	
300	0.248
334	0.278
377	0.289
422	0.330

T	C_p
CURVE 10	
47	0.027
172	0.130
297	0.215
CURVE 11*	
47	0.042
172	0.171
297	0.231
CURVE 12*	
47	0.037
172	0.176
297	0.230
CURVE 13	
47	0.023
172	0.126
297	0.211
CURVE 14*	
299	0.239
323	0.254
373	0.286
396	0.301
423	0.318
444	0.326
466	0.326
474	0.323
494	0.314
510	0.303
523	0.290
539	0.268
551	0.245
562	0.219
CURVE 15*	
313	0.239
323	0.249
373	0.272
413	0.291
423	0.298
446	0.306

T	C_p
CURVE 15 (cont.)*	
460	0.310
473	0.310
487	0.308
504	0.298
523	0.282
544	0.261
567	0.227
CURVE 16*	
313	0.239
323	0.248
423	0.280
473	0.292
496	0.295
523	0.295
535	0.291
552	0.280
573	0.256
CURVE 17*	
298	0.239
323	0.257
373	0.288
400	0.306
414	0.313
423	0.317
448	0.317
473	0.307
494	0.293
522	0.270
538	0.252
549	0.237
559	0.218
564	0.201
CURVE 18*	
298	0.239
323	0.252
373	0.277
423	0.298
447	0.304
473	0.306
497	0.299
523	0.283

T	C_p
CURVE 18 (cont.)*	
537	0.271
554	0.252
568	0.229
CURVE 19*	
298	0.239
323	0.251
373	0.267
423	0.285
451	0.298
473	0.310
487	0.318
504	0.324
523	0.326
537	0.326
553	0.322
569	0.309
CURVE 20*	
298	0.239
309	0.242
323	0.247
340	0.252
356	0.259
373	0.268
386	0.277
396	0.284
CURVE 21*	
298	0.239
323	0.243
346	0.249
359	0.253
373	0.257
385	0.263
400	0.272
414	0.278
423	0.282
438	0.286
452	0.288
473	0.289
489	0.287
507	0.282
522	0.274

T	C_p
CURVE 21 (cont.)*	
541	0.263
555	0.254
567	0.244
CURVE 22*	
311	0.250
422	0.250
589	0.250
CURVE 23*	
311	0.241
422	0.241
589	0.241
CURVE 24	
273	0.238
323	0.281
373	0.325
423	0.365
473	0.410
523	0.452
573	0.496
623	0.537
CURVE 25	
273	0.230
323	0.263
373	0.301
423	0.336
473	0.375
523	0.408
573	0.445
CURVE 26	
43	0.021
61	0.041
89	0.064
116	0.088
144	0.111
172	0.131
200	0.151
228	0.171

* Not shown in figure.

TABLE 6-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE (continued)

T	C_p
CURVE 26 (cont.)	
255	0.188
283	0.205
296	0.214
CURVE 27*	
55	0.028
61	0.036
89	0.060
116	0.084
144	0.106
172	0.127
200	0.148
228	0.167
255	0.185
283	0.203
295	0.211
CURVE 28*	
39	0.047
61	0.081
89	0.117
116	0.153
144	0.186
172	0.217
200	0.246
228	0.275
255	0.302
283	0.328
297	0.339
CURVE 29*	
25	0.010
33	0.024
61	0.061
83	0.097
103	0.111
116	0.126
130	0.137
144	0.150
172	0.172
200	0.190
228	0.205
255	0.217
283	0.228
298	0.233

T	C_p
CURVE 30*	
30	0.019
33	0.024
41	0.029
51	0.039
61	0.053
89	0.088
101	0.101
109	0.111
116	0.121
130	0.136
144	0.152
154	0.159
161	0.166
169	0.173
176	0.176
186	0.185
200	0.194
214	0.201
228	0.208
241	0.212
255	0.217
269	0.222
283	0.226
298	0.230
CURVE 31*	
27	0.006
33	0.014
61	0.044
89	0.070
116	0.095
130	0.106
144	0.119
156	0.127
172	0.138
186	0.146
200	0.155
228	0.171
255	0.182
283	0.192
299	0.196
CURVE 32	
233	0.100
255	0.133
281	0.170

T	C_p
CURVE 32 (cont.)	
313	0.208
333	0.228
366	0.247
398	0.262
438	0.276
478	0.290
510	0.297
533	0.300
558	0.300
569	0.291
589	0.272
621	0.234
655	0.188
CURVE 33	
233	0.181
255	0.188
293	0.201
311	0.209
366	0.238
422	0.267
478	0.291
533	0.314
552	0.323
559	0.323
568	0.317
589	0.288
616	0.242
644	0.191
661	0.160
CURVE 34	
238	0.252
255	0.252
279	0.253
297	0.255
311	0.258
331	0.262
348	0.268
366	0.275
399	0.287
422	0.300
454	0.319
478	0.334
498	0.345
521	0.351

T	C_p
CURVE 34 (cont.)	
544	0.351
559	0.348
570	0.339
588	0.310
609	0.268
629	0.215
644	0.175
655	0.142
CURVE 35	
241	0.143
255	0.153
283	0.175
311	0.194
339	0.212
366	0.228
400	0.243
422	0.252
452	0.262
478	0.268
533	0.275
566	0.276
587	0.275
603	0.273
613	0.267
625	0.250
644	0.212
661	0.159
CURVE 36	
233	0.158
255	0.169
311	0.200
366	0.228
422	0.251
478	0.272
506	0.281
533	0.289
546	0.293
560	0.293
573	0.288
589	0.275
618	0.251
644	0.227
655	0.216

T	C_p
CURVE 37	
211	0.270
255	0.270
366	0.271
422	0.271
467	0.273
478	0.278
488	0.285
507	0.310
533	0.344
568	0.385
CURVE 38	
225	0.262
255	0.262
311	0.262
343	0.264
366	0.267
422	0.278
478	0.290
533	0.301
589	0.312
611	0.317

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of glass fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific resin, curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost and specific properties desired. The softening point of cured epoxy resin is near 450 K. No experimental data for the heat of fusion/softening of such cured epoxy resin were located in the literature.

d. Thermal Linear Expansion

There are 73 sets of experimental data available for the thermal linear expansion of glass fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 6-8. The experimental data are tabulated in Table 6-9 and partially shown in Figures 6-3A through 6-3F. These data sets cover the following types of composites:

E-Glass/Epon 828 epoxy (curves 6-17),
YM-31-A glass/DER 332 epoxy (curves 19-21, 24-29, 36-41, and 52-54),
E-Glass/DER 332 epoxy (curves 30-35 and 42-45),
E-Glass/DEN 438 epoxy (curves 18 and 46-51),
S-Glass/DER 332 epoxy (curves 62-65), and
S-Glass/Epon 828 epoxy (curves 66-69).

It is worth noting that, although there are several data sets available for each of composites, the forms of glass used in the same type of composite are different. The various forms commonly used are fibers, rovings, and filaments. Similarly, the curing agents and curing processes used are also different. Most of the composites do not show reasonably stable behaviour after first heating and cooling cycle, resulting in scattered thermal linear expansion data. Secondly, most of these data sets are not corroborated. These make the data analysis very difficult. It is practically impossible from the available information to separate out the effects of individual factors affecting the thermal expansion of composites, i.e., fiber type and content, epoxy type and content, curing agent, curing process, and heating/cooling cycles. It may be safe to assume that the effect due to curing agent is smaller as compared with that due to curing process.

Since the transverse thermal linear expansion (measured across the thickness) is several times higher than the longitudinal thermal linear expansion (measured along fiber plane), these two are discussed separately in the following sections. The provisional values generated are based mainly on the data for stable thermal cycle.

Expansion Along Fiber Direction (Longitudinal)

(1) YM-31-A Glass Fiber/DER-332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3A are derived primarily from the measurements of Campbell et al. [121] (curve 19), Pears et al. [126] (curves 24 and 25), and Haskins et al. [120] (curve 54). These values are for cured composite with epoxy content of 20-40 weight percent and with parallel glass fiber

reinforcement. This type of composite begins to degrade near 550 K. The uncertainty of the values is about ± 10%. It is worth noting that the thermal linear expansion for this composite is similar to YM-31-A glass fiber/Epon 828 composite (curve 6). Similar composite with cross-plied fibers has slightly higher expansion and shows considerable scatter in the thermal linear expansion data (curves 36 and 37).

(2) E-Glass Fiber/DER-332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3B are derived primarily from the measurements of Pears et al. [126] (curves 30 and 31). These values are for cured composite with epoxy content of about 30 weight percent and with parallel glass fiber reinforcement. This type of composite begins to decompose near 550 K. The uncertainty of the provisional values is about ± 10%. This composite has a lower longitudinal thermal linear expansion than YM-31-A glass fiber/DER 332 epoxy composite and E-glass fiber/Epon 828 epoxy composite. The composite with cross-plied fibers shows considerable scatter in the thermal linear expansion data and the expansion data during heating and cooling cycles are not reproducible.

(3) E-Glass Fiber/DEN 438 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3C are derived primarily from the measurements of Pears et al. [126] (curves 46 and 47). These values are for cured composite with epoxy content of 20 weight percent and with parallel glass fiber reinforcement. The uncertainty of the provisional values is ± 10%. This composite begins to degrade near 600 K and has an intermediate thermal linear expansion between YM-31-A glass fiber/DER 332 epoxy composite and E-glass fiber/DER 332 epoxy composite.

Expansion Along Fiber Thickness (Transverse)

The thermal linear expansion in the fiber thickness direction is generally about 2 to 5 times higher than that in the direction along fiber plane (reinforcement direction). Unlike the expansion in the reinforcement direction, the thermal linear expansion along the fiber thickness is greatly affected by warpage and delamination, especially at temperatures near 475 K. Therefore, the available data in the fiber thickness direction show considerable scatter making the data less useful for the purpose of analysis.

(1) YM-31-A Glass Fiber/DER 332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3D are derived primarily from the measurements of Pears et al. [126] (curves 25 and 26) and of

Haskins et al. [120] (curves 52 and 53). These values are for cured composite with epoxy content of 20-30 weight percent and with parallel glass fiber reinforcement. The uncertainty of these values is about ± 15%. The composite with cross-plied fibers has considerably higher and more irregular expansion (curves 38 and 39).

(2) E-Glass Fiber/DER 332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3E are derived primarily from the measurements of Pears et al. [126] (curves 32 and 33). These values are for cured composite with about 20 weight percent epoxy resin and with parallel glass fiber reinforcement. The uncertainty of these values is ± 15%. The composite with cross-plied fiber shows abnormally high thermal linear expansion above 475 K, possibly due to delamination of the composite.

(3) E-Glass Fiber/DEN 438 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3F are derived primarily from the measurements of Pears et al. [126] (curves 48 and 49). These values are for cured composite with epoxy content of 20 weight percent and with parallel glass fiber reinforcement. The uncertainty of these values is ± 15%. This composite has higher expansion than similar YM-31-A glass fiber/DER 332 composite and E-glass fiber/DER 332 composite.

The values of the instantaneous coefficient of thermal linear expansion, α, for the above composites are obtained by differentiation of empirical equations which are used to fit the provisional thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about ± 20%.

TABLE 6-7 PROVISIONAL THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, $10^{-6}\,K^{-1}$]

a. Expansion Along Fiber Direction

T	YM-31-A/DER-332		E/DER-332		E/DEN-438	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α	$\Delta L/L_0$	α
25	-0.133	3.9				
30	-0.131	4.0				
40	-0.127	4.1				
50	-0.123	4.2				
60	-0.119	4.3				
70	-0.115	4.4				
80	-0.110	4.5				
90	-0.106	4.5				
100	-0.101	4.6				
150	-0.077	5.0				
200	-0.051	5.3				
250	-0.024	5.5				
273.15	-0.011	5.6				
293	0.000	5.7	0.000	4.4	0.000	5.1
300	0.004	5.7	0.003	4.4	0.004	5.1
350	0.033	5.8	0.025	4.5	0.029	5.2
400	0.062	5.8	0.048	4.6	0.056	5.3
450	0.091	5.8	0.071	4.6	0.082	5.4
500	0.120	5.8	0.094	4.7	0.109	5.4
550	0.148	5.8	0.118	4.8	0.137	5.5

b. Expansion Along Fiber Thickness

25	-0.643	22.1				
30	-0.632	22.1				
40	-0.610	22.1				
50	-0.588	22.2				
60	-0.566	22.2				
70	-0.544	22.3				
80	-0.521	22.4				
90	-0.499	22.5				
100	-0.476	22.6				
150	-0.361	23.4				
200	-0.242	24.5				
250	-0.115	26.1				
273.15	-0.054	26.9				
293	0.000	27.7	0.000	12.7	0.000	27.8
300	0.019	28.0	0.009	13.5	0.020	29.1
350	0.164	30.2	0.089	18.7	0.188	38.3
400	0.322	32.8	0.196	23.9	0.403	47.5
450	0.494	35.8	0.328	29.0	0.663	56.7
500	0.682	39.2	0.486	34.2	0.970	66.0
550	0.886	42.9	0.670	39.3	1.324	75.4

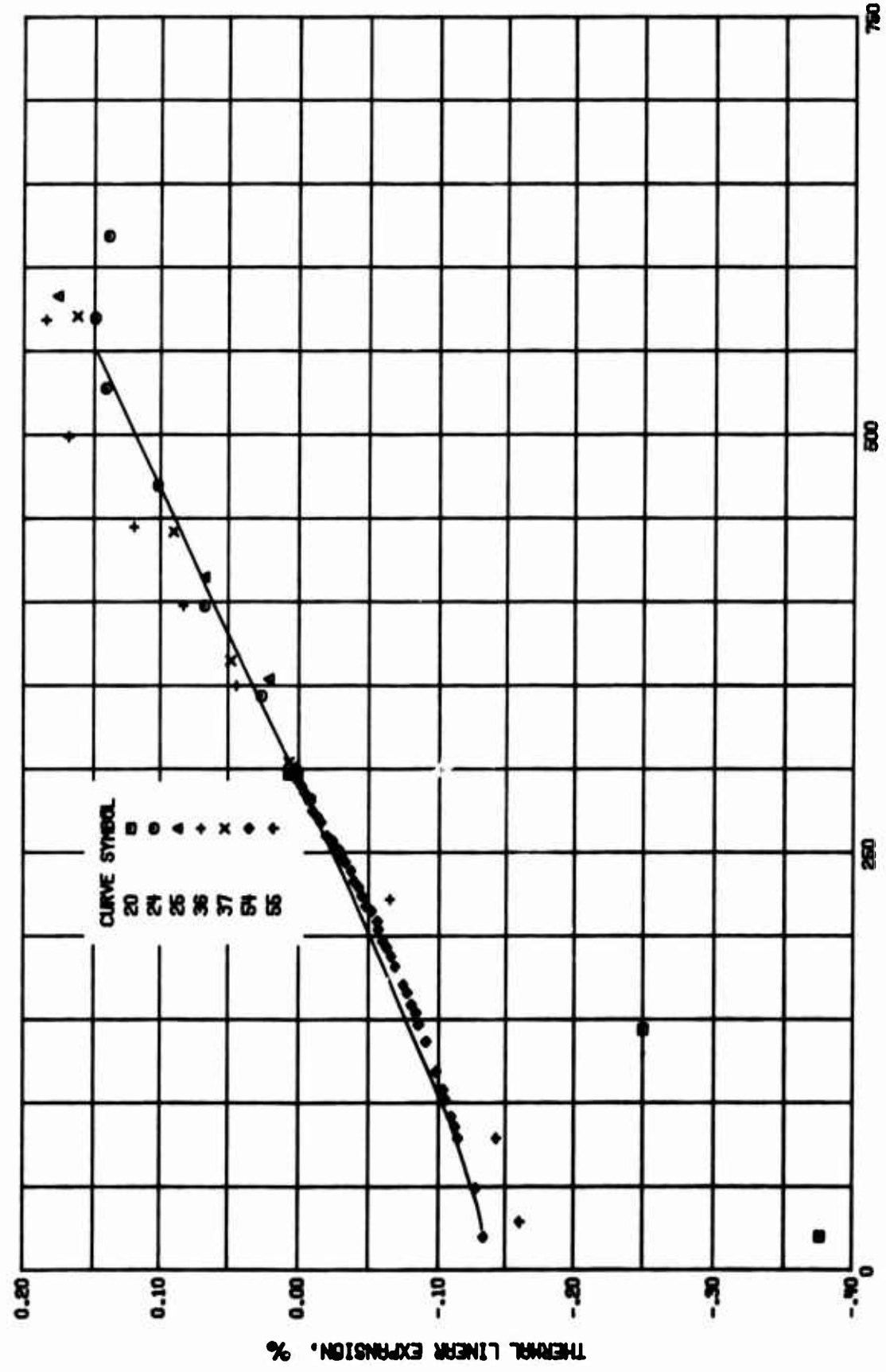

FIGURE 6-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF YH-31-A GLASS FIBER DER 332 EPOXY COMPOSITES.

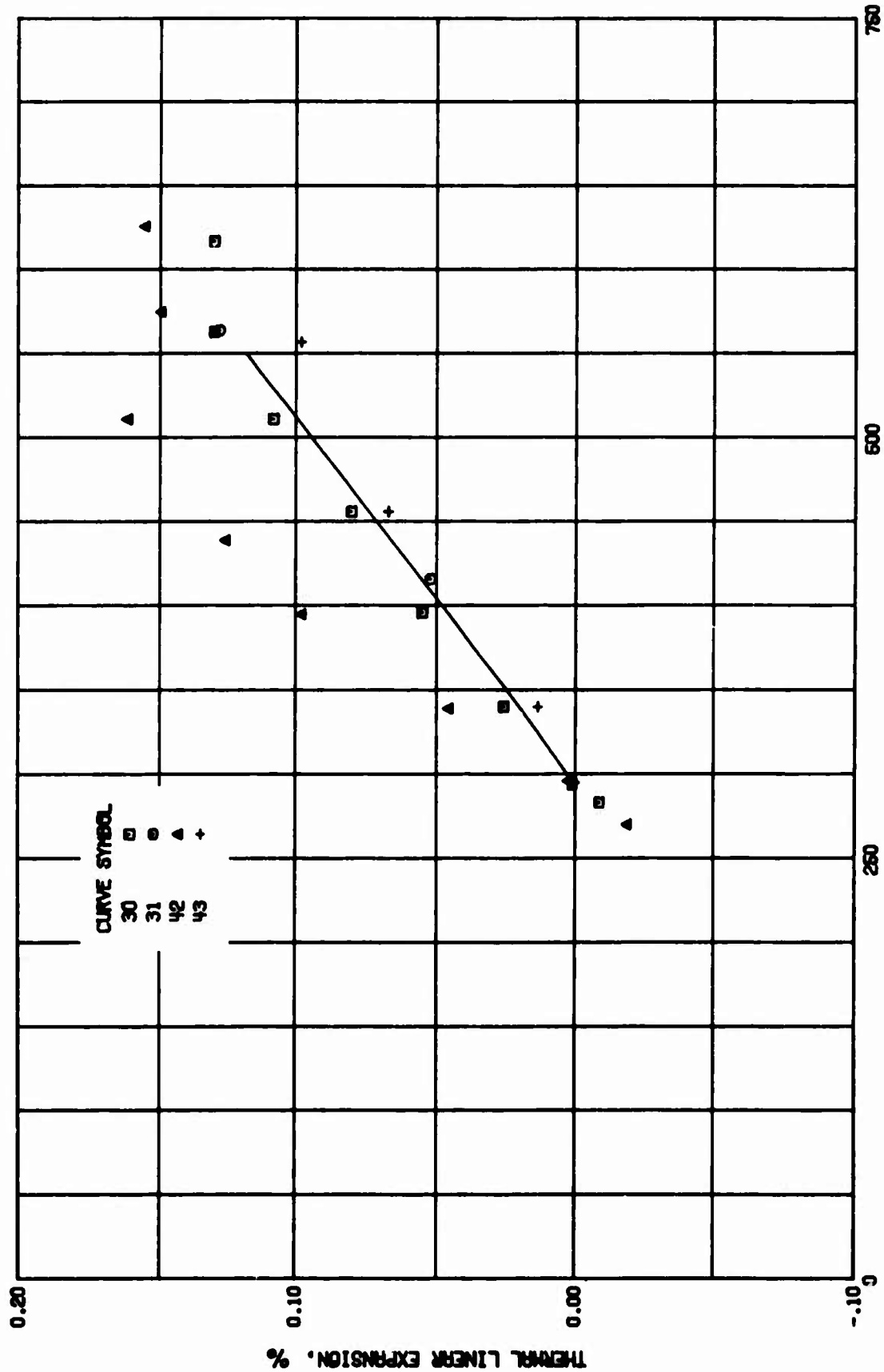

FIGURE 6-38. LONGITUDINAL THERMAL LINEAR EXPANSION OF E-GLASS FIBER DER 332 EPOXY COMPOSITES.

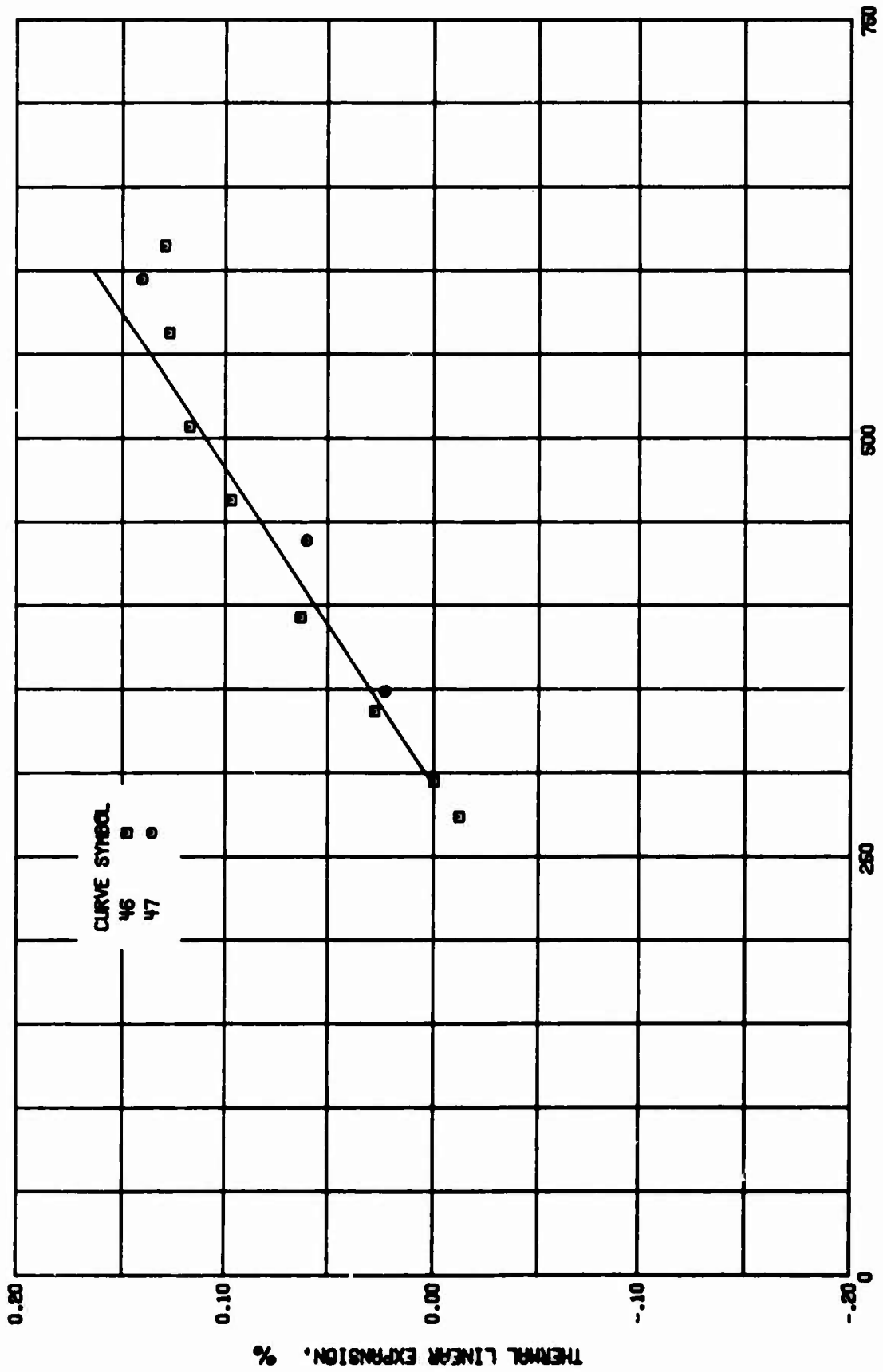

FIGURE 6-3C. LONGITUDINAL THERMAL LINEAR EXPANSION OF E-GLASS FIBER DEN 438 EPOXY COMPOSITES.

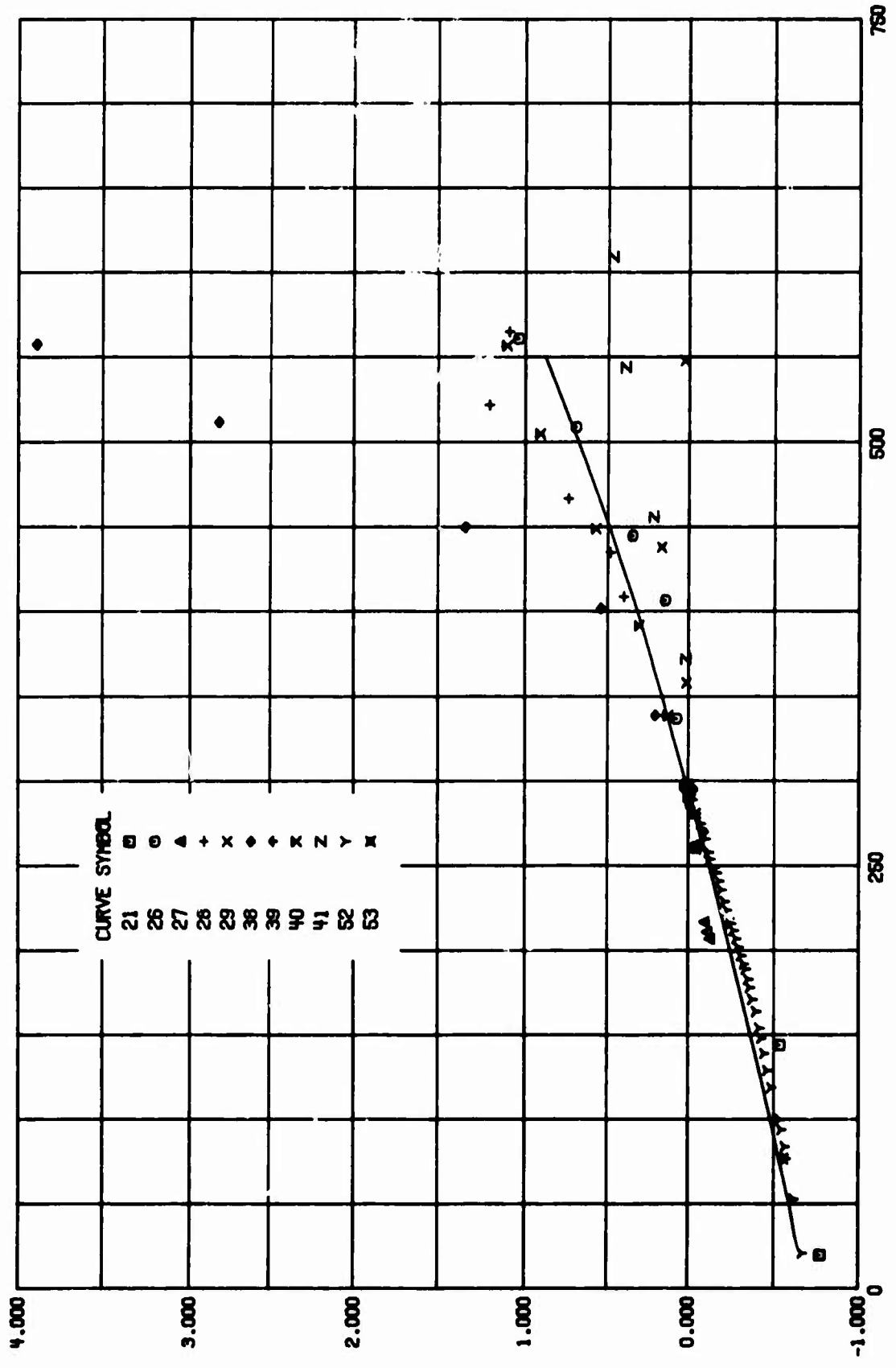

FIGURE 6-30. TRANSVERSE THERMAL LINEAR EXPANSION OF YM-31-A GLASS FIBER DER 332 EPOXY COMPOSITES.

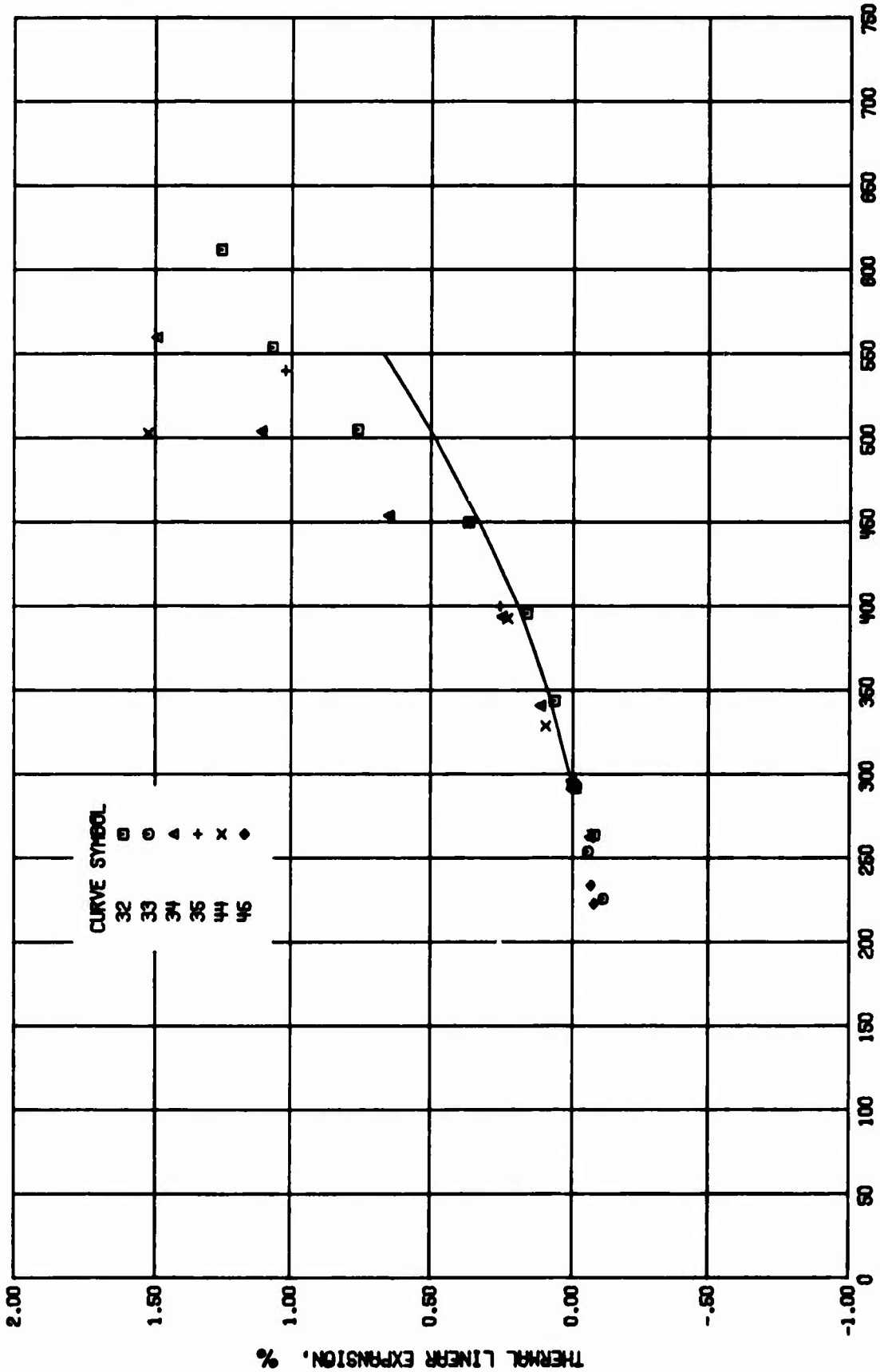

FIGURE 6-3E. TRANSVERSE THERMAL LINEAR EXPANSION OF E-GLASS FIBER DER 332 EPOXY COMPOSITES.

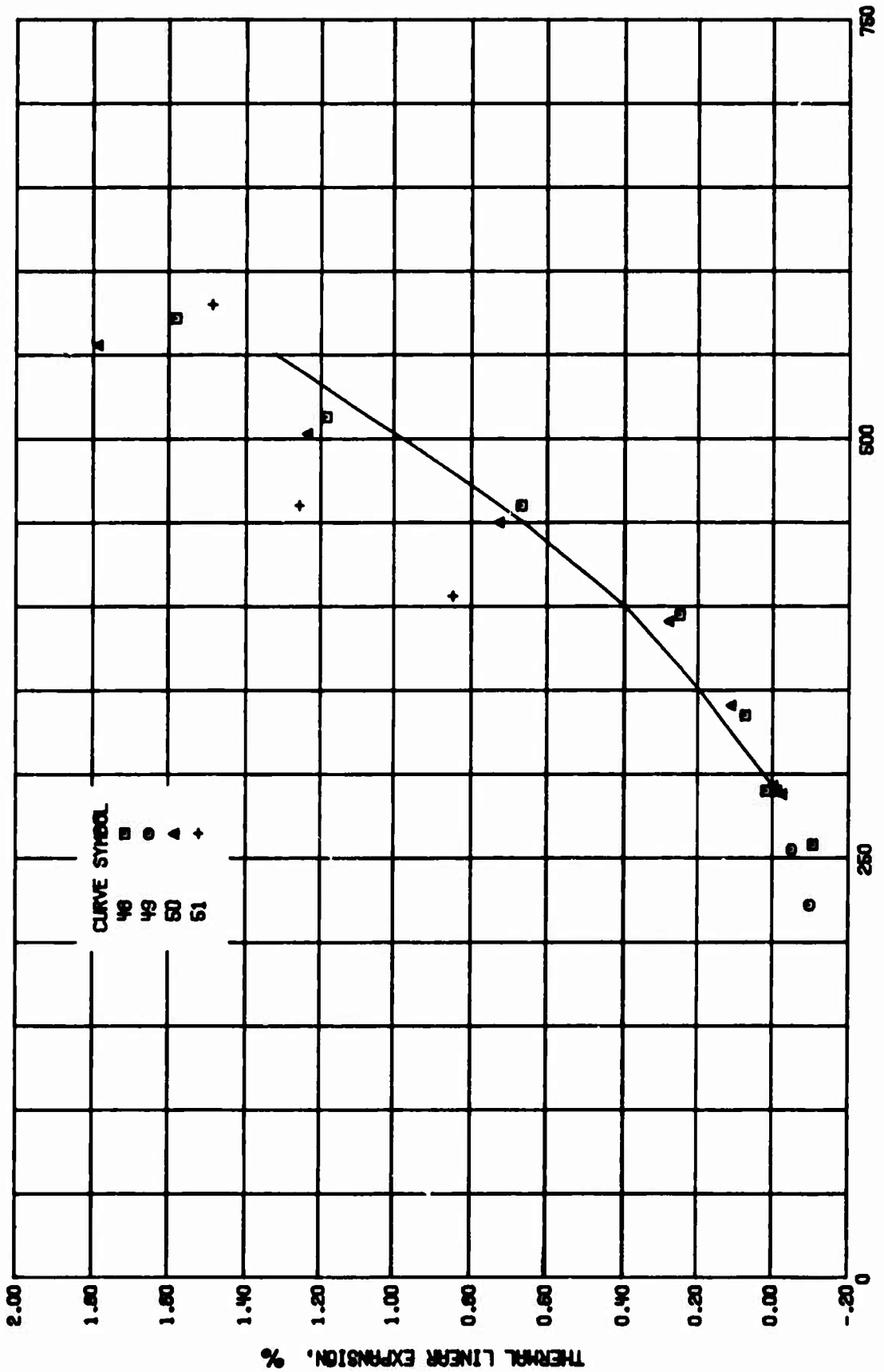

FIGURE 6-3F. TRANSVERSE THERMAL LINEAR EXPANSION OF E-GLASS FIBER DEN 438 EPOXY COMPOSITES.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	139	Gulati, S.T. and Plummer, W.A.	1972	L	153-327	LRG-18R	Longitudinal bar of quasi-isotropic composite fabricated using scotchply (3 M Co.) reinforced plastic type 1002 containing 44 volume percent of E-glass fiber in epoxy resin.
2*	139	Gulati, S.T. and Plummer, W.A.	1972	L	153-308	LRG-41	Similar to the above specimen except transverse bar; zero-point correction is 0.009%.
3*	140, 141	Kritsuk, A.A.	1972	L	78-476	GRP	Glass reinforced plastic cut with diamond disc from sheets prepared by "wet" winding on a metal mandrel and cured under ~10 kg f cm^{-2} pressure; epoxy-amine formulation (ED-6 epoxy resin hardened with triethanolamine titanate) used as binder and nonalkaline NS/6 glass fiber used as filler; epoxy content 19.5 weight percent; measurements along the reinforcement; zero-point correction -0.005%.
4*	140, 141	Kritsuk, A.A.	1972	L	78-370		Similar to the above specimen except measurements along transverse direction; zero-point correction is -0.018%.
5*	140, 141	Kritsuk, A.A.	1972	L	78-420		Similar to the above specimen except measurements for glass reinforced plastic with 1:1 structure; zero-point correction is -0.003%.
6*	142	General Electric Co.	1964	V	122-478		Glass fibers ("E" glass) from Pittsburgh Glass Co. placed in shell Epon 828 solid fibers placed longitudinally; specimen cured 2 hr at 366 K, 4 hr at 394 K, and 6 hr at 422 K; soaked 30 min at 116 K and tested with heating at 0.6 deg/min; expansion measured parallel to fibers; zero-point correction is -0.097%.
7*	142	General Electric Co.	1964	V	133-477		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.197%.
8*	142	General Electric Co.	1964	V	118-478		Similar to the above specimen except expansion measured transverse to solid fibers; zero-point correction is -0.220%.
9*	142	General Electric Co.	1964	V	118-478		The above specimen; second run; zero-point correction is -0.295%.
10*	142	General Electric Co.	1964	V	117-478		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.428%.
11*	142	General Electric Co.	1964	V	117-478		Similar to the above specimen; second cycle; zero-point correction is -0.394%.
12*	142	General Electric Co.	1964	V	118-477		Similar to the above specimen except solid fibers placed in 90 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.175%.
13*	142	General Electric Co.	1964	V	118-453		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.217%.
14*	142	General Electric Co.	1964	V	114-478		Similar to the above specimen except solid fibers placed in 90 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.175%.
15*	142	General Electric Co.	1964	V	114-454		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.245%.
16*	142	General Electric Co.	1964	V	117-478		Similar to the above specimen except solid fibers placed in 60 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.261%.
17*	142	General Electric Co.	1964	V	117-478		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.337%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18*	133	Lagedrost, J. F., Fabish, T. J., Eldridge, E. A., Deem, H. W., Krause, H. H., and Vaughan, D. A.	1968	L	293-593		Composite consisted of anhydride cured (nadic methyl anhydride 38.7 weight percent) epoxy novolac (Dow Chemical Co. DEN-438, 45.6 weight percent) and chopped (1/32 in. hammer-milled) 15 weight percent fiber glass; density 1.33 g cm^{-3} at 293 K and 1.20 g cm^{-3} at 573 K; measurements in argon atmosphere; zero-point correction is 0.02%.
19*	121	Campbell, M. D., Haskins, J. F., O'Barr, G. L., and Hertz, J.	1966	L	20-297	Specimen D	Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish, and 20 weight percent Dow Chemical DER-332 epoxy resin cured with acid anhydride, unidirectional, parallel fibers; flat molding; average density 2.01 g cm^{-3}; zero-point correction is 0.002%.
20	121	Campbell, M. D., et al.	1966	L	20-297	Specimen E	Simulated helical filament wound fiber-reinforced epoxy; 20 weight percent (36.2 weight percent average of two panels) Dow Chemical DER-332 epoxy resin cured with acid anhydride; Owens-Corning YM-31-A glass fiber roving with HTS finish; alternat layers of roving cross plied at angles of 57 and 303 deg from horizontal axis; density 1.94 g cm^{-3}; expansion measured normal to the thickness direction; normal to 57 deg ply; zero-point correction is -0.007%.
21	121	Campbell, M. D., et al.	1966	L	20-297	Specimen E	Similar to the above specimen; expansion measured along the thickness direction; parallel to 57 deg ply; zero-point correction is -0.003%.
22*	138	Campbell, M. D., O'Barr, G. L., Haskins, J. F., and Hertz, J.	1965	L	20-296		Composite system from CTL, division of Studbaker; S-994 glass roving; E-787 epoxy resin (30 weight percent) from U.S. Polymeric; specimen unidirectional molding of HTS finish; glass roving and resin pressed; heated to 366 K and held for 1/2 hr; raised temperature to 427 K and held for 1.5 hr; average of runs on two similar specimens; measurements along thickness direction; zero-point correction is 0.005%.
23*	138	Campbell, M. D., et al.	1965	L	20-296		The above specimen; measurements parallel to fibers; zero-point correction is 0.001%.
24	126	Pears, C. D., Engelke, W. T., and Thornburgh, J. D.	1964	L	282-619	Material C1	Composite (density 1.91 g cm^{-3}, void content 5-10 volume percent) from Raytheon Corp. containing 40 weight percent DER-332 epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin and DMP 30, 2 parts per 100 parts of resin; Owens-Corning high modulus YM31-A glass fiber roving; HTS finish; unidirectional parallel to surface lay up; cured at 200 psi; heated at 366 K for 2 hr and 394 K for 2 hr; heating cycle; measurements parallel to the fiber direction; zero-point correction is 0.003%.
25	126	Pears, C. D., et al.	1964	L	583-296	Material C1	The above specimen; cooling cycle; zero-point correction is 0.224%.
26	126	Pears, C. D., et al.	1964	L	261-561	Material C1	The above specimen; expansion measured in the thickness direction; heating cycle; specimen continued to expand on cooling; zero-point correction is 0.05%.
27	126	Pears, C. D., et al.	1964	L	262-207	Material C1	The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is -0.01%.
28	126	Pears, C. D., et al.	1964	L	260-565	Material C1	The above specimen; expansion measured in the perpendicular to the reinforcement direction; heating cycle; zero-point correction is -0.006%.
29	126	Pears, C. D., et al.	1964	L	548-293	Material C1	The above specimen; expansion measured in the perpendicular to the reinforcement direction; cooling cycle; zero-point correction is 1.748%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
30	126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1964	L	283-617	Material C2	Composite (density 1.85 g cm^{-3}, void content 5 volume percent) from Raytheon Corp. containing 30 weight percent (28.23 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol A cured with nadic anhydride 80 parts per 100 gr. resin and DMP-30, 30 parts per 100 parts of resin; Owens-Corning "E" glass fiber roving; HTS finish; 40 layers parallel to surface lay up; cured at 200 psi, 2 hr at 366 K, 2 hr at 394 K; heating cycle; expansion measured in the direction parallel to reinforcement.
31	126	Pears, C.D., et al.	1964	L	564-296	Material C2	The above specimen; measurements in the direction parallel to reinforcement; cooling cycle; zero-point correction is 0.119%.
32	126	Pears, C.D., et al.	1964	L	264-612	Material C2	The above specimen; expansion measured in the thickness direction; heating cycle; zero-point correction is -0.004%.
33	126	Pears, C.D., et al.	1964	L	254-226	Material C2	The above specimen; expansion measured in the thickness direction; cooling cycle.
34	126	Pears, C.D., et al.	1964	L	263-560	Material C2	The above specimen; expansion measured in the direction perpendicular to the reinforcement; heating cycle; zero-point correction is 0.006%.
35	126	Pears, C.D., et al.	1964	L	540-294	Material C2	The above specimen; expansion measured in the direction perpendicular to the reinforcement; cooling cycle; zero-point correction is 1.423%.
36	126	Pears, C.D., et al.	1964	L	222-569	Specimen C-3	Composite (density 1.94 g cm^{-3}, void content 5-10 volume percent) from Raytheon Corp., containing 40 weight percent (32.15 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol cured with methyl nadic anhydride, 80 parts per 100 gms of resin, and DMP 30, 2 parts per 100 gms of resin; Owens-Corning high modulus YM-31-A glass fiber roving; HTS finish; 40 layers cross plied parallel and 66 deg from the horizontal axis; cured at 200 psi; 2 hr at 366 K, and 2 hr at 394 K; heating cycle; expansion measured in the direction of material.
37	126	Pears, C.D., et al.	1964	L	571-304	Specimen C-3	The above specimen; expansion measured in the direction of material; cooling cycle; zero-point correction is 0.312%.
38	126	Pears, C.D., et al.	1964	L	270-558	Specimen C-3	The above specimen; expansion measured in the thickness direction; heating cycle; zero-point correction is 0.028%.
39	126	Pears, C.D., et al.	1964	L	435-294	Material C-3	The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is -0.321%.
40	126	Pears, C.D., et al.	1964	L	281-557	Material C-3	The above specimen; expansion measured in the direction perpendicular to fiber orientation; heating cycle; zero-point correction is -0.014%.
41	126	Pears, C.D., et al.	1964	L	609-291	Material C-3	The above specimen; expansion measured in the direction perpendicular to fiber orientation; cooling cycle; zero-point correction is 1.557%.
42	126	Pears, C.D., et al.	1964	L	270-626	Material C-4	Composite (density 2.10 g cm^{-3}, void content 5 volume percent) from Raytheon Corp., containing 20 weight percent (17.7 weight percent after cure) Dow Chemical DER-332 (bisphenol) epoxy cured with methyl nadic anhydride 80 parts per 100 gms resin and DMP-30, 2 parts per 100 gms resin; Owens-Corning "E" glass fiber roving, HTS finish; lay ups parallel to surface, 40 layers cross plied; cured at 200 psi; 2 hr at 360 K, 2 hr at 394 K; expansion measured in the direction of fiber; heating cycle; zero-point correction is 0.003%.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
43	126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1964	L	557-295	Material C-4	The above specimen; expansion measured in the direction of fiber; cooling cycle; zero-point correction is 0.064%.
44	126	Pears, C.D., et al.	1964	L	264-503	Material C-4	The above specimen; expansion measured in the thickness direction; heating cycle.
45	126	Pears, C.D., et al.	1964	L	234-223	Material C-4	The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is 0.036%.
46	126	Pears, C.D., et al.	1964	L	274-615	Material C-5	Composite (density 2.06 g cm^{-3}, void content 5 volume percent) from Raytheon Corp., containing 20 weight percent (21.06 weight percent after cure) Dow Chemical DEN-438 epoxy cured as above; Owens-Corning "E" glass fiber roving 20 end, HTS finish, unidirectional 40 layers parallel to surface; cured at 200 psi; 2 hr at 366 K, 2 hr at 394 K; expansion measured parallel to the reinforcement direction; heating cycle.
47	126	Pears, C.D., et al.	1964	L	595-349	Material C-5	The above specimen; expansion measured parallel to the reinforcement direction; cooling cycle; zero-point correction is 0.096%.
48	126	Pears, C.D., et al.	1964	L	258-572	Material C-5	The above specimen; measurement in the thickness direction; heating cycle; zero-point correction is 0.010%.
49	126	Pears, C.D., et al.	1964	L	255-222	Material C-5	The above specimen; measurement in the thickness direction; cooling cycle.
50	126	Pears, C.D., et al.	1964	L	288-615	Material C-5	The above specimen; measurement in the perpendicular to reinforcement; heating cycle.
51	126	Pears, C.D., et al.	1964	L	648-406	Material C-5	The above specimen; measurement in the perpendicular to reinforcement; cooling cycle; zero-point correction is 3.028%.
52	120	Haskins, J.F., Campbell, M.D., Hertz, J., and Percy, J.L.	1964	L	21-298		Owens-Corning high modulus YM-31-A glass fiber roving (80 weight percent) with HTS finish; Dow Chemical DER-332 epoxy resin cured with acid anhydride; unidirectional, parallel fibers, flat molding; specimen 0.117 x 0.117 x 20 in. stacked and loaded by series of 0.5 in. wide pieces in the thickness direction from the panel; zero-point correction is 0.003%.
53	120	Haskins, J.F., et al.	1964	L	77-298		The above specimen; immediately cycled while still in the dilatometer; third cycle; expansion measured in the thickness direction; zero-point correction is 0.005%.
54	120	Haskins, J.F., et al.	1964	L	20-298		The above specimen; expansion measured parallel to reinforcement; first run; using vertical dilatometer in subliquid hydrogen temperature and data corrected; zero-point correction is 0.003%.
55	143	Brechna, H. and Haldemann, W.	1965	L	5-301	S994/HTS	S994/HTS glass roving with 19 weight percent Union Carbide ERL 2256/MPDA epoxy resin; average density 2.1 g cm^{-3}.
56*	129, 130	Toth, L.W., Boller, T.J., Butcher, I.R., Karlotis, A.H., and Yoder, F.D.	1965	L	20-297	BFW	Reinforced plastic using S/HTS glass from U.S. Polymeric Chem. Inc.; 20-end roving filament wound in bidirectional (0-90 deg., 1/1 dispersion) orientation; preimpregnated with 19.10% E-787 epoxy system; expansion measured normal to reinforcement.
57*	129, 130	Toth, L.W., et al.	1965	L	20-297	BFW	The above specimen; second run.
58*	129, 130	Toth, L.W., et al.	1965	L	20-297	BFW	Similar to the above specimen except expansion measured parallel to the reinforcement.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
59*	129, 130	Toth, L.W., et al.	1965	L	20-297	BFW	The above specimen; second run.
60*	129, 130	Toth, L.W., et al.	1965	L	20-297	UFW	Similar to the above specimen except filament wound in unidirectional orientation; resin content 18.03%; expansion measured normal to reinforcement.
61*	129, 130	Toth, L.W., et al.	1965	L	20-297	UFW	The above specimen except expansion measured parallel to reinforcement.
62*	130	Toth, L.W., Boller, T.J., Butcher, I.R., Kariotis, A.H., and Yoder, F.D.	1966	L	77-297	S Glass-DER 332/BF_3	Reinforced plastic consisted of 17.4% DER-332 epoxy resin; BF_3 curing agent and 20-end S/HTS glass roving; expansion measured parallel to reinforcement.
63*	130	Toth, L.W., et al.	1966	L	77-297	S Glass-DER 332/BF_3	The above specimen; expansion measured normal to reinforcement.
64*	130	Toth, L.W., et al.	1966	L	77-297	S Glass-DER 332/DEH 50	Reinforced plastic, consisted of 19% DER-332 epoxy resin, DEH 50 curing agent and 20-end S/HTS glass roving; expansion measured parallel to reinforcement.
65*	130	Toth, L.W., et al.	1966	L	77-297	S Glass-DER 332/DEH 50	The above specimen; expansion measured normal to reinforcement.
66*	144	Soffer, L.M. and Molho, R.	1968	L	22-294	Resin 2 Laminate	Resin 2 laminates were prepared from Epon 828/DSA/1040/BDMA resin system by in-process winding (S-901 glass filament) on a 6 x 8 in. flat mandrel, after cure the panels were cut and sanded into rectangular beam specimen, three specimens prepared for testing in the longitudinal (parallel to the filament orientation) direction; resin content 17.1 weight percent.
67*	144	Soffer, L.M. and Molho, R.	1968	L	17-294	Resin 2 Laminate	Similar to the above specimen except three specimens were prepared for testing in the transverse (normal to the filament orientation) direction; resin content 14.4 weight percent.
68*	144	Soffer, L.M. and Molho, R.	1968	L	17-294	Resin 4A Laminate	Resin 4A laminates were prepared from Epon 828/Epon 871/L-100/MOCA resin system by applying on the mandrel alternate layers of roving (S-901 glass filament) and coating of resin applied by brush; a heat gun trained on the mandrel maintained a temperature of 338 K; after cure the panels were cut and sanded into rectangular beam specimens, three specimens prepared for testing in the longitudinal (parallel to the filament orientation) direction; resin content 37.7 weight percent.
69*	144	Soffer, L.M. and Molho, R.	1968	L	17-294	Resin 4A Laminate	Similar to the above specimen except three specimens were prepared for testing in the transverse (normal to the fiber orientation) direction; resin content 30.4 weight percent.
70*	145	Kalnin, I.L.	1974	L	293-411	S-glass	UD (unidirectional) composite made from prepegged S-glass (Ferro, S-1014) yarn bundles by the "leaky" pressure molding technique; fiber content 69 volume percent; void content 2.5% ignored in the calculation; specimen length 50 mm; cycled 2-3 times from room temperature to 423 K to relieve non-equilibrium thermal stresses; measurements in transverse direction; heating cycle; zero-point correction is 0.006%.
71*	145	Kalnin, I.L.	1974	L	411-293	S-glass	The above specimen; cooling cycle; zero-point correction is 0.006%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
72*	145	Kalnin, I. L.	1974	L	293-399	S-glass	The above specimen; measurements in the axial direction; heating cycle; zero-point correction is 0.001%.
73*	145	Kalnin, I. L.	1974	L	399-293	S-glass	The above specimen; cooling cycle; zero-point correction is 0.001%.

* Not shown in figure.

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1*	
153	-0.202
162	-0.189
172	-0.170
183	-0.159
193	-0.147
202	-0.131
212	-0.117
222	-0.103
232	-0.089
242	-0.075
253	-0.058
263	-0.041
287	-0.011
293	0.000
298	0.002
308	0.007
318	0.010
327	0.015
CURVE 2*	
153	-0.204
162	-0.192
173	-0.178
183	-0.162
193	-0.144
202	-0.133
213	-0.118
222	-0.106
232	-0.090
242	-0.073
252	-0.056
262	-0.043
273	-0.020
287	-0.003
293	0.000
308	0.021
CURVE 3*	
78	-0.112
100	-0.105
125	-0.092
150	-0.083
175	-0.073
200	-0.057
225	-0.043
250	-0.027
275	-0.011
293	0.000
300	0.002
325	0.010
350	0.020
375	0.029
400	0.038
425	0.049
450	0.058
476	0.067
CURVE 4*	
78	-0.379
100	-0.359
125	-0.330
150	-0.296
175	-0.256
200	-0.215
225	-0.167
250	-0.113
275	-0.048
293	0.000
300	0.012
320	0.067
325	0.073
330	0.076
350	0.078
370	0.079
CURVE 5*	
78	-0.183
100	-0.169
125	-0.150
150	-0.132
175	-0.112
200	-0.091
225	-0.067
250	-0.044
275	-0.017
293	0.000
300	0.012
325	0.027
350	0.041
375	0.050
400	0.060
420	0.067
CURVE 6*	
122	-0.097
158	-0.076
194	-0.056
225	-0.042
253	-0.025
280	-0.006
305	0.005
328	0.023
351	0.044
373	0.053
394	0.063
413	0.073
435	0.082
454	0.093
478	0.103
CURVE 7*	
133	-0.197
158	-0.186
194	-0.160
225	-0.126
258	-0.085
280	-0.016
305	0.015
328	0.063
351	0.103
373	0.153
394	0.173
413	0.194
435	0.204
453	0.213
477	0.235
CURVE 8*	
118	-0.220
159	-0.176
195	-0.185
226	-0.127
254	-0.080
281	-0.041
308	0.048
329	0.093
351	0.168
373	0.202
394	0.166
413	0.060
435	0.121
455	0.324
478	0.495
CURVE 9*	
118	-0.295
159	-0.277
195	-0.215
226	-0.161
254	-0.089
280	-0.022
308	0.025
329	0.093
351	0.153
373	0.218
394	0.307
411	0.424
435	0.638
455	0.833
478	1.062
CURVE 10*	
117	-0.428
158	-0.396
195	-0.344
227	-0.271
254	-0.209
280	-0.049
305	0.045
329	0.174
350	0.283
373	0.356
394	0.294
412	0.294
435	0.436
455	0.637
478	0.834
CURVE 11*	
117	-0.394
158	-0.377
195	-0.356
227	-0.274
254	-0.128
280	-0.047
305	0.042
329	0.150
351	0.251
373	0.348
394	0.484
412	0.610
435	0.795
454	0.934
478	1.092
CURVE 12*	
118	-0.194
158	-0.163
194	-0.135
224	-0.094
252	-0.054
280	-0.016
305	0.014
328	0.045
349	0.076
373	0.094
394	0.124
414	0.144
434	0.154
453	0.165
477	0.176
CURVE 13*	
118	-0.217
158	-0.167
193	-0.116
224	-0.097
252	-0.077
280	-0.027
305	0.024
328	0.084
349	0.144
373	0.202
392	0.225
413	0.253
433	0.275
453	0.286
CURVE 14*	
114	-0.175
158	-0.154
194	-0.114
224	-0.095
253	-0.055
280	-0.015
306	0.014
329	0.045
352	0.074
373	0.093
394	0.113
413	0.142
435	0.163
454	0.174
478	0.182
CURVE 15*	
114	-0.245
158	-0.224
194	-0.163
224	-0.124
252	-0.085
280	-0.026
305	0.025
330	0.085
353	0.145
373	0.203
393	0.226
412	0.236
434	0.244
454	0.253

* Not shown in figure.

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 16*	
117	-0.261
158	-0.234
195	-0.170
224	-0.121
251	-0.063
280	-0.022
304	0.018
330	0.066
351	0.119
373	0.159
395	0.128
414	0.105
435	0.177
454	0.307
478	0.423
CURVE 17*	
117	-0.337
158	-0.292
195	-0.221
224	-0.197
251	-0.113
280	-0.038
304	0.032
330	0.127
352	0.213
374	0.293
393	0.372
412	0.480
434	0.592
452	0.691
478	0.791
CURVE 18*	
293	0.00
299	0.02
323	0.18
349	0.34
373	0.49
395	0.64
420	0.83
443	1.02
463	1.24
473	1.38
473	1.53
479	1.71

T	$\Delta L/L_0$
CURVE 18 (cont.)*	
487	1.85
499	2.01
510	2.15
518	2.22
530	2.43
544	2.72
553	2.91
565	3.07
573	3.19
593	3.36
CURVE 19*	
20	-0.132
144	-0.087
297	0.005
CURVE 20	
20	-0.376
144	-0.250
297	0.007
CURVE 21	
20	-0.777
144	-0.537
297	0.003
CURVE 22*	
20	-0.339
52	-0.315
76	-0.296
86	-0.287
96	-0.280
113	-0.262
124	-0.249
131	-0.243
148	-0.222
159	-0.218
171	-0.194
181	-0.182
188	-0.171
194	-0.163
200	-0.153
205	-0.144
212	-0.131

T	$\Delta L/L_0$
CURVE 22 (cont.)*	
219	-0.123
222	-0.116
229	-0.107
235	-0.096
245	-0.080
255	-0.068
260	-0.056
267	-0.044
279	-0.026
285	-0.014
289	-0.005
292	-0.002
296	0.005
CURVE 23*	
20	-0.068
46	-0.064
77	-0.058
77	-0.057
85	-0.055
94	-0.053
102	-0.052
118	-0.049
123	-0.048
143	-0.043
152	-0.041
165	-0.037
171	-0.035
179	-0.034
187	-0.031
200	-0.029
207	-0.029
219	-0.025
228	-0.023
234	-0.021
240	-0.019
251	-0.014
260	-0.011
265	-0.009
269	-0.007
275	-0.006
281	-0.004
293	0.000
298	0.001

T	$\Delta L/L_0$
CURVE 24	
282	-0.008
297	0.001
297	0.003
344	0.026
398	0.067
470	0.102
528	0.141
570	0.149
619	0.139
CURVE 25	
583	0.176
415	0.067
354	0.021
296	0.001
CURVE 26	
261	-0.040
295	0.001
297	0.022
337	0.071
407	0.141
445	0.350
509	0.700
561	1.039
CURVE 27	
262	-0.030
217	-0.092
211	-0.107
207	-0.124
CURVE 28	
260	-0.068
295	0.013
339	0.152
409	0.401
467	0.742
522	1.203
565	1.092
CURVE 29	
548	0.026

T	$\Delta L/L_0$
CURVE 29 (cont.)	
438	0.163
358	0.012
293	0.000
CURVE 30	
283	-0.009
294	0.001
340	0.026
396	0.055
456	0.080
511	0.108
563	0.130
617	0.130
CURVE 31	
564	0.128
416	0.052
296	0.001
CURVE 32	
264	-0.080
292	-0.011
293	0.000
344	0.066
396	0.166
450	0.368
505	0.762
554	1.073
612	1.265
CURVE 33	
254	-0.056
226	-0.113
CURVE 34	
263	-0.061
296	0.006
341	0.118
394	0.251
454	0.653
504	1.114
560	1.495

T	$\Delta L/L_0$
CURVE 35	
540	1.024
400	0.258
294	0.000
CURVE 36	
222	-0.065
292	0.000
350	0.044
398	0.083
445	0.120
499	0.168
569	0.184
CURVE 37	
571	0.162
442	0.090
365	0.048
304	0.007
CURVE 38	
270	-0.089
295	-0.029
295	0.017
339	0.201
402	0.545
450	1.341
512	2.822
558	3.894
CURVE 39	
435	0.486
294	0.000
CURVE 40	
281	-0.044
287	-0.014
339	0.118
392	0.305
449	0.574
505	0.911
557	1.102

* Not shown in figure.

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 41	
609	0.473
544	0.394
456	0.216
372	0.018
291	0.000
CURVE 42	
270	-0.019
296	0.003
339	0.046
395	0.098
439	0.126
511	0.162
575	0.150
626	0.156
CURVE 43	
557	0.098
456	0.067
340	0.014
295	0.000
CURVE 44	
264	-0.070
294	-0.006
294	0.006
329	0.098
393	0.231
503	1.524
CURVE 45	
234	-0.067
223	-0.079
CURVE 46	
274	-0.012
295	0.000
337	0.028
393	0.063
463	0.097
507	0.118
563	0.128
615	0.130

T	$\Delta L/L_0$
CURVE 47	
595	0.141
439	0.060
349	0.023
CURVE 48	
258	-0.106
290	-0.010
290	0.016
335	0.071
395	0.251
460	0.667
513	1.185
572	1.582
CURVE 49	
255	-0.051
222	-0.098
CURVE 50	
288	-0.024
293	0.000
341	0.110
391	0.282
450	0.727
503	1.239
556	1.789
615	1.849
CURVE 51	
648	1.786
580	1.488
460	1.260
406	0.849
CURVE 52	
21	-0.675
53	-0.625
77	-0.577
84	-0.568
94	-0.548
100	-0.537
119	-0.487
129	-0.463

T	$\Delta L/L_0$
CURVE 52 (cont.)	
139	-0.446
148	-0.428
154	-0.415
164	-0.396
171	-0.376
178	-0.362
183	-0.351
189	-0.338
192	-0.327
197	-0.311
202	-0.294
207	-0.283
212	-0.267
216	-0.253
219	-0.244
224	-0.229
229	-0.214
236	-0.196
241	-0.183
246	-0.167
249	-0.151
254	-0.132
258	-0.122
266	-0.102
275	-0.076
281	-0.049
289	-0.028
292	-0.016
298	0.003
CURVE 53	
77	-0.560
298	0.005
CURVE 54	
20	-0.133
49	-0.127
79	-0.114
86	-0.112
92	-0.109
102	-0.105
108	-0.103
119	-0.098
137	-0.091
147	-0.086
154	-0.084

T	$\Delta L/L_0$
CURVE 54 (cont.)	
159	-0.081
166	-0.078
171	-0.075
182	-0.069
188	-0.066
193	-0.063
197	-0.060
204	-0.057
209	-0.056
215	-0.052
218	-0.048
224	-0.045
229	-0.043
233	-0.039
239	-0.037
244	-0.033
248	-0.030
252	-0.028
257	-0.024
260	-0.020
268	-0.016
271	-0.014
275	-0.010
282	-0.007
286	-0.004
290	-0.002
298	0.001
CURVE 55	
5	-0.166
29	-0.161
79	-0.143
301	0.002
CURVE 56*	
20	-0.160
77	-0.146
197	-0.078
297	0.003
CURVE 57*	
20	-0.135
77	-0.120
197	-0.063
297	0.003

T	$\Delta L/L_0$
CURVE 58*	
20	-0.153
77	-0.141
197	-0.075
297	0.003
CURVE 59*	
20	-0.163
77	-0.144
197	-0.075
297	0.003
CURVE 60*	
20	-0.356
77	-0.319
197	-0.163
297	0.007
CURVE 61*	
20	-0.059
77	-0.054
197	-0.029
297	0.001
CURVE 62*	
77	-0.112
120	-0.097
200	-0.057
297	0.002
CURVE 63*	
77	-0.121
120	-0.100
200	-0.056
297	0.002
CURVE 64*	
77	-0.057
120	-0.052
200	-0.032
297	0.001

T	$\Delta L/L_0$
CURVE 65*	
77	-0.111
120	-0.094
200	-0.056
297	0.002
CURVE 66*	
17	-0.047
33	-0.048
61	-0.047
89	-0.045
116	-0.041
144	-0.036
172	-0.031
200	-0.025
227	-0.018
255	-0.010
283	-0.004
294	0.000
CURVE 67*	
17	-0.409
33	-0.400
47	-0.389
61	-0.377
74	-0.365
89	-0.352
102	-0.334
116	-0.317
130	-0.299
144	-0.277
158	-0.254
172	-0.232
186	-0.207
200	-0.182
213	-0.154
227	-0.127
241	-0.100
255	-0.077
269	-0.053
283	-0.023
294	0.000
CURVE 68*	
17	-0.102
33	-0.101

* Not shown in figure.

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 68 (cont.)*	
61	-0.096
89	-0.089
116	-0.078
144	-0.070
172	-0.058
200	-0.045
227	-0.034
255	-0.019
283	-0.005
294	0.000
CURVE 69*	
17	-0.787
33	-0.778
47	-0.769
61	-0.755
74	-0.742
89	-0.728
102	-0.707
116	-0.684
130	-0.658
144	-0.623
158	-0.585
172	-0.547
186	-0.503
200	-0.454
213	-0.400
227	-0.344
241	-0.278
255	-0.213
269	-0.130
283	-0.047
294	0.000
CURVE 70*	
293	0.000
298	0.006
310	0.024
323	0.044
335	0.064
348	0.088
360	0.110
373	0.140
385	0.170
398	0.204
411	0.232

T	$\Delta L/L_0$
CURVE 71*	
411	0.232
398	0.212
385	0.186
373	0.166
360	0.142
348	0.118
335	0.092
323	0.066
310	0.038
298	0.006
293	0.000
CURVE 72*	
293	0.000
298	0.001
310	0.002
323	0.004
335	0.005
348	0.009
360	0.012
373	0.015
385	0.019
398	0.023
399	0.025
CURVE 73*	
399	0.025
398	0.025
385	0.023
373	0.020
360	0.016
348	0.012
335	0.010
323	0.006
310	0.003
298	0.001
293	0.000

* Not shown in figure.

e. Thermal Diffusivity

There is only one set of data available for the thermal diffusivity of glass fiber epoxy composite. This data set is tabulated in Table 6-11 and the information on specimen specification and measurement condition is given in Table 6-10.

The only available data set covers a narrow temperature range and the information on specimen characterization is too scarce. Therefore, no recommended values are given. The calculation of the thermal diffusivity from the tabulated values of thermal conductivity, specific heat, and density has not been carried out because the thermal diffusivity of a composite is not a well-defined quantity and because the values of the other properties are not for the very same material.

TABLE 6-10. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF GLASS FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	132	Ogawa, K. and Noguchi, Y.	1968		300–422	LE-61N	Epoxy resin reinforced by nonalkaline glass cloth; 95 x 65 x 0.99 mm; density 1.76 g cm^{-3}; measured by infrared radiation method.

TABLE 6-11. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Diffusivity, α, $cm^2\ s^{-1}$]

T	α
CURVE 1*	
300	0.001775
334	0.001673
377	0.001502
422	0.001338

* No figure given.

3.7. Graphite Fiber Epoxy Composite

The graphite fibers used in the composites are made by the carbonization of organic filaments. The filaments most often used are made from polyacrylonitrile (PAN), although rayon and acrylic fibers have been used to a limited extent. The mechanical properties of graphite fiber depend on the temperature at which the carbonization process takes place. Carbonization at a temperature in the range 2800-3300 K results in fibers with high elastic modulus but relatively low tensile strength and at a temperature in the range 1800-2300 K yields fibers of the greatest tensile strength but only moderate modulus of elasticity. The density of the fibers varies from 1.74 to 1.94 g cm^{-3} depending on the carbonization temperatures used. The filaments are normally produced in untwisted, loose bundles or tows, consisting of ten thousand fibers.

Modified epoxy resins developed specifically for use in composites with graphite fibers are available commercially. These are thermosetting resins used for low pressure laminating and normally cannot be used in continuous service above about 450 K, although intermittent service at a higher temperature up to 490 K is possible. Many of the various epoxy resins used as matrix constituents of composites are proprietory formulations, the exact chemical compositions of which are not available.

For aerospace design, graphite fiber epoxy composites are generally supplied by the manufacturer as prepregs. These are tapes or broadgoods consisting of graphite fibers impregnated with epoxy resin matrix and have only been partially cured and consequently have a limited shelf life and require special storage facilities. The prepregs are used in the fabrication of laminates whose layer orientations are tailored to match individual design requirements. Consequently, large numbers of individually different cross-plied laminates are likely to be encountered, each of which has distinctive properties and characteristics, and hence must be distinctly identified whenever it is to be associated with specific quantitative data.

a. Thermal Conductivity

There are twenty-two sets of data available for the thermal conductivity of graphite fiber epoxy composites. The experimental data are tabulated in Table 7-3 and shown partially in Figure 7-1. The information on specimen characterization and measurement condition is given in Table 7-2. Most of the data are for composites with epoxy content of around 50 volume percent. The variation in the reported thermal conductivity values is quite substantial. Furthermore, the data by Gille [116] (curves 1 and 2) and by Hertz et al. [117] (curve 19-22) show different temperature dependences. The provisional

values tabulated in Table 7-1 and shown in Figure 7-1 are for a composite with 50 volume percent epoxy content. These values are based on the data of Knibbs et al. [146] (curves 7-18) and of Hertz et al. [117] (curves 19-22). Their uncertainty is estimated to be ±25%.

TABLE 7-1. PROVISIONAL THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k	
	50 volume percent epoxy	
	a	b
50	0.039	0.0032
100	0.057	0.0046
150	0.073	0.0058
200	0.087	0.0068
250	0.099	0.0078
273	0.105	0.0082
300	0.111	0.0087
350	0.122	0.0096
400	0.130	0.0105

a Heat flow parallel to fiber direction.
b Heat flow perpendicular to fiber direction.

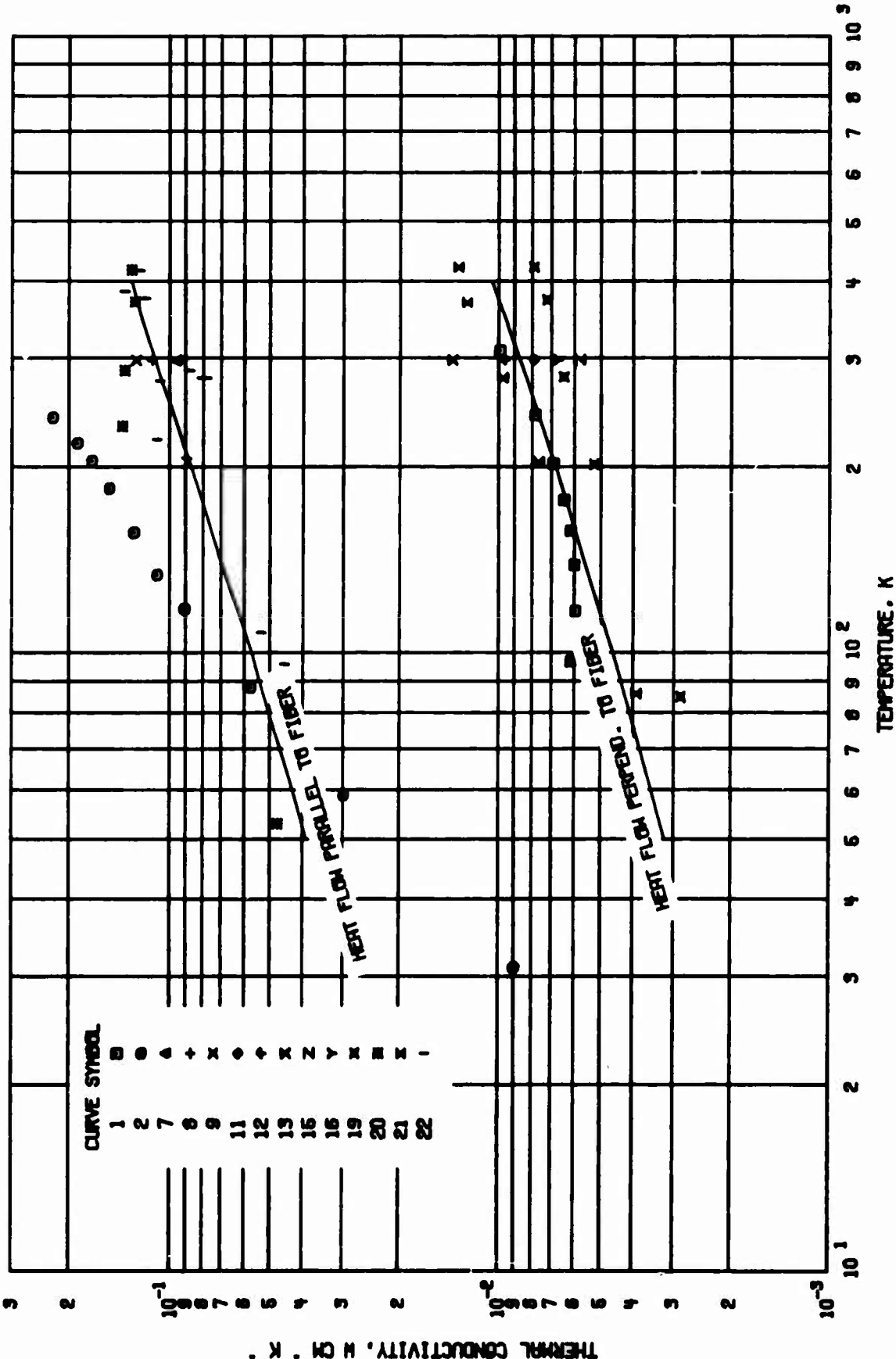

FIGURE 7-1. THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITES.

TABLE 7-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	116	Gille, J.P.	1969	L	97-309	5	60" Thornel 50" graphite fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.005 in. I.D., 1.137 in. O.D., and 0.635 in. in effective length; heat flow perpendicular to fibers; data taken from smooth curve.
2	116	Gille, J.P.	1969	L	31-241	6	60" Thornel 50" graphite fibers bonded with Polaris epoxy resin; cylindrical shell specimen 0.998 in. I.D., 1.114 in. O.D., and 1.[illegible]0 in. in effective length; heat flow parallel to fibers; data taken from smooth curve.
3*	146	Knibbs, R.H., Baker, D.J., and Rhodes, G.	1971	C	298		40 v/o surface treated Type I high modulus carbon fibers bonded with epoxy resin; 10 x 0.9 x 0.9 cm; molded; density 1.38 g cm^{-3}; electrical resistivity 2.19 mΩ cm; heat flow along fiber direction; Armco iron used as comparative material; reported error ± 5%.
4*	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.48 g cm^{-3}, and electrical resistivity 1.90 mΩ cm.
5*	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.57 g cm^{-3}, and electrical resistivity 1.51 mΩ cm.
6*	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.47 g cm^{-3}, and electrical resistivity 1.80 mΩ cm.
7	146	Knibbs, R.H., et al.	1971	C	298		40 v/o surface treated Type II high strength carbon fibers bonded by epoxy resin; 10 x 0.9 x 0.9 cm; molded; density 1.30 g cm^{-3}; electrical resistivity 3.95 mΩ cm; heat flow along fiber direction; Armco iron used as comparative material; reported error ± 5%.
8	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.40 g cm^{-3}, and electrical resistivity 2.88 mΩ cm.
9	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.44 g cm^{-3}, and electrical resistivity 2.42 mΩ cm.
10*	146	Knibbs, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.41 g cm^{-3}, and electrical resistivity 2.90 mΩ cm.
11	146	Knibbs, R.H., et al.	1971	L	298		40 v/o surface treated Type I high modulus carbon fibers bonded by epoxy resin; 5 cm disc specimen; molded; density 1.38 g cm^{-3}; electrical resistivity 435 mΩ cm; heat flow perpendicular to fibers; reported error ±20%.
12	146	Knibbs, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.48 g cm^{-3}, and electrical resistivity 270 mΩ cm.
13	146	Knibbs, R.H., et al.	1971	L	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.57 g cm^{-3}, and electrical resistivity 196 mΩ cm.
14*	146	Knibbs, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.47 g cm^{-3}, and electrical resistivity 385 mΩ cm.
15	146	Knibbs, R.H., et al.	1971	L	298		40 v/o surface treated Type II high strength carbon fibers bonded by epoxy resin; 5 cm disc specimen; molded; density 1.30 g cm^{-3}; electrical resistivity 833 mΩ cm; heat flow perpendicular to fibers; reported error ±20%.
16	146	Knibbs, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.40 g cm^{-3}, and electrical resistivity 323 mΩ cm.

* Not shown in figure.

TABLE 7-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17*	146	Knibbs, R.H., Baker, D.J., and Rhodes, G.	1971	L	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.44 g cm^{-3}, and electrical resistivity 172 mΩ cm.
18*	146	Knibbs, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.41 g cm^{-3}, and electrical resistivity 370 mΩ cm.
19	117	Hertz, J., Christian, J.L., and Varlas, M.	1972	L	85-422	HT-S/X-90	8 x 8 x 0.5 in. unidirection panel prepared by bonding HT-S graphite fibers with X-904 epoxy resin; heat flow perpendicular to fibers.
20	117	Hertz, J., et al.	1972	L	53-418	HT-S/X-904	Similar to the above specimen but heat flow parallel to fibers.
21	117	Hertz, J., et al.	1972	L	86-422	GY-70/HM-S/ X-904	8 x 8 x 0.5 in. panel prepared by bonding GY-70 and HM-S graphite fibers with X-904 epoxy resin, with GY-70 and HM-S in alternate layers; panel orientation; [0°GY-70/90°HM-S/0°GY-70] 4T; heat flow perpendicular to fibers.
22	117	Hertz, J., et al.	1972	L	96-417	GY-70/HM-S/ X-904	Similar to the above specimen but heat flow parallel to GY-70 fibers.

* Not shown in figure.

TABLE 7-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1}]

T	k
CURVE 1	
97	0.00616
117	0.00587
139	0.00602
158	0.00618
177	0.00646
203	0.00694
243	0.00786
309	0.00995
CURVE 2	
31	0.00900
59	0.0299
86	0.0573
118	0.0909
134	0.109
157	0.128
185	0.151
205	0.171
219	0.189
241	0.225
CURVE 3*	
298	0.393
CURVE 4*	
298	0.511
CURVE 5*	
298	0.649
CURVE 6*	
298	0.661
CURVE 7	
298	0.096
CURVE 8	
298	0.113
CURVE 9	
298	0.126
CURVE 10*	
298	0.117
CURVE 11	
298	0.0079
CURVE 12	
298	0.0096
CURVE 13	
298	0.0138
CURVE 14*	
298	0.0088
CURVE 15	
298	0.0058
CURVE 16	
298	0.0067
CURVE 17*	
298	0.0071
CURVE 18*	
298	0.0067
CURVE 19	
85	0.00286
202	0.00524
280	0.00646
373	0.00724
422	0.00792
CURVE 20	
53	0.0476
233	0.138
287	0.136
371	0.127
418	0.130
CURVE 21	
86	0.00392
204	0.00767
279	0.00976
370	0.0125
422	0.0133
CURVE 22	
96	0.0454
108	0.0532
207	0.0896
222	0.109
276	0.107
279	0.0779
279	0.0812
287	0.0878
376	0.118
386	0.136
417	0.123

* Not shown in figure.

b. Specific Heat

There are five sets of experimental data available for the specific heat of graphite fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 7-5. The experimental data are tabulated in Table 7-6 and partially shown in Figure 7-2. These data sets cover the following types of composites:

HT-S/X-904 (curves 1, 4, 5),
GY-70/X-904 (curve 2), and
GY-70/HM-S/X-904 (curve 3).

The provisional values generated as discussed in the following sections are for well cured and thermally stable composites. The resin content of each composite is given together with the specific heat values.

HTS/X-904 Composite

The provisional values tabulated in Table 7-4 and shown in Figure 7-2 are based on the measurements of Hertz, Christian, and Varlas [117] (curve 1). These values are considered accurate to about ± 10%.

GY-70/X-904 Composite

The provisional values tabulated in Table 7-4 and shown in Figure 7-2 are based on the measurements of Hertz, Christian, and Varlas [117] (curve 2). These values are considered accurate to about ± 10%.

TABLE 7-4. PROVISIONAL SPECIFIC HEAT OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p	
	GY-70/25 percent X-904	HT-S/28 percent X-904
100	0.082	0.079
150	0.118	0.117
200	0.152	0.155
250	0.186	0.192
273.15	0.202	0.208
293	0.214	0.222
300	0.219	0.228
350	0.252	0.263
400	0.284	0.297
450	0.315	0.329

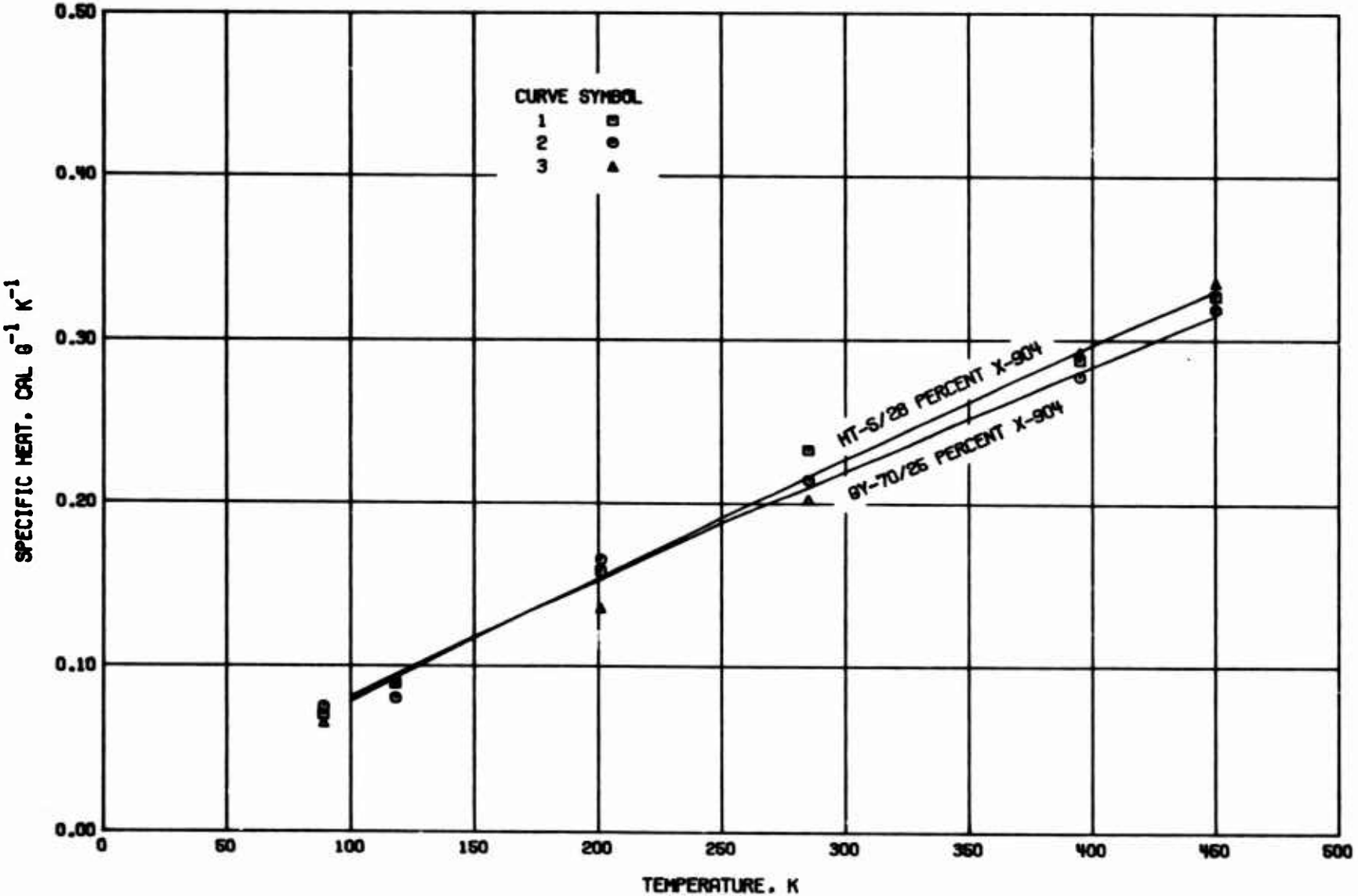

FIGURE 7-2. SPECIFIC HEAT OF GRAPHITE FIBER EPOXY COMPOSITES .

TABLE 7-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GRAPHITE EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	117	Hertz, J., Christian, J. L., and Varias, M.	1972		89-450	Panel OC16-C3	HT-S/X-904 composite; specific gravity 1.58; resin content 28 percent.
2	117	Hertz, J., et al.	1972		89-450	Panel OC15-1-C2	GY-70/X-904 composite; specific gravity 1.706; resin content 24.8 percent.
3	117	Hertz, J., et al.	1972		89-450	Panel OC15-1-CC2	GY-70/HM-S/X-904 composite.
4*	117	Hertz, J., et al.	1972		82-450	1A-39-1	HT-S/X-904 composite.
5*	117	Hertz, J., et al.	1972		83-450	1A-39-1	Similar to the above specimen; water boiled for 24 hr.

TABLE 7-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF GRAPHITE FIBER EPOXY

[Temperature, T, K; Specific Heat, C_p, cal g^{-1} K^{-1}]

T	C_p
CURVE 1	
89	0.071
118	0.090
201	0.158
285	0.234
395	0.288
450	0.327
CURVE 2	
89	0.076
118	0.081
201	0.165
285	0.215
395	0.278
450	0.319

T	C_p
CURVE 3	
89	0.066
118	0.092
201	0.135
285	0.203
395	0.293
450	0.335
CURVE 4*	
82	0.065
89	0.070
116	0.093
144	0.113
172	0.134
200	0.155
228	0.176
255	0.196

T	C_p
CURVE 4 (cont.)*	
283	0.219
311	0.239
339	0.261
366	0.282
394	0.304
422	0.324
450	0.344
CURVE 5*	
83	0.064
89	0.069
116	0.091
144	0.111
172	0.133
200	0.153
228	0.176

T	C_p
CURVE 5 (cont.)*	
255	0.197
283	0.218
311	0.239
339	0.262
366	0.282
394	0.303
422	0.323
450	0.344

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of graphite fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific resin, a specific curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost, and the specific properties desired in the cured resin. The softening point of cured epoxy resin is near 450 K. No experimental data for the heat of fusion/softening of cured epoxy resin and for the heat of fusion of graphite were located in the literature. Graphite sublimes without melting at atmospheric pressure. Leidler, Krikorian, and Young [147] reported a value of 2500 cal g^{-1} for the heat of fusion of carbon at the triple point, 4600-4800 K and 48000 atm.

d. Thermal Linear Expansion

There are 154 sets of experimental data available for the thermal linear expansion of graphite fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 7-8. The experimental data are tabulated in Table 7-9 and partially shown in Figures 7-3A through 7-3E. These data sets are for unidirectional, cross-plied, angle-plied, orthotropic, and pseudo-isotropic laminates and cover the following types of composites:

Courtaulds HMS/Hercules 3002 epoxy (curves 3-11),
Courtaulds HTS/ERLA 4617 epoxy (curves 92-94),
Courtaulds HTS/Faberite X-904 epoxy (curves 107-126 and 151-154),
Modmor I/ELRB 4617 epoxy (curves 104-106),
Modmor II/Narmco 5206 epoxy (curves 12-17),
GY-70/CRC 350A epoxy (curves 18-37),
GY-70/Faberite X-904 epoxy (curves 95-98 and 127-137),
GY-70/HMS/Faberite X-904 epoxy (curves 139-150),
Thornel-25/Epon 815 epoxy (curves 60-63),
Thornel-50/Epon 815 epoxy (curves 56-59),
Thornel-75/Epon 815 epoxy (curves 52-55),
Thornel-75S/ELRB 4617 epoxy (curves 101-103),
Hercules HTS/Bloomingdale BP-907 epoxy (curves 65-68),
Hercules HTS/Hercules 3002 epoxy (curves 69-81),
Hercules HMS/Hercules 3002 epoxy (curves 82-89), and
Hercules HMS/Bloomingdale BP-907 epoxy (curves 90 and 91).

Although several data sets are available for each type of composites, it is practically impossible from the available limited information to separate out the contributions of individual factors affecting the thermal expansion of composites. These factors include the type of fiber used, namely high modulus or high tensile strength, type of epoxy, fiber to epoxy ratio, curing process, and tendency of graphite fiber epoxy composite to absorb moisture. Most of the data sets do not show a reasonably stable thermal expansion behavior after one or two thermal cycles. Nakamura and Larsen [119] and Freeman and Campbell [148] from their extensive investigations have attributed this unstable expansion behavior to the absorption of moisture by the composite material. Thus the variation of thermal expansion from material to material may be due to one of the above reasons, the absorbed moisture being a major factor. A knowledge of the exact nature of these effects is required by the designer when these advanced

materials are used in structural applications under various environmental conditions. For these and other reasons, it is practically impossible to derive the most probable values which can be applied to composites in general.

The thermal expansion behavior of graphite fiber epoxy composites can be summarized as follows. The high modulus graphite fiber/epoxy composite has slightly lower thermal expansion that the high tensile strength graphite fiber/epoxy composite. The experimental results for the complex construction composites indicate that it is feasible to tailor the laminate orientations, fiber modulus, and fiber volume in a manner that will provide a structure with exceptional two dimensional thermal stability (i.e., low expansion) over a wide temperature range. The phenomenon of unstable expansion behavior relates to the absorption of moisture by fiber reinforced epoxy composites is significant.

The provisional thermal expansion values generated as discussed in the following sections are for the moisture-free composite and are based mainly on the data for stable thermal cycle for a given composite. The values are given for unidirectional and pseudo-isotropic laminates along fiber orientation and thickness direction. The thermal expansions of composites with high modulus graphite fiber and with high tensile strength graphite fiber are treated separately below.

High Modulus Graphite Fiber Epoxy Composite

(1) Unidirectional Fiber Orientation - Longitudinal

The provisional values tabulated in Table 7-7 and shown in Figure 7-3A are derived primarily from the measurements of Nakamura and Larsen [119] (curves 3-6), and of Freeman and Campbell [148] (curves 84, 85, and 90). Thermal expansion data of Kalnin [145] (curves 34 and 35) and of Freeman and Campbell [148] (curve 82) show unusually high contraction at temperatures above 293 K, and this may be due to the absorbed moisture by their composite specimens. The provisional values are for cured and moisture-free composite with high-modulus unidirectional graphite fibers (fiber modulus 50 to 70 x 10^6 psi). The modulus of epoxy is 0.5 to 0.7 x 10^6 psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber orientation direction. The uncertainty of the values is within ±20%.

(2) Unidirectional Fiber Orientation - Transverse

The provisional values tabulated in Table 7-7 and shown in Figure 7-3B are derived primarily from the measurements of Nakamura and Larsen [119] (curves 7-10),

Kalnin [145] (curves 36 and 37), Knibbs and Morris [149] (curve 44), Freeman and Campbell [148] (curves 83, 86, and 91), and of Goggin [150] (curves 103 and 106). These values are for cured and moisture-free composite with high-modulus unidirectional graphite fibers (fiber modulus 50 to 70 x 10^6 psi). The fiber content is 50-60 volume percent, the epoxy modulus is 0.5 to 0.7 x 10^6 psi, and the thermal expansion is along the fiber thickness direction. The uncertainty of the values is within ±20%.

(3) Pseudo-Isotropic Fiber Orientation - Along Fiber Plane

The provisional values tabulated in Table 7-7 and shown in Figure 7-3C are derived primarily from the measurements of Nakamura and Larsen [119] (curve 11), Kalnin [145] (curves 18 and 19), and of Freund [151] (curve 95). Thermal expansion data of Freeman and Campbell [148] (curve 87) are considerably higher which may be due to the variation in the fiber orientation and experimental condition. The values are for cured and moisture-free composite with high-modulus pseudo-isotropically oriented graphite fibers (fiber modulus 50 to 70 x 10^6 psi). The epoxy modulus is 0.5 to 0.7 x 10^6 psi, the fiber content is about 50 volume percent, and the thermal expansion is along the fiber plane. The uncertainty of the values is within ±20%.

High Tensile Strength Graphite Fiber Epoxy Composite

(1) Unidirectional Fiber Orientation - Longitudinal

The provisional values tabulated in Table 7-7 and shown in Figure 7-3D are derived from the measurements of Freeman and Campbell [148] (curves 69 and 70). Thermal expansion data of Nakamura and Larsen [119] (curve 16) and of Freeman and Campbell [148] (curve 65) show unusually low contraction at temperatures above 293 K, possibly due to absorbed moisture. The values are for cured and moisture-free composite with high-tensile-strength unidirectional graphite fibers (fiber modulus 30 to 40 x 10^6 psi). The epoxy modulus is 0.5 to 0.7 x 10^6 psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber orientation direction. The uncertainty of the values is within ±25%.

(2) Unidirectional Fiber Orientation - Transverse

The provisional values tabulated in Table 7-7 and shown in Figure 7-3E are based on the measurements of Nakamura and Larsen [119] (curves 13-15), Knibbs and Morris [149] (curve 51), and of Freeman and Campbell [148] (curves 66, 68, and 72-74). These values are for cured and moisture-free composite with high-tensile-strength unidirectional graphite fibers (fiber modulus 30 to 40 x 10^6 psi). The epoxy modulus is

0.5 to 0.7 x 10^6 psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber thickness direction. The uncertainty of the values is within ±25%.

(3) Pseudo-Isotropic Fiber Orientation - Along Fiber Plane

The provisional values tabulated in Table 7-7 and shown in Figure 7-3C are based on the measurements of Nakamura and Larsen [119] (curve 17). These values are for cured and moisture-free composite with high-tensile-strength pseudo-isotropically oriented graphite fibers (fiber modulus 30 to 40 x 10^6 psi). The epoxy modulus is 0.5 to 0.7 x 10^6 psi, the fiber content is 50 volume percent, and the thermal expansion is along the fiber plane. The uncertainty of the values is within ±25%.

The values of the instantaneous coefficient of thermal linear expansion, α, for the above composites are obtained by differentiation of empirical equations which are used to fit the provisional thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about ±25%.

TABLE 7-7. PROVISIONAL THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α, 10^{-6} K^{-1}]

a. High Modulus Graphite Fiber Epoxy Composite

T	Unidirectional Fiber Orientation				Pseudo-Isotropic Fiber Orientation	
	Longitudinal		Transverse		Along Fiber Plane	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α	$\Delta L/L_0$	α
75			-0.564	19.4		
80			-0.555	19.6		
90			-0.535	20.1		
100	0.0124	-0.8	-0.515	20.6		
150	0.0086	-0.7	-0.405	23.3		
200	0.0052	-0.6	-0.280	26.6		
250	0.0022	-0.6	-0.138	30.4	-0.0011	0.2
273.15	0.0010	-0.5	-0.066	32.3	-0.0006	0.3
293	0.0000	-0.5	0.000	34.0	0.0000	0.4
300	-0.0004	-0.5	0.024	34.6	0.0003	0.4
350	-0.0027	-0.4	0.209	39.4	0.0025	0.5
400	-0.0042	-0.3	0.419	44.[illegible]	0.0049	0.5
450	-0.0054	-0.2	0.656	50.4	0.0069	0.5

b. High Tensile Strength Graphite Fiber Epoxy Composite

75	0.0080	-0.4	-0.442	15.8		
80	0.0078	-0.4	-0.434	16.0		
90	0.0074	-0.4	-0.418	16.3		
100	0.0070	-0.4	-0.402	16.6		
150	0.0051	-0.4	-0.314	18.5		
200	0.0033	-0.4	-0.216	20.5		
250	0.0015	-0.4	-0.106	23.4	-0.0020	0.4
273.15	0.0007	-0.3	-0.050	24.8	-0.0010	0.5
293	0.0000	-0.3	0.000	26.1	0.0000	0.6
300	-0.0002	-0.3	0.018	26.5	0.0004	0.6
350	-0.0020	-0.3	0.160	30.0	0.0037	0.7
400	-0.0036	-0.3	0.319	33.9	0.0073	0.8
450	-0.0052	-0.3	0.500	38.2	0.0110	0.8

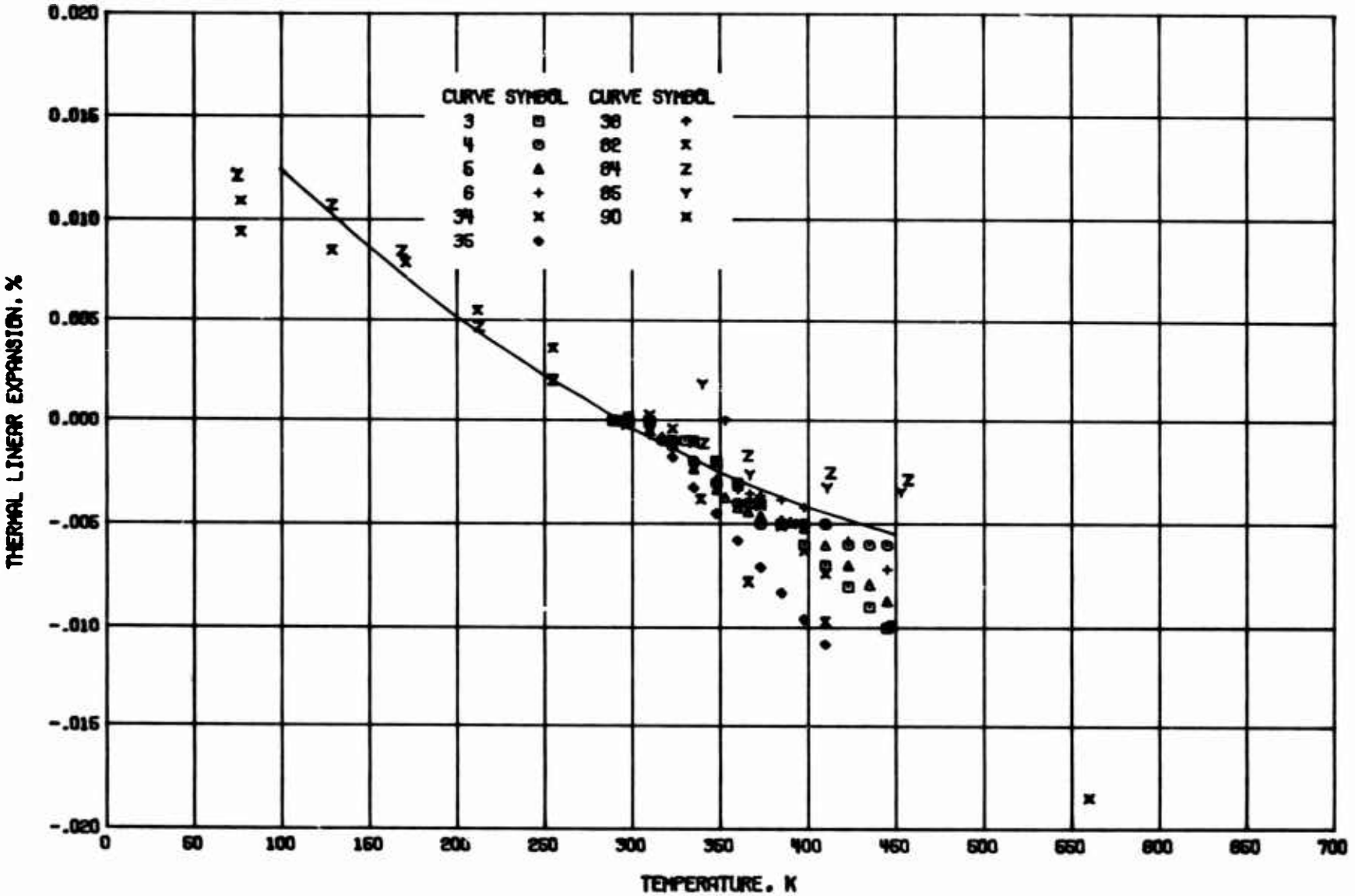

FIGURE 7-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF HIGH MODULUS GRAPHITE FIBER EPOXY COMPOSITES.

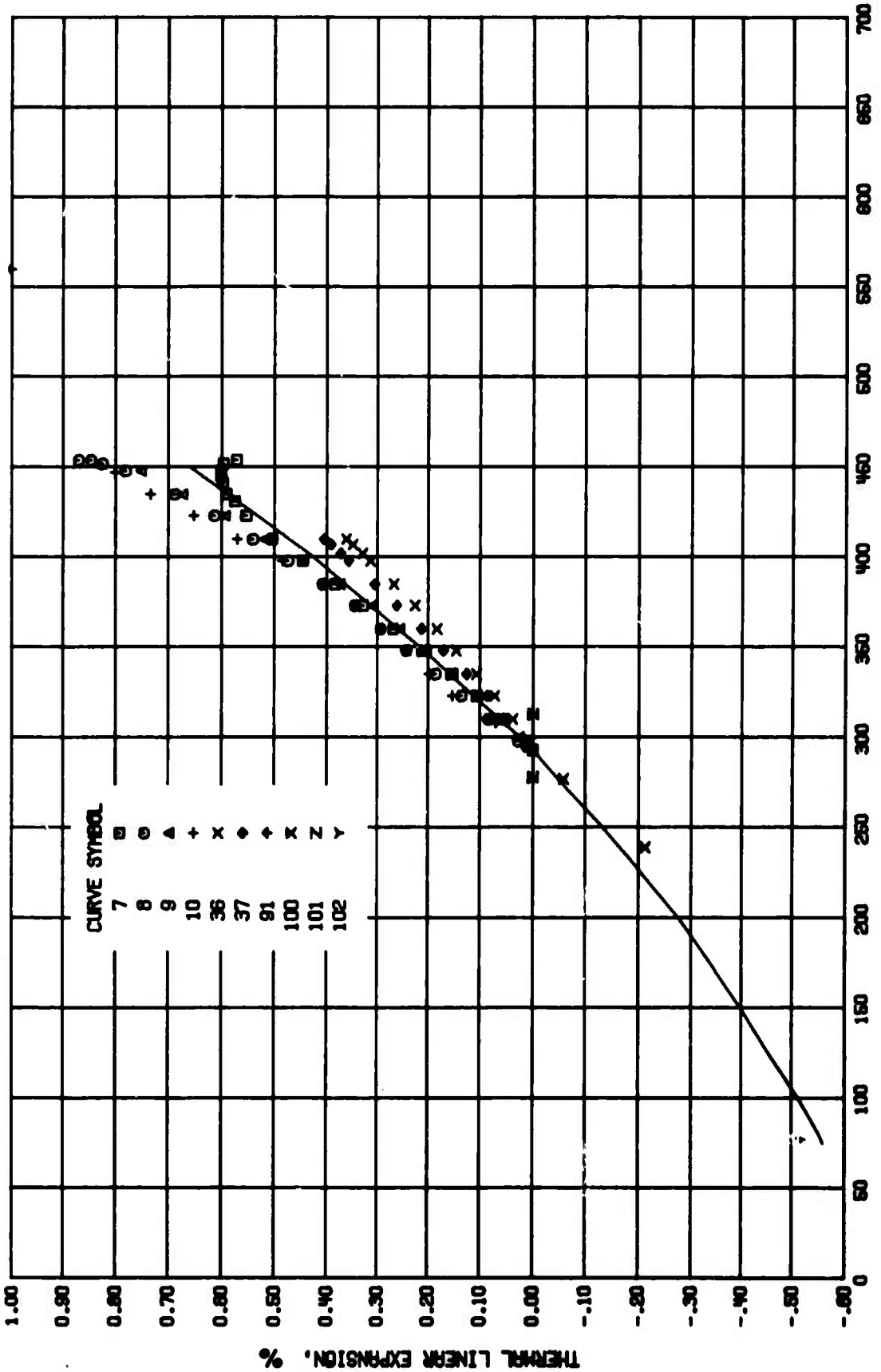

FIGURE 7-38. TRANSVERSE THERMAL LINEAR EXPANSION OF HIGH MODULUS GRAPHITE FIBER EPOXY COMPOSITES.

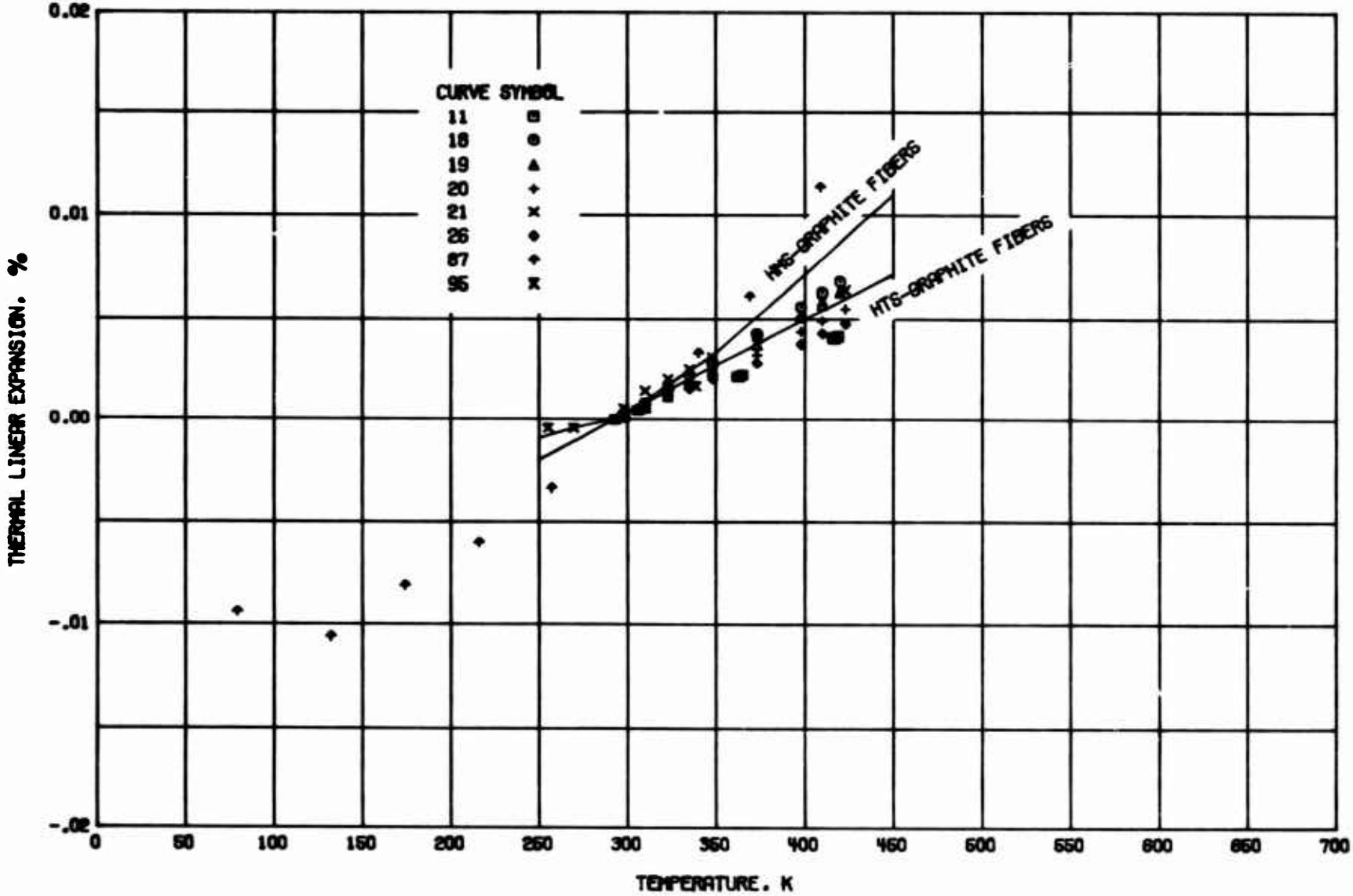

FIGURE 7-3C. THERMAL LINEAR EXPANSION OF PSEUDO-ISOTROPIC GRAPHITE FIBER EPOXY COMPOSITES .

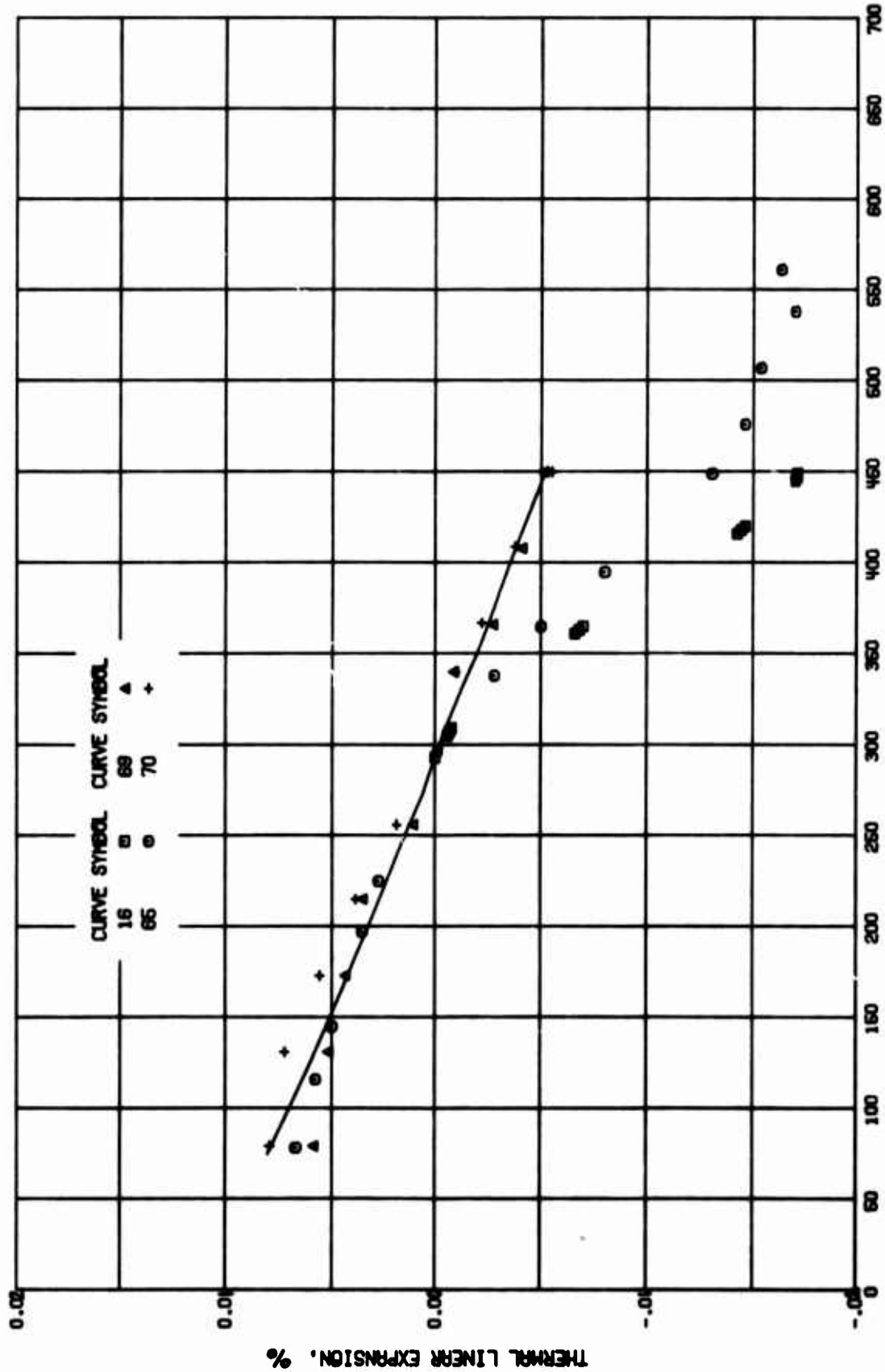

FIGURE 7-3D. LONGITUDINAL THERMAL LINEAR EXPANSION OF HIGH STRENGTH GRAPHITE FIBER EPOXY COMPOSITES .

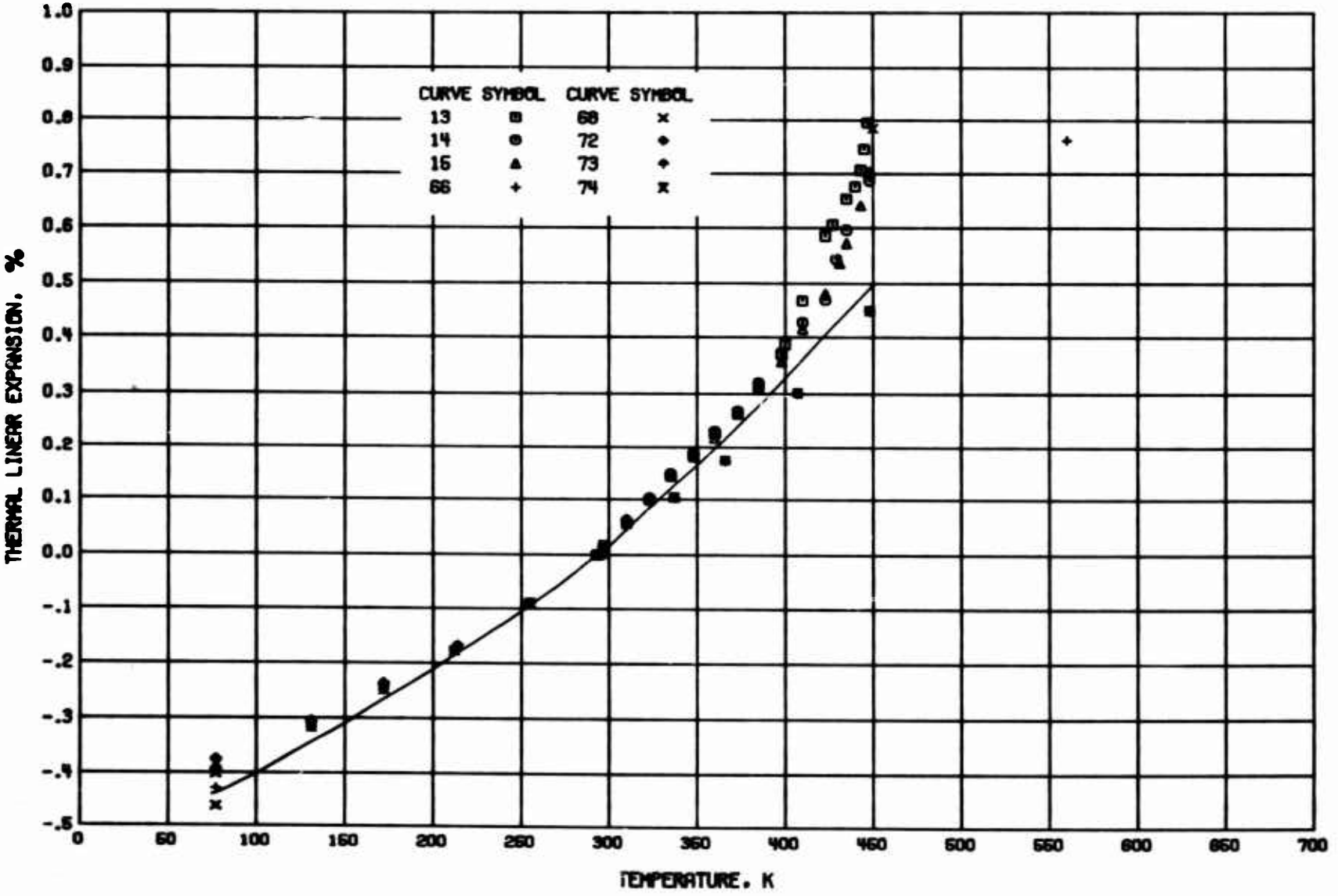

FIGURE 7-3E. TRANSVERSE THERMAL LINEAR EXPANSION OF HIGH STRENGTH GRAPHITE FIBER EPOXY COMPOSITES .

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	152	Prime, R. B., Barrall, II; E. M., Logan, J. A., and Duke, P. J.	1974		323	Pseudo-random Courtaulds HMS	High modulus graphite fibers/epoxy matrix; six plies $(0 \pm 60)_s$; 45-50 volume % chopped fibers; orientation of composite is 0 deg with respect to surface fibers; measured using thermomechanical analysis technique.
2*	152	Prime, R. B., et al.	1974		323	Pseudo-random Courtaulds HMS	The above specimen except orientation of composite material is 90 deg with respect to surface fibers.
3	119	Nakamura, H. H. and Larsen, D. C.	1974	L	289-445	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm^{-3}; fiber tensile modulus 45 x 10^6 psi; composite stiffness 27 x 10^6 psi; six plies of 0 deg (longitudinal) fiber orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles, fiber 50 volume % ; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; expansion in the specimen (and specimens in curves thru 17) measured along length direction for three specimens of single 0.5 x 2 in. laminate roughly 0.050 in. thick; specimen exhibited 0.1-0.3% weight loss; first heating cycle; significant shrinkage observed.
4	119	Nakamura, H. H. and Larsen, D. C.	1974	L	445-290	Courtaulds HMS/Hercules 3002 M	The above specimen; first cooling cycle; zero-point correction is 0.003%.
5	119	Nakamura, H. H. and Larsen, D. C.	1974	L	290-445	Courtaulds HMS/Hercules 3002 M	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.003%.
6	119	Nakamura, H. H. and Larsen, D. C.	1974	L	445-288	Courtaulds HMS/Hercules 3002 M	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.005%.
7	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-454	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm^{-3}; fiber tensile modulus 45 x 10^6 psi; composite stiffness 27 x 10^6 psi; eight plies of 90 deg (transverse) orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; first heating cycle; significant shrinkage observed; specimens exhibited weight loss of 0.1 to 0.3%; zero-point correction is 0.013%.
8	119	Nakamura, H. H. and Larsen, D. C.	1974	L	454-293	Courtaulds HMS/Hercules 3002 M	The above specimen; first cooling cycle; zero-point correction is 0.312%.
9	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-448	Courtaulds HMS/Hercules 3002 M	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.307%.
10	119	Nakamura, H. H. and Larsen, D. C.	1974	L	447-293	Courtaulds HMS/Hercules 3002 M	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.372%.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
11	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-447	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm^{-3}; fiber tensile modulus 45 x 10^6 psi; composite stiffness 27 x 10^6 psi; nine plies of balanced symmetric unidirectional-angle ply orientation designated $[0/45/135/0/\overline{90}]_s$; plies stacked in directions (0/+45/-45/0/90/0/-45/+45/0); individual ply thickness 5-8 mils; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
12*	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-447	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3}; fiber modulus 38 x 10^6 psi; composite strength 161 ksi; eight plies of 90 deg (transverse) orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; first heating cycle; significant shrinkage observed; zero-point correction is 0.009%.
13	119	Nakamura, H. H. and Larsen, D. C.	1974	L	447-293	Modmor II/ Narmco 5206	The above specimen; first cooling cycle; zero-point correction is 0.485%.
14	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-448	Modmor II/ Narmco 5206	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.485%.
15	119	Nakamura, H. H. and Larsen, D. C.	1974	L	448-293	Modmor II/ Narmco 5206	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.500%.
16	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-449	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3}; fiber modulus 38 x 10^6 psi; composite strength 161 ksi; six plies of 0 deg (longitudinal) fiber orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
17*	119	Nakamura, H. H. and Larsen, D. C.	1974	L	293-420	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3}; fiber modulus 38 x 10^6 psi; composite strength 161 ksi; nine plies of balanced symmetric unidirectional-angle ply orientation designated $[0/45/135/0/\overline{90}]_s$; plies stacked in directions (0/+45/-45/0/90/0/-45/+45/0); individual ply thickness 5.8 mils; fiber 50 volume %; autoclave process provided final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
18	145	Kalnin, I. L.	1974	L	293-420	GY-70/350 A Laminate	Quasi-isotropic multidirectional laminates made by vacuum/pressure bagging of oriented layups of high modulus (75 x 10^6 psi) UD Celion® GY-70 graphite tape 7.5 cm wide, prepregged with CRC 350 A resin - a novolac base epoxy/anhydride system; eight plies $[90, 45, 0, -45]_s$; fiber content 60 volume %; cure cycle of 6 hr at 450 K and external pressure of 75 psi; length of the specimen (and specimens in the curves thru 37) is 50 mm; to eliminate nonequilibrium thermal stresses the specimen (and specimens in curves thru 37) cycled 2-3 times between room temperature and 423 K prior to actual measurements; measurements in the principal laminate direction of 0 deg; heating cycle.
19	145	Kalnin, I. L.	1974	L	420-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
20	145	Kalnin, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 45 deg; heating cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
21	145	Kalnin, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
22*	145	Kalnin, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 90 deg; heating cycle.
23*	145	Kalnin, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
24*	145	Kalnin, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of -45 deg; heating cycle.
25*	145	Kalnin, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
26	145	Kalnin, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except twelve plies $[+60, 0, -60]_s$ laminate; measurements in the principle laminate direction of 0 deg; average of heating and cooling.
27*	145	Kalnin, I. L.	1974	L	293-421	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 30 deg; heating cycle.
28*	145	Kalnin, I. L.	1974	L	421-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
29*	145	Kalnin, I. L.	1974	L	293-424	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 45 deg; heating cycle.
30*	145	Kalnin, I. L.	1974	L	424-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
31*	145	Kalnin, I. L.	1974	L	293-424	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 60 deg; heating cycle.
32*	145	Kalnin, I. L.	1974	L	424-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
33*	145	Kalnin, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 90 deg.
34	145	Kalnin, I. L.	1974	L	293-410	UD GY-70/ 350 A	Composites of density 1.68 g cm^{-3} were made from prepregged GY-70 graphite yarn bundles by the "leaky" pressure molding technique in the form of bars 2.5 cm wide and 25-30 cm long; fiber content 60 ± 1 volume %; void content of < 3% neglected in the calculations; cured panels trimmed, jigged and cut to 0.65 cm strips along those directions in which expansion were to be measured; measurements along axial direction; heating cycle.
35	145	Kalnin, I. L.	1974	L	410-293	UD GY-70/ 350 A	The above specimen except cooling cycle.
36	145	Kalnin, I. L.	1974	L	293-410	UD GY-70/ 350 A	The above specimen except measurements along transverse direction; heating cycle.
37	145	Kalnin, I. L.	1974	L	410-293	UD GY-70/ 350 A	The above specimen except cooling cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
38*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Composite made from high modulus carbon fibers and conventional epoxide resin using hardener, diamino diphenyl methane (D. D. M.); final fiber 50 volume %; 1.7 to 6 volume % voids, specimen of 8 x 1.1 x 0.9 cm was cut at an angle 0 deg to the lay of fibers.
39*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 10 deg to the lay of fibers.
40*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 20 deg to the lay of fibers.
41*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 30 deg to the lay of fibers.
42*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 45 deg to the lay of fibers.
43*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 65 deg to the lay of fibers.
44*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 90 deg to the lay of fibers.
45*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Composite made from high strength carbon fibers and conventional epoxide resin using hardener diamino diphenyl methane (D. D. M.); final fiber 50 volume %, 1.7 to 6 volume % voids, specimen of 8 x 1.1 x 0.9 cm was cut at an angle 0 deg to the lay of fibers.
46*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 10 deg to the lay of fibers.
47*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 20 deg to the lay of fibers.
48*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 30 deg to the lay of fibers.
49*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 45 deg to the lay of fibers.
50*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 65 deg to the lay of fibers.
51*	149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 90 deg to the lay of fibers.
52*	153	Dauksys, R. J.	1973		243-303		Discontinuous graphite fiber modification of epoxy potting compound of density 1.19 g cm^{-3} obtained by mixing chopped Thornel-75 (Union Carbide) continuous yarn (average modulus 83 x 10^6 psi; tensile strength 330 ksi) with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen is 2 x 0.375 x 0.25 in.; average of two runs.
53*	153	Dauksys, R. J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.22 g cm^{-3}.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy.
55*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.23 g cm^{-3}.
56*	153	Dauksys, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.19 g cm^{-3} obtained by mixing chopped Thornel-50 (Union Carbide) continuous yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen 2 x 0.375 x 0.25 in.
57*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.19 g cm^{-3}.
58*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy; density 1.18 g cm^{-3}.
59*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.18 g cm^{-3}.
60*	153	Dauksys, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.17 g cm^{-3} obtained by mixing chopped Thornel-25 (Union Carbide) continuous yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA), rectangular cross section of specimen 2 x 0.375 x 0.25 in.; average of two runs.
61*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.01 g cm^{-3}.
62*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy; density 1.44 g cm^{-3}.
63*	153	Dauksys, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.19 g cm^{-3}.
64*	153	Dauksys, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.16 g cm^{-3} obtained by mixing chopped continuous yarn (designated as VYB-105-1/5) of lower modulus than Thornel yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen 2 x 0.375 x 0.25 in.
65	148	Freeman, W.T. and Campbell, M.D.	1972	L	78-561	Specimen 4 P13N-T	TRW P13N resin (modulus 0.55 Msi) reinforced with Hercules high tensile (modulus 36.6 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 57.6 volume %; void content 5.3%; specimen stored in dry helium at 297 K for 18 hr (pretest storage environment); shrinkage 1.07×10^{-2} % after first high temperature cycle; longitudinal lamina expansion.
66	148	Freeman, W.T. and Campbell, M.D.	1972	L	78-561	Specimen 5 P13N-T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 57 volume %; void content 5.8%; specimen stored in dry helium at 297 K for 18 hr; shrinkage 13.54×10^{-2}% after first high temperature cycle; transverse lamina expansion.
67*	148	Freeman, W.T. and Campbell, M.D.	1972	L	84-365	Specimen 6 BP907-T	Bloomingdale BP-907 resin (modulus 0.50 Msi) reinforced with Hercules high tensile (modulus 34.9 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 60.2 volume %; void content 0.4%; stored in dry helium at 297 K for 18 hr; shrinkage 0.13×10^{-2}% after first high temperature cycle; longitudinal lamina expansion.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
68	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 7 BP907-T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 60.2 volume %; void content 0.4%; specimen stored in dry helium at 297 K for 18 hr; shrinkage 15.88 x 10^{-4} % after first high temperature cycle; transverse lamina expansion.
69	148	Freeman, W.T. and Campbell, M.D.	1972	L	79-450	Specimen 8 3002T	Hercules 3002 resin (modulus 0.7 Msi) reinforced with Hercules high tensile (modulus 36.0 Msi) graphite fibers, fiber orientation 0 deg to the top ply; fiber 66.2 volume %; void content 0.0%; to assure constant fiber volume and thickness, small prepreg sheets were laminated with fiber orientation and press cured in the same mold; stored in dry helium at 297 K for 18 hr; shrinkage 1.02 x 10^{-4} % after first high temperature cycle; specimen cycled three times from 297 K to 450 K and final cycle from 297 K to 67 K.
70	148	Freeman, W.T. and Campbell, M.D.	1972	L	79-450	Specimen 9 3002T	Similar to the above specimen except shrinkage 0.28 x 10^{-4} % after first high temperature cycle.
71*	148	Freeman, W.T. and Campbell, M.D.	1972	S	227-367	Specimen 10 3002T	Similar to the above specimen except stored in 50% relative humidity at 297 K; shrinkage 0.04 x 10^{-4} % after first high temperature cycle.
72	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-448	Specimen 11 3002T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 65.9 volume %; stored in dry helium at 297 K for 18 hr; cycled three times to 77 K and final to 450 K; shrinkage 3.31 x 10^{-4} % after first high temperature cycle; transverse lamina expansion.
73	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-448	Specimen 12 3002T	Similar to the above specimen except stored in dry helium at 297 K for 48 hr; cycled three times to 450 K and final to 77 K; shrinkage 7.74 x 10^{-4} % after first high temperature cycle; transverse lamina expansion.
74	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-448	Specimen 13 3002T	Similar to the above specimen except specimen stored in vacuum at 297 K for 24 hr; shrinkage 1.43 x 10^{-4} % after first high temperature cycle; transverse lamina expansion.
75*	148	Freeman, W.T. and Campbell, M.D.	1972	S	200-433	Specimen 14 3002T	Similar to the above specimen except stored in 50% relative humidity at 297 K; shrinkage 0.2 x 10^{-4} % after first high temperature cycle; transverse lamina expansion.
76*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 15 3002T	Orthotropic laminates prepared from Hercules 3002 resin (modulus 0.70 Msi) with Hercules high tensile (modulus 36.0 Msi) graphite fibers, fiber orientation 0, ±45, 90 deg to the top ply, fiber 65.1 volume %; void content 0.0%; stored in dry helium at 297 K for 98 hr; to assure constant fiber volume and thickness, small prepreg sheets were laminated with fiber orientation and press cured in the same mold; shrinkage 1.27 x 10^{-4} % after first high temperature cycle.
77*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 16 3002T	Similar to the above specimen except fiber orientation 0, 90 deg to the top ply; fiber 65.6 volume %, void content 0.0%; stored in dry helium at 297 K for 72 hr; shrinkage 0.56 x 10^{-4} % after first high temperature cycle.
78*	148	Freeman, W.T. and Campbell, M.D.	1972	S	297-450	Specimen 17 3002T	Similar to the above specimen; stored in 50% relative humidity at 297 K; shrinkage 0.31 x 10^{-4} % after first high temperature cycle.
79*	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 18 3002T	Similar to the above specimen except fiber orientation ±30 deg to the top ply; fiber 65 volume %; specimen stored in dry helium at 297 K for 122 hr; shrinkage 0.41 x 10^{-4} % after first high temperature cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
80*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 19 3002T	Similar to the above specimen except fiber orientation ±45 deg to the top ply; fiber 65.6 volume %; specimen stored in dry helium at 297 K for 146 hr; shrinkage 1.78×10^{-2} % after first high temperature cycle.
81*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 20 3002T	Similar to the above specimen except fiber orientation ±60 deg to the top ply; fiber 65.6 volume %; specimen stored in dry helium at 297 K for 170 hr; shrinkage 4.3×10^{-2} % after first high temperature cycle.
82	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 21 3002M	Hercules 3002 resin (modulus 0.70 Msi) reinforced with Hercules high modulus (57.2 Msi) graphite fibers; fiber orientation 0 deg to the top ply, fiber 56.3 volume %, void content 2.4%; stored in dry helium at 297 K for 18 hr; shrinkage 0.56×10^{-2} % after first high temperature cycle; longitudinal lamina expansion.
83*	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 22 3002M	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber volume 56.3%, void content 2.4%; stored in dry helium at 297 K for 18 hr; shrinkage 2.83×10^{-2} % after first high temperature cycle.
84	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 23 3002M	Similar to the above specimen except fiber orientation 0 deg to the top ply; fiber 49.2 volume %, void content 2.8%; stored in air at 394 K for 40 hr; shrinkage 0.36×10^{-2} % after first high temperature cycle; longitudinal lamina expansion; first run.
85	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 23 3002M	Same as the above specimen; second run.
86*	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 24 3002M	Similar to the above specimen except fiber orientation 90 deg to the top ply; shrinkage 4.30×10^{-2} %.
87	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 25 3002M	Similar to the above specimen except fiber orientation of quasi-isotropic laminate 0 ±60 to the top ply; specimen machined along the unidirectional fiber lamina in the plate; fiber 48.6 volume %, void content 3.4%; stored in air at 394 K for 40 hr; shrinkage 0.43×10^{-2} %.
88*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-450	Specimen 26 3002M	Similar to the above specimen except specimen machined at 15 deg angle clockwise positive to the top unidirectional ply.
89*	148	Freeman, W.T. and Campbell, M.D.	1972	L	77-408	Specimen 27 3002M	Similar to the above specimen except specimen machined at 30 deg angle clockwise positive to the top unidirectional ply.
90	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 28 BP907M	Bloomingdale BP-907 resin (modulus 0.50 Msi) reinforced with Hercules high modulus (modulus 55.0 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 62.3 volume %; void content 0.0%; stored in desiccant at 297 K for 24 hr; shrinkage 0.10×10^{-2} % after first high temperature cycle; longitudinal lamina expansion.
91	148	Freeman, W.T. and Campbell, M.D.	1972	L	297-450	Specimen 29 BP970M	Similar to the above specimen except fiber orientation 90 deg to the top ply; shrinkage 3.49×10^{-2} % after first high temperature cycle; transverse lamina expansion.
92*	154	Pirgon, O., Wostenholm, G.H., and Yates, B.	1973	I			Specimen from test bars of 13 mm^2 cross section, contains 50 volume % carbon fibers Courtaulds HTS carbon fibers, batch PTT 112/212 prepared from polyacrilonitril together with resin ERLA4617 batch B14 hardened with metaphenylene diamine; fibers were assembled in the form of 22 layers of 8 tows per layer; each tow contains 10^4 fibers giving a total of 1.76×10^6 fibers over the cross section of the specimen; cut in a direction perpendicular to the fiber axis; measurements on the similar bar cut parallel to the fiber axis give widely scattered data, so these results were not tabulated.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
93*	154	Pirgon, O., Wostenholm, G.H., and Yates, B.	1973	I			Similar to the above specimen except specimen cut 45 deg to the fiber axis.
94*	154	Pirgon, O., et al.	1973	I			Similar to the above specimen except specimen cut perpendicular to the fiber axis.
95	151	Freund, N.P.	1974		255-338		Manufactured by GD/Convair, ultrahigh modulus Gr/Ep system composed of GY-70 graphite fibers by Celanese Corp., and X-904 epoxy resin by Faberite Corp.; pseudo isotropic lay ups with symmetric configuration $(0/\pm45/90)_s$; measurements parallel to the outer most fiber orientation; average of 2 tests.
96*	151	Freund, N.P.	1974		255-338		Similar to the above specimen except measurements 90 deg to the outermost fiber orientation.
97*	151	Freund, N.P.	1974				Similar to the above specimen except measurements at an angle 45 deg to the outermost fiber orientation.
98*	151	Freund, N.P.	1974				Similar to the above specimen except measurements normal to surface.
99*	155	Keller, L.B. and Raech, H.	1974	L			Long fiber molding compound from Fiberite Corp; comprised of bundles of 1 in. long Celanese GY-70 fibers impregnated with proprietary epoxy resin; exposed to seven-day aging at 400 K; zero rebulking observed; test panels were cut from them at 450 K and 1000 psi; cured for 1.5 hr followed by 2 hr post cure at 450 K; fiber content 48.2 volume %; density 1.64 g cm^{-3}; measurements parallel to fibers.
100	155	Keller, L.B. and Raech, H.	1974	L			Similar to the above specimen; measurements perpendicular to fibers.
101	150	Goggin, W.R.	1974	L	278-313		Composite from Goodyear Corp. of Akron, Ohio; six plies made of Thornel 75S graphite fibers embedded in ELRB/4617 epoxy resin; nominal composition 37 weight % resin; measurements parallel (in plane) to the fiber orientation.
102	150	Goggin, W.R.	1974	L	278-313		The above specimen except measurements after exposure to 77 K.
103*	150	Goggin, W.R.	1974	L	278-313		Similar to the above specimen except measurements perpendicular to laminate.
104*	150	Goggin, W.R.	1974	L	278-313		Similar to the above specimen except Modmor 1 graphite fibers used; measurements parallel (in plane) to the fiber orientation.
105*	150	Goggin, W.R.	1974	L	278-313		The above specimen except measurements after exposure to 77 K; no further changes observed after six additional cycles.
106*	150	Goggin, W.R.	1974	L	278-313		Similar to the above specimen except measurements perpendicular to laminate plane.
107*	117	Hertz, J., Christian, J.L., and Varlas, M.	1972	L	80-450	NO568	Courtaulds HTS/Faberite X-904; expansion for unidirectional lay up in 0 deg direction.
108*	117	Hertz, J., et al.	1972	L	80-450	NO602	Similar to the above specimen and conditions.
109*	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 684	Similar to the above specimen and conditions; panel 1A-39-1.
110*	117	Hertz, J., et al.	1972	L	78-450	Specimen No. 685	Similar to the above specimen and conditions; last stable cycle.
111*	117	Hertz, J., et al.	1972	L	89-450	Specimen No. 715	Similar to the above specimen and condition; specimen water boiled for 24 hr.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
112*	117	Hertz, J., Christian, J. L., and Varlas, M.	1972	L	79–450	Specimen No. 716	Similar to the above specimen and conditions.
113*	117	Hertz, J., et al.	1972	L	79–450	NO566	Similar to the one from Curve 107; expansion for unidirectional layup in 90 deg direction; zero-point correction 0.013%.
114*	117	Hertz, J., et al.	1972	L	79–450	NO567	Similar to the above specimen and conditions; zero-point correction 0.01%.
115*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 692	Similar to the above specimen and conditions; panel 1A-39-1; zero-point correction 0.028%.
116*	117	Hertz, J., et al.	1972	L	76–450	Specimen No. 693	Similar to the above specimen and conditions; zero-point correction 0.02%.
117*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 720	Similar to the above specimen and conditions; last stable cycle; zero-point correction 0.04%.
118*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 718	Similar to the above specimen and conditions; zero-point correction 0.02%.
119*	117	Hertz, J., et al.	1972	L	86–455	NO530	Similar to the above specimen; expansion for $[\pm 45^\circ]_c$ layup in 0 deg direction; zero-point correction 0.003%.
120*	117	Hertz, J., et al.	1972	L	84–457	NO531	Similar to the above specimen and conditions; panel 0C16-C5; zero-point correction 0.001%.
121*	117	Hertz, J., et al.	1972	L	84–456	NO537	Similar to the above specimen, expansion for $[\pm 45^\circ]_c$ layup in 45 deg direction.
122	117	Hertz, J., et al.	1972	L	84–452	NO536	Similar to the above specimen and conditions; zero-point correction 0.002%.
123*	117	Hertz, J., et al.	1972	L	81–450	NO569	Similar to the above specimen and conditions; expansion for $[0_2^\circ/\pm 45^\circ]_s$ in the 0 deg direction.
124*	117	Hertz, J., et al.	1972	L	81–450	NO570	Similar to the above specimen and conditions.
125*	117	Hertz, J., et al.	1972	L	80–444	NO571	Similar to the above specimen and conditions; expansion for $[0_2^\circ/\pm 45^\circ]_s$ in the 90 deg direction; zero-point correction 0.005%.
126*	117	Hertz, J., et al.	1972	L	80–444	NO572	Similar to the above specimen and conditions.
127*	117	Hertz, J., et al.	1972	L	79–450	NO573	Celanese GY-70/Faberite X-904; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.002%.
128*	117	Hertz, J., et al.	1972	L	79–450	NO579	Similar to the above specimen and conditions; zero-point correction -0.001%.
129*	117	Hertz, J., et al.	1972	L	80–450	NO575	Similar to the above specimen and conditions; expansion in the 90 deg direction; zero-point correction 0.022%.
130*	117	Hertz, J., et al.	1972	L	79–446	NO577	Similar to the above specimen and conditions; zero-point correction 0.034%.
131*	117	Hertz, J., et al.	1972	L	78–450	NO587	Similar to the above specimen and conditions; expansion for $[\pm 45^\circ]_c$ lay up in the 45 deg direction.
132*	117	Hertz, J., et al.	1972	L	79–449	NO588	Similar to the above specimen and conditions; zero-point correction -0.001%.
133*	117	Hertz, J., et al.	1972	L	79–449	NO590	Similar to the above specimen and conditions; expansion in 0 deg direction.
134*	117	Hertz, J., et al.	1972	L	79–452	NO591	Similar to the above specimen and conditions.
135*	117	Hertz, J., et al.	1972	L	131–450	NO593	Similar to the above specimen and conditions; expansion for $[0_2^\circ/\pm 45^\circ]_s$ in 0 deg direction.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
136*	117	Hertz, J., Christian, J. L., and Varlas, M.	1972	L	76–450	NO597	Similar to the above specimen and conditions.
137*	117	Hertz, J., et al.	1972	L	74–448	NO599	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.001%.
138*	117	Hertz, J., et al.	1972	L	76–446	NO600	Similar to the above specimen and conditions; zero-point correction 0.002%.
139*	117	Hertz, J., et al.	1972	L	83–451	NO538	Celanese GY-70/Courtaulds HM-S/Faberite X-904; panel 0C15-L-CC2; expansion for unidirectional lay up in 0 deg direction.
140*	117	Hertz, J., et al.	1972	L	83–450	NO539	Similar to the above specimen and conditions.
141*	117	Hertz, J., et al.	1972	L	80–451	NO565	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.002%.
142*	117	Hertz, J., et al.	1972	L	80–408	NO540	Similar to the above specimen and conditions; zero-point correction -0.001%.
143*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 709	Similar to the above specimen and conditions; panel 70-HMS-E-2, Batch 1A-13; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.001%.
144*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 710	Similar to the above specimen and conditions.
145*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 712	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.02%.
146*	117	Hertz, J., et al.	1972	L	77–450	Specimen No. 713	Similar to the above specimen and conditions; zero-point correction 0.001%.
147*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 724	Similar to the above specimen and conditions; specimen water boiled for 24 hr; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.003%.
148*	117	Hertz, J., et al.	1972	L	89–450	Specimen No. 729	Similar to the above specimen and conditions; zero-point correction -0.001%.
149*	117	Hertz, J., et al.	1972	L	78–448	Specimen No. 726	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.007%.
150*	117	Hertz, J., et al.	1972	L	78–450	Specimen No. 727	Similar to the above specimen and conditions; zero-point correction 0.002%.
151*	117	Hertz, J., et al.	1972	L	80–450	NO630	Good Year random molded HT-S/X-904 laminate; expansion in 0 deg direction.
152*	117	Hertz, J., et al.	1972	L	79–453	NO634	Similar to the above specimen and conditions; zero-point correction -0.001%.
153*	117	Hertz, J., et al.	1972	L	80–451	NO632	Similar to the above specimen; expansion in 30 deg direction; zero-point correction 0.01%.
154*	117	Hertz, J., et al.	1972	L	76–451	NO631	Similar to the above specimen and conditions; zero-point correction 0.005%.

* Not shown in figure.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$
CURVE 1*	
293	0.000
323	0.008
CURVE 2*	
293	0.000
323	0.008
CURVE 3	
289	0.000
293	0.000
298	0.000
310	0.000
323	-0.001
330	-0.001
335	-0.001
348	-0.002
360	-0.003
367	-0.004
373	-0.004
385	-0.005
398	-0.006
410	-0.007
423	-0.008
435	0.009
445	-0.010
CURVE 4	
445	-0.006
435	-0.006
423	-0.006
410	-0.005
398	-0.005
385	-0.005
373	-0.005
367	-0.004
360	-0.004
348	-0.003
335	-0.002
323	-0.001
317	-0.001
310	0.000
298	0.000
293	0.000
290	0.000

T	$\Delta L/L_0$
CURVE 5	
290	0.00008
293	0.00000
298	-0.00009
310	-0.0005
317	-0.0008
323	-0.0012
335	-0.0023
348	-0.0033
353	-0.0037
360	-0.0042
366	-0.0044
373	-0.0046
385	-0.0048
390	-0.0049
398	-0.0052
410	-0.0060
423	-0.0070
435	-0.0079
445	-0.0087
CURVE 6	
445	-0.0072
435	-0.0066
423	-0.0058
410	-0.0050
398	-0.0042
385	-0.0036
373	-0.0036
367	-0.0035
360	-0.0033
348	-0.0028
335	-0.0021
323	-0.0014
310	-0.0007
298	-0.0002
293	0.00000
288	0.00002
CURVE 7	
293	0.000
297	0.013
310	0.062
323	0.106
335	0.156
348	0.211

T	$\Delta L/L_0$
CURVE 7 (cont.)	
360	0.268
373	0.328
385	0.384
398	0.446
410	0.504
423	0.553
431	0.575
435	0.590
441	0.597
445	0.601
448	0.601
452	0.596
454	0.571
CURVE 8	
454	0.870
454	0.846
452	0.824
448	0.781
435	0.688
423	0.613
410	0.541
398	0.474
385	0.408
373	0.344
360	0.293
348	0.241
335	0.185
323	0.135
310	0.083
298	0.028
295	0.011
293	0.000
CURVE 9	
293	0.000
300	0.026
310	0.062
323	0.105
335	0.152
348	0.204
360	0.255
373	0.310
385	0.374
398	0.447

T	$\Delta L/L_0$
CURVE 9 (cont.)	
410	0.519
423	0.594
435	0.674
448	0.752
CURVE 10	
447	0.801
435	0.734
423	0.652
410	0.570
398	0.485
385	0.410
373	0.345
360	0.292
348	0.244
335	0.198
323	0.153
310	0.089
308	0.070
293	0.000
CURVE 11	
293	0.0000
306	0.0005
308	0.0006
310	0.0006
362	0.0022
363	0.0022
365	0.0023
416	0.0041
417	0.0041
419	0.0042
CURVE 12*	
293	0.000
297	0.013
306	0.035
312	0.052
323	0.091
335	0.135
348	0.179

T	$\Delta L/L_0$
CURVE 12 (cont.)*	
360	0.225
372	0.277
379	0.305
385	0.323
389	0.332
395	0.338
400	0.338
404	0.327
408	0.312
410	0.302
413	0.377
415	0.251
417	0.242
418	0.240
423	0.236
426	0.236
431	0.246
436	0.260
441	0.284
447	0.320
CURVE 13	
447	0.796
445	0.746
443	0.707
440	0.677
435	0.654
427	0.606
423	0.586
410	0.469
400	0.388
398	0.371
385	0.314
373	0.265
360	0.228
348	0.185
335	0.143
323	0.099
310	0.057
297	0.014
293	0.000
CURVE 14	
293	0.000
297	0.014

T	$\Delta L/L_0$
CURVE 14 (cont.)	
310	0.061
323	0.102
335	0.149
348	0.189
360	0.231
373	0.269
385	0.319
398	0.368
410	0.428
423	0.470
429	0.545
435	0.596
448	0.688
CURVE 15	
448	0.703
443	0.642
435	0.573
431	0.537
423	0.482
410	0.416
398	0.358
385	0.313
373	0.263
360	0.218
348	0.181
335	0.147
323	0.104
310	0.064
297	0.018
293	0.000
CURVE 16	
293	0.0000
305	-0.0006
307	-0.0007
309	-0.0008
361	-0.0066
363	-0.0068
365	-0.0070
416	-0.0142
418	-0.0144
420	-0.0146
445	-0.0171
447	-0.0172
449	-0.0172

* Not shown in figure.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 17*		CURVE 21*		CURVE 25*		CURVE 29*		CURVE 33*		CURVE 36 (cont.)	
293	0.0000	423	0.0064	423	0.0057	293	0.0000	293	0.0000	385	0.266
307	0.0010	410	0.0059	410	0.0051	298	0.0003	298	0.0002	398	0.313
308	0.0011	398	0.0053	398	0.0047	310	0.0010	310	0.0008	402	0.329
310	0.0012	373	0.0042	373	0.0037	323	0.0015	323	0.0014	407	0.348
362	0.0048	348	0.0032	348	0.0027	335	0.0020	335	0.0020	410	0.361
363	0.0049	335	0.0026	335	0.0022	348	0.0025	348	0.0026		
365	0.0050	323	0.0021	323	0.0018	373	0.0035	373	0.0038	CURVE 37	
417	0.0087	310	0.0015	310	0.0012	398	0.0045	398	0.0051		
419	0.0088	298	0.0006	298	0.0004	410	0.0050	410	0.0057	410	0.405
420	0.0089	293	0.0000	293	0.0000	424	0.0065	423	0.0063	407	0.392
										402	0.372
CURVE 18		CURVE 22*		CURVE 26		CURVE 30*		CURVE 34		398	0.356
										385	0.305
293	0.0000	293	0.0000	293	0.0000	424	0.0050	293	0.0000	373	0.260
298	0.0003	298	0.0002	298	0.0003	410	0.0045	298	0.0002	360	0.212
310	0.0009	310	0.0007	310	0.0008	398	0.0040	310	0.0003	348	0.170
323	0.0016	323	0.0010	323	0.0012	373	0.0031	323	-0.0004	335	0.125
335	0.0023	335	0.0014	335	0.0016	348	0.0022	335	-0.0011	323	0.086
348	0.0029	348	0.0017	348	0.0021	335	0.0017	348	-0.0021	310	0.047
373	0.0043	373	0.0023	373	0.0029	323	0.0013	360	-0.0030	298	0.013
398	0.0056	398	0.0030	398	0.0038	310	0.0008	373	-0.0041	293	0.000
410	0.0063	410	0.0033	410	0.0043	298	0.0002	385	-0.0051		
420	0.0068	423	0.0036	423	0.0048	293	0.0000	398	-0.0063	CURVE 38*,†	
								410	-0.0074		
CURVE 19		CURVE 23*		CURVE 27*		CURVE 31*				353	0.000
								CURVE 35		393	-0.005
420	0.0063	423	0.0002	293	0.0000	293	0.0000				
410	0.0057	410	-0.0001	398	0.0003	298	0.0002	410	-0.0108	CURVE 39*,†	
398	0.0051	398	-0.0003	310	0.0008	310	0.0008	398	-0.0096		
373	0.0038	373	-0.0007	323	0.0014	323	0.0013	385	-0.0083	353	0.000
348	0.0025	348	-0.0008	335	0.0018	335	0.0018	373	-0.0071	393	0.000
335	0.0018	335	-0.0008	348	0.0024	348	0.0024	360	-0.0058		
323	0.0012	323	-0.0007	373	0.0034	373	0.0034	348	-0.0045	CURVE 40*,†	
310	0.0006	310	-0.0006	398	0.0044	398	0.0055	335	-0.0032		
298	0.0001	298	-0.0002	410	0.0049	410	0.0050	323	-0.0018	353	0.000
293	0.0000	293	0.0000	421	0.0053	424	0.0056	310	-0.0003	393	0.019
								298	0.0002		
CURVE 20		CURVE 24*		CURVE 28*		CURVE 32*		293	0.0000	CURVE 41*,†	
293	0.0000	293	0.0000	421	0.0043	424	0.0053	CURVE 36		353	0.000
298	0.0002	298	0.0003	410	0.0039	410	0.0047			393	0.043
310	0.0008	310	0.0008	398	0.0034	398	0.0041	293	0.000		
323	0.0013	323	0.0012	373	0.0025	373	0.0030	298	0.011	CURVE 42*,†	
335	0.0018	335	0.0016	348	0.0017	348	0.0020	310	0.038		
348	0.0023	348	0.0021	335	0.0012	335	0.0015	323	0.072	353	0.000
373	0.0033	373	0.0031	323	0.0009	323	0.0010	335	0.106	393	0.077
398	0.0044	398	0.0040	310	0.0005	310	0.0005	348	0.145		
410	0.0049	410	0.0045	298	0.0002	298	0.0001	360	0.183		
423	0.0055	423	0.0050	293	0.0000	293	0.0000	373	0.225		

* Not shown in figure.

† This curve is here reported using the first given temperature as reference temperature at which $\Delta L/L_0 = 0$.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 43*,†	
353	0.000
393	0.149
CURVE 44*,†	
353	0.000
393	0.231
CURVE 45*,†	
353	0.0000
393	-0.0084
CURVE 46*,†	
353	0.0000
393	-0.0052
CURVE 47*,†	
353	0.0000
393	0.0242
CURVE 48*,†	
353	0.0000
393	0.0474
CURVE 49*,†	
353	0.0000
393	0.1162
CURVE 50*,†	
353	0.0000
393	0.2008
CURVE 51*,†	
353	0.0000
393	0.2456
CURVE 52*	
243	-0.128
293	0.000
303	0.026

T	$\Delta L/L_0$
CURVE 53*	
243	-0.101
293	0.000
303	0.020
CURVE 54*	
243	-0.082
293	0.000
303	0.016
CURVE 55*	
243	-0.061
293	0.000
303	0.012
CURVE 56*	
243	-0.132
293	0.000
303	0.026
CURVE 57*	
243	-0.096
293	0.000
303	0.020
CURVE 58*	
243	-0.067
293	0.000
303	0.013
CURVE 59*	
243	-0.067
293	0.000
303	0.013
CURVE 60*	
243	-0.244
293	0.000*
303	0.049

T	$\Delta L/L_0$
CURVE 61*	
243	-0.180
293	0.000
303	0.036
CURVE 62*	
243	-0.133
293	0.000
303	0.027
CURVE 63*	
243	-0.111
293	0.000
303	0.022
CURVE 64*	
243	-0.233
293	0.000
303	0.047
CURVE 65	
78	0.0067
116	0.0058
145	0.0050
197	0.0036
225	0.0028
338	-0.0028
365	-0.0050
395	-0.0080
449	-0.0130
476	-0.0146
507	-0.0154
538	-0.0171
561	-0.0164
CURVE 66	
77	-0.428
297	0.011
560	0.763
CURVE 67*	
84	-0.0032
115	-0.0037

T	$\Delta L/L_0$
CURVE 67 (cont.)*	
142	-0.0037
172	-0.0036
200	-0.0024
227	-0.0024
255	-0.0007
293	0.0000
331	0.0002
365	0.0011
CURVE 68	
77	-0.463
297	0.019
450	0.785
CURVE 69	
79	0.0059
131	0.0052
173	0.0044
215	0.0036
256	0.0011
297	-0.0001
340	-0.0009
366	-0.0027
408	-0.0041
450	-0.0051
CURVE 70	
79	0.0079
131	0.0072
173	0.0056
215	0.0039
256	0.0019
297	-0.0001
340	-0.0010
367	-0.0022
409	-0.0038
450	-0.0055
CURVE 71*	
227	-0.0101
255	-0.0055
326	0.0043
367	0.0096

T	$\Delta L/L_0$
CURVE 72	
77	-0.376
131	-0.305
172	-0.236
214	-0.167
254	-0.090
297	0.001
337	0.103
366	0.173
407	0.301
448	0.449
CURVE 73	
77	-0.392
131	-0.317
172	-0.249
212	-0.178
255	-0.090
337	0.103
366	0.174
407	0.301
448	0.449
CURVE 74	
77	-0.401
131	-0.317
172	-0.249
212	-0.178
255	0.090
337	0.103
366	0.174
407	0.301
448	0.449
CURVE 75*	
200	-0.215
224	-0.166
250	-0.111
289	-0.018
346	0.128
370	0.203
384	0.245
405	0.328
411	0.349
425	0.404
434	0.430

T	$\Delta L/L_0$
CURVE 76*	
77	-0.0364
129	-0.0277
171	-0.0217
214	-0.0152
252	-0.0076
293	0.0000
338	0.0082
365	0.0147
406	0.0273
450	0.0407
CURVE 77*	
77	-0.0271
130	-0.0212
171	-0.0160
212	-0.0110
252	-0.0059
293	0.0000
338	0.0084
364	0.0148
406	0.0273
450	0.0409
CURVE 78*	
77	-0.074
297	0.002
450	0.045
CURVE 79*	
77	-0.0388
297	-0.0012
450	-0.0504
CURVE 80*	
77	-0.0345
130	-0.0268
172	-0.0198
214	-0.0140
253	-0.0086
339	0.0071
366	0.0131
407	0.0233
451	0.0349

* Not shown in figure.
† This curve is here reported using the first given temperature as reference temperature at which $\Delta L/L_0 = 0$.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 81*	
77	-0.218
297	0.007
450	0.291
CURVE 82	
77	0.0094
129	0.0085
171	0.0079
212	0.0055
255	0.0036
339	-0.0038
366	-0.0078
410	-0.0097
448	-0.0099
CURVE 83*	
77	-0.450
297	0.013
450	0.517
CURVE 84	
75	0.0121
129	0.0107
169	0.0085
213	0.0047
255	0.0020
293	0.0000
341	-0.0011
366	-0.0017
413	-0.0025
457	-0.0028
CURVE 85	
453	-0.0034
411	-0.0032
367	-0.0026
340	0.0018
298	0.0000
75	0.0122
CURVE 86*	
77	-0.523
297	0.008
450	0.585
CURVE 87	
79	-0.0094
132	-0.0106
174	-0.0081
216	-0.0060
257	-0.0034
297	0.0003
340	0.0034
369	0.0061
409	0.0114
451	0.0214
CURVE 88*	
76	-0.0197
131	-0.0168
172	-0.0134
214	-0.0084
256	-0.0045
293	0.0000
339	0.0060
365	0.0101
409	0.0199
451	0.0263
451	0.0306
CURVE 89*	
79	-0.0205
131	-0.0171
171	-0.0129
215	-0.0101
255	-0.0051
293	0.0000
340	0.0055
367	0.0079
409	0.0172
CURVE 90	
77	0.0109
297	-0.0002
560	-0.0185
CURVE 91	
77	-0.517
297	0.014
560	1.000
CURVE 92*	
§	
CURVE 93*	
95	-0.257
106	-0.247
115	-0.238
126	-0.227
135	-0.217
146	-0.205
156	-0.193
167	-0.179
177	-0.167
188	-0.153
198	-0.140
207	-0.128
215	-0.116
225	-0.102
234	-0.089
246	-0.072
255	-0.058
265	-0.043
293	0.000
299	0.009
309	0.026
316	0.038
319	0.043
326	0.056
329	0.062
338	0.080
345	0.094
347	0.099
356	0.120
358	0.125
370	0.157
376	0.175
382	0.195
394	0.240
401	0.271
CURVE 94*	
81	-0.529
92	-0.510
100	-0.495
109	-0.478
120	-0.457
130	-0.436
140	-0.414
CURVE 94 (cont.)*	
150	-0.392
161	-0.366
172	-0.340
183	-0.314
193	-0.290
201	-0.270
210	-0.247
219	-0.223
225	-0.206
234	-0.179
242	-0.155
255	-0.115
264	-0.088
293	0.000
300	0.023
311	0.060
319	0.089
323	0.103
332	0.137
347	0.199
355	0.236
363	0.275
372	0.322
378	0.361
389	0.424
CURVE 95	
255.2	-0.0005
269.7	-0.0005
298.0	0.0002
298.6	0.0002
299.4	0.0002
339.0	0.0017
CURVE 96*	
255.4	-0.0008
268.7	-0.0004
273.2	-0.0004
299.2	0.0001
300.7	0.0001
339.2	0.0002
CURVE 97*	
255.4	-0.0004
269.7	-0.0002
299.2	0.0001
CURVE 97 (cont.)*	
300.2	0.0001
339.0	0.0001
CURVE 98*	
255.4	-0.330
268.5	-0.170
269.7	-0.170
296.0	0.010
299.7	0.030
300.7	0.030
339.2	0.209
CURVE 99*	
239	-0.0049
277	-0.0014
311	0.0016
344	0.0046
CURVE 100	
239	-0.213
277	-0.059
311	0.067
344	0.175
CURVE 101	
278	0.0002
313	-0.0003
CURVE 102*	
278	0.0005
313	-0.0006
CURVE 103*	
278	-0.078
313	0.104
CURVE 104*	
278	-0.0016
313	0.0022
CURVE 105*	
278	-0.0011
313	0.0015
CURVE 106*	
278	-0.099
313	0.132
CURVE 107*	
80	0.0076
133	0.0059
160	0.0043
215	0.0023
256	-0.0013
299	-0.0001
341	-0.0028
366	-0.0025
450	-0.0094
CURVE 108*	
80	0.0081
174	0.0053
215	0.0036
256	0.0016
300	-0.0001
366	-0.0024
410	-0.0028
450	-0.0035
CURVE 109*	
78	0.0023
133	0.0023
174	0.0024
215	0.0022
255	0.0008
298	0.0000
339	-0.0006
370	-0.0006
409	0.0023
450	0.0058
CURVE 110*	
78	0.0023
131	0.0016
174	0.0011

* Not shown in figure.
§ No experimental data tabulated, see Specification Table.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 110 (cont.)*	
215	0.0006
255	0.0002
298	0.0000
340	-0.0007
366	-0.0018
409	-0.0028
450	0.0014
CURVE 111*	
89	0.0031
131	0.0043
173	0.0025
215	0.0024
255	0.0012
299	0.0000
340	-0.0012
366	-0.0015
409	-0.0007
450	0.0015
CURVE 112*	
79	0.0023
130	0.0024
171	0.0036
214	0.0016
255	0.0007
297	0.0000
338	-0.0002
367	0.0000
407	0.0005
450	0.0022
CURVE 113*	
79	-0.4430
130	-0.3574
171	-0.2760
213	-0.2080
255	-0.1067
298	0.0149
338	0.1424
365	0.2429
407	0.4130
450	0.5850

T	$\Delta L/L_0$
CURVE 114*	
79	-0.4388
130	-0.3484
171	-0.2790
213	-0.2041
255	-0.0966
298	0.0119
338	0.1474
365	0.2464
407	0.4100
450	0.5831
CURVE 115*	
78	-0.472
131	-0.396
171	-0.308
214	-0.207
255	-0.094
298	0.015
339	0.154
366	0.259
409	0.435
450	0.625
CURVE 116*	
76	-0.521
131	-0.421
172	-0.337
214	-0.229
255	-0.111
297	0.014
339	0.159
366	0.266
409	0.435
450	0.635
CURVE 117*	
78	-0.534
130	-0.423
172	-0.341
214	-0.226
255	-0.108
297	0.040
339	0.188
366	0.284
408	0.462
450	0.674

T	$\Delta L/L_0$
CURVE 118*	
78	-0.605
130	-0.504
172	-0.402
214	-0.294
255	-0.154
297	0.020
339	0.171
366	0.279
408	0.453
450	0.657
CURVE 119*	
86	-0.0712
133	-0.0580
174	-0.0460
217	-0.0335
258	-0.0165
301	-0.0006
336	0.0147
370	0.0294
412	0.0483
455	0.0673
CURVE 120*	
84	-0.0240
131	-0.0169
176	-0.0126
216	-0.0082
257	-0.0043
300	0.0010
334	0.0060
369	0.0091
411	0.0125
457	0.0179
CURVE 121*	
84	-0.0223
131	-0.0171
173	-0.0117
215	-0.0080
257	-0.0039
300	0.0000
334	0.0042
369	0.0066
411	0.0109
456	0.0146

T	$\Delta L/L_0$
CURVE 122*	
84	-0.0515
132	-0.0401
174	-0.0303
217	-0.0214
258	-0.0114
336	0.0094
370	0.0159
411	0.0281
452	0.0408
CURVE 123*	
81	0.0080
132	0.0069
173	0.0068
215	0.0048
255	0.0029
298	0.0000
339	-0.0022
366	-0.0038
407	-0.0064
450	-0.0095
CURVE 124*	
81	0.0010
130	0.0013
171	0.0020
212	0.0008
254	0.0001
298	0.0000
336	-0.0011
364	-0.0019
406	-0.0041
450	-0.0067
CURVE 125*	
80	-0.169
130	-0.134
173	-0.104
216	-0.071
255	-0.035
299	0.006
340	0.050
366	0.083
409	0.132
444	0.172

T	$\Delta L/L_0$
CURVE 126*	
80	-0.175
130	-0.141
174	-0.109
216	-0.076
255	-0.042
299	0.006
340	0.056
366	0.091
409	0.145
444	0.208
CURVE 127*	
79	0.0250
129	0.0214
172	0.0175
213	0.0123
254	0.0065
298	0.0019
339	-0.0025
366	-0.0041
408	-0.0061
450	-0.0123
CURVE 128*	
79	0.0205
130	0.0181
173	0.0138
214	0.0087
255	0.0041
298	-0.0019
340	-0.0050
366	-0.0071
408	-0.0100
450	-0.0156
CURVE 129*	
80	-0.491
132	-0.400
174	-0.314
214	-0.213*
255	-0.100
299	0.018*
340	0.173*
367	0.289*
408	0.463*
450	0.653*

T	$\Delta L/L_0$
CURVE 130*	
79	-0.501
129	-0.410
172	-0.321
213	-0.212
254	-0.100
296	0.031
338	0.175
364	0.288
405	0.448
446	0.628
CURVE 131*	
78	-0.0036
130	-0.0026
173	-0.0020
229	-0.0025
258	-0.0014
302	0.0001
340	0.0025
368	0.0047
409	0.0069
450	0.0094
CURVE 132*	
79	0.0150
131	0.0122
174	0.0092
214	0.0060
255	0.0023
299	-0.0005
339	-0.0046
367	-0.0066
409	-0.0094
449	-0.0120
CURVE 133*	
79	0.0180
131	0.0145
174	0.0115
214	0.0080
255	0.0041
299	0.0000
339	-0.0042
367	-0.0059
409	-0.0085
449	-0.0113

* Not shown in figure.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
CURVE 134*	
79	0.0012
131	0.0009
173	0.0013
219	0.0005
259	-0.0003
302	0.0001
341	0.0002
369	0.0006
411	0.0013
452	0.0025
CURVE 135*	
131	0.0197
173	0.0153
215	0.0091
255	0.0043
340	-0.0059
366	-0.0072
409	-0.0114
450	-0.0155
CURVE 136*	
76	0.0187
131	0.0136
173	0.0117
215	0.0066
255	0.0026
297	0.0000
340	-0.0045
366	-0.0063
409	-0.0104
450	-0.0135
CURVE 137*	
74	0.021
128	0.020*
170	0.012*
212	-0.002
255	-0.012*
296	0.001*
338	0.005*
366	0.011*
406	0.029
448	0.062

T	$\Delta L/L_0$
CURVE 138*	
76	-0.042
130	-0.035
171	-0.028
214	-0.019
255	-0.011
296	0.002
336	0.020
366	0.036
406	0.066
446	0.107
CURVE 139*	
83	0.0125
131	0.0113
174	0.0087
215	0.0051
256	0.0021
300	-0.0000
335	-0.0015
366	-0.0040
408	-0.0050
451	-0.0084
CURVE 140*	
83	0.0135
130	0.0118
173	0.0101
215	0.0058
256	0.0031
300	0.0001
366	-0.0034
408	-0.0055
450	-0.0096
CURVE 141*	
80	-0.059
130	-0.048
173	-0.0409
214	-0.0254
255	-0.0117
298	0.002
340	0.0085
369	0.0200
410	0.0352
451	0.0417

T	$\Delta L/L_0$
CURVE 142*	
83	0.0185
130	0.0124
171	0.0083
214	0.0057
254	0.0026
298	-0.0010
333	0.0017
366	-0.0010
408	-0.0010
CURVE 143*	
78	0.0121
130	0.0099
173	0.0084
214	0.0054
255	0.0013
296	-0.0010
339	-0.0028
366	-0.0041
406	-0.0067
450	-0.0063
CURVE 144*	
78	0.0113
131	0.0101
159	0.0084
214	0.0052
255	0.0019
298	-0.0010
339	-0.0028
366	-0.0039
409	-0.0063
450	-0.0063
CURVE 145*	
78	-0.103
130	-0.090
173	-0.077
213	-0.063
255	-0.044
296	0.020
340	0.052
366	0.066
409	0.088
450	0.087

T	$\Delta L/L_0$
CURVE 146*	
77	-0.0420
130	-0.0290
172	-0.0217
214	-0.0129
255	-0.0046
297	0.0010
339	0.0182
366	0.0278
408	0.0439
450	0.0538
CURVE 147*	
78	0.0127
130	0.0110
172	0.0082
214	0.0051
255	0.0011
297	-0.0030
339	-0.0054
366	-0.0065
408	-0.0086
450	-0.0091
CURVE 148*	
89	0.0131
130	0.0100
172	0.0075
214	0.0046
255	0.0025
297	-0.0010
339	-0.0040
366	-0.0062
408	-0.0079
450	-0.0106
CURVE 149*	
78	-0.0260
132	-0.0187
174	-0.0137
214	-0.0074
255	-0.0017
296	0.0070
296	0.0439
338	0.0265
366	0.0368

T	$\Delta L/L_0$
CURVE 149 (cont.)*	
408	0.0589
448	0.0764
448	0.1058
CURVE 150*	
78	-0.0515
128	-0.0465
172	-0.0365
214	-0.0230
255	-0.0111
297	0.0020
339	0.0136
366	0.0345
450	0.0631
450	0.0814
CURVE 151*	
80	-0.0053
130	-0.0100
173	-0.0154
216	-0.0129
255	-0.0060
300	0.0000
340	0.0028
368	0.0093
412	0.0177
450	0.0219
CURVE 152*	
79	0.025
131	0.017
173	0.010
220	0.002
255	0.002
300	-0.001
340	-0.001
366	-0.002
411	-0.001
453	0.000
CURVE 153*	
80	-0.164
132	-0.142
173	-0.120

T	$\Delta L/L_0$
CURVE 153 (cont.)*	
215	-0.083
255	-0.042
298	0.011
338	0.062
366	0.100
408	0.169
451	0.257
CURVE 154*	
76	-0.110
132	-0.095
173	-0.077
215	-0.055
255	-0.026
298	0.003
338	0.041
366	0.069
409	0.124
451	0.199

* Not shown in figure.

e. Thermal Diffusivity

There are no experimental data available for the thermal diffusivity of graphite fiber epoxy composites.

In view of the difficulty of establishing the recommended values for the thermal conductivity, and of the fact that the thermal diffusivity of a composite is not a well-defined quantity, the calculation of the thermal diffusivity from specific heat, thermal conductivity, and density values has not been carried out.

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