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MEASUREMENT OF THE THERMAL PROPERTIES OF VARIOUS AIRCRAFT STRUCTURAL MATERIALS

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FOREWORD

This report was prepared by Southern Research Institute under USAF Contract No. AF 33(616)-3328, Supplement Agreement No. 2 (57-834). The contract was initiated under Project No. 7340, "Rubber, Plastic, and Composite Materials," Task No. 73400, "Structural Plastics." The work was administered under the director of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Capt. Frank Zaleski acting as project engineer.

This report covers the work conducted from January 1, 1957, to January 1, 1958.

ABSTRACT

Thermal expansion, specific heat, and thermal conductivity properties were measured for six structural panels and cores through a temperature range from -100 to 600° F. In addition, some physical tests were made on these materials. The materials covered in the investigation consisted of one asbestos-resin laminate, three fiberglass-resin laminates, and two fiberglass-resin fluted core sandwich panels.

The test procedures and equipment used in the thermal property evaluations are modifications of the procedure described in WADC TR 54-306 according to MIL and Federal specifications.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

L. F. SALZBERG
Chief, Materials
Physics Branch
Materials Laboratory

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

MEASUREMENT OF THE THERMAL PROPERTIES OF VARIOUS AIRCRAFT STRUCTURAL MATERIALS

INTRODUCTION

Some thermal and physical properties were determined for six structural panels. Thermal conductivity, specific heat, and thermal expansion data were collected through the temperature range of -100° F to 600° F on one asbestos-phenolic laminate, three fiberglass plastic laminates, and two fluted-core sandwich panels. The physical properties measured in this investigation consist of Barcol hardness, flexural strength, and resin content.

TEST MATERIALS

The following materials were tested in this investigation:

a. Laminate: X-1068 resin, 181 glass fabric

b. Laminate: X-131 resin, 181 glass fabric

c. Laminate: CTL 37-9X Modified Phenolic resin, 181 glass fabric

d. Laminate: Asbestos-Phenolic, Raybestos-Manhattan 9526D

e. Fluted core sandwich: Polyester, Selectron 5016 resin, 181 glass fabric

f. Fluted core sandwich: Epoxy, Shell X-131 resin, 181 glass fabric

The nominal thickness of all the laminates was 1/8 in. The Selectron 5016 fluted core measured 7/16 in. thick, and the Shell X-131 fluted core was nominally 5/8 in. thick. Table I provides detailed manufacturers' specifications on all test materials.

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Table I. Test Materials Specifications

Fabric No.	Finish	Resin Type	No. of Plies	Catalyst
181	Garan	Tac-Polyester Vibrin X-1068	13	1.5% Benzoyl Peroxide
181	Volan A	Epoxy, Shell X-131	12	13 parts/wt. Pyromellitic Dianhydride 19 parts/wt. Maleic Anhydride
[1] Raybestos-Manhattan 9526D	None Noted	Phenolic	3	
181	Volan A	Polyester Selectron - 5016	15 (both sides)	2% Benzoyl Peroxide
181	Volan A	Epoxy, Shell X-131	15 (one side) 11 (other side)	13 parts/wt. Maleic Anhydride
181	A-1100	Modified Phenolic CTL 37-9X	12	

[1] Most of this material was received without surface resin. The sheet had been fabricated and the surface then sanded.

Note: Brunswick-Balke-Collender Company fabricated all materials.

Table I. Test Materials Specifications (continued)

Fabric No.	Flute Size	Density lb/ft^3	Curing Process
181	---	112	200° F - 12 hours } under vacuum 250° F - 3 hours } under vacuum Postcure 300° F - 1 hour 350° F - 5 hours 400° F - 1 hour
181	---	117	200° F - 2 hours at 25 psi 300° F - 4 hours
Raybestos-Manhattan 9526D	---	78	300° F - 1/2 hour at 400 psi Postcure 300° F - 4 hours 350° F - 8 hours
181	0.143" thick 0.375" wide 0.0075" wall thickness	105	250° F - 5 hours
181	0.300" wide 0.350" thick 0.0075" wall thickness	124	200° F - 2 hours under vacuum Postcure 300° F - 4 hours
181	---	103[2] (approximately)	280° F - 1/2 hour at 175 psi Postcure 250° F - 24 hours 300° F - 24 hours 350° F - 24 hours 400° F - 24 hours

[2] Calculated value.

SAMPLE PREPARATION

Specific heat specimens were prepared by cutting out 1 in. by 1 in. squares the same thickness as the sheet. The laminates were built up into multiple thicknesses in order to increase the mass and improve the test accuracy. The multiple thickness samples were held together by 1/8 in. diameter pins made from the same test panel.

Thermal expansion specimens were prepared by cutting samples in the plane of the sheet 1 in. wide by 7 in. long. These samples were cut in three directions with respect to the fabric lay up — longitudinal, transverse, and diagonal. The specimen ends were rounded to a two-inch radius in order to insure point contact during the tests. The laminates were built up in multiple thicknesses similar to the specific heat samples to prevent bending during the tests. A thermocouple well was drilled in the center of the sample.

Thickness expansion specimens were prepared by cutting 1 in. diameter disks from the sheet with a hole saw. The frayed edges were then sanded smooth and the disks stacked to an adequate height to produce measurably large expansion values.

Thermal conductivity specimens were prepared by simply cutting two samples, 14 inches square, from each material. The CTL 37-9X laminate could not be furnished in widths larger than 11 inches so that this specimen measured 11 inches square.

Flexural specimens were cut in accordance with Federal specification LP-406. The dimensions for these specimens are presented in Table II.

PHYSICAL PROPERTIES

Flexural strength, Barcol hardness, and resin content tests were conducted on all the materials in accordance with Federal specification LP-406(b).

Flexural Strength

Five flexural strength specimens were cut from each panel in the longitudinal direction of the panel. The flutes of the fluted core panels were in the longitudinal direction. All flexural tests were conducted on a Baldwin Universal Testing Machine at a crosshead speed of approximately 0.25 in./min. The ultimate flexural strength was calculated from the formula:

$$S = \frac{mc}{I}$$

where

S = maximum fiber stress, psi

m = moment produced by the load at the point of loading, inch-pounds

c = 1/2 thickness of specimen, in.

I = moment of inertia of beam cross-section, in.^4

A comparison of the flexural strength properties (Table II) and resin content (Table IV) indicates a correlation between the two properties, regardless of the type of resin or fabric. For example, the Shell X-131 panels, in both the fluted core and laminate forms, exhibited the highest strength and also contained the highest resin content. The asbestos phenolic panel had both the lowest strength and the lowest resin content among all the laminates. Experience shows, however, that an optimum resin content exists for maximum flexural strength in a laminate system. The optimum resin content may vary from one laminate system to another.

All the laminate panels failed in either tension or compressions. Some laminates failed due to simultaneous tension and compression fractures. The fluted core panels, however, failed in shear rather than tension or compression. Shear occurred between the ribs of the flutes and the skin sections and also within the ribs themselves. Since the strength tests proved to be a measure of the rib strength or of the rib-to-skin bond, the ultimate flexural strength formula does not apply. However, the strength of the fluted core sandwich in terms of component skin and core properties may be determined by appropriate formulas in MIL-STD-401A and in the ANC-23 bulletin.

Table II. Flexural Strength Data

Sample	b Width of Beam	d Depth of Beam	L Length of Span	P Load Lbs	S Psi	Average S Psi
X-1068	.520	.123	4.00	60	45,500	
	.516	.124	4.00	68	51,400	
	.535	.124	4.00	65	47,500	
	.525	.124	4.00	60	44,500	
	.518	.123	4.00	65	45,700	46,900
Shell X-131 Laminate	.530	.138	4.00	95	56,300	
	.533	.138	4.00	95	55,800	
	.535	.138	4.00	100	58,700	
	.524	.137	4.00	95	57,000	
	.520	.138	4.00	95	57,400	57,040
Asbestos-Phenolic 9526D Laminate	.518	.085	4.00	30	48,200	
	.540	.096	4.00	32	38,500	
	.520	.085	4.00	28	44,700	
	.513	.088	4.00	30	45,300	
	.521	.104	4.00	34	36,300	42,600
CTL 37-9X	.533	.155	4.00	100	47,000	
	.514	.152	4.00	78	38,700	
	.528	.152	4.00	96	47,000	
	.523	.155	4.00	95	47,500	
	.510	.153	4.00	90	45,000	45,400
Selectron 5016 Fluted Core	.890	.443	7.00	310	18,600	
	.895	.443	7.00	320	19,100	
	.870	.443	7.00	285	17,500	
	.902	.437	7.00	255	15,500	
	.866	.442	7.00	270	16,700	17,480
Shell X-131 Fluted Core	1.014	.662	11.00	582	21,500	
	1.010	.660	11.00	585	21,800	
	1.000	.663	11.00	550	20,500	
	1.028	.662	11.00	700	25,500	
	1.000	.662	11.00	560	21,000	22,060

Barcol Hardness

The hardness of the surface finish was determined with a Barcol hardness tester. Data for the six test materials are presented in Table III.

The CTL 37-9X laminate had the lowest and widest range of Barcol hardness of the test materials.

The 9526D laminate yielded three ranges of hardness values obtained from three different areas in the test panel. Since only a very small area was furnished with the cured surface resin, essentially all of the test samples were taken from the sanded section.

Resin Content

Resin content data are presented in Table IV. Excluding the panels containing the X-131 resin, which ranged from 41 percent to 43 percent resin content, the glass fabric samples contained essentially the same percent resin content. The 9526D material had the lowest resin content.

SPECIFIC HEAT

Apparatus and Procedure

Specific heat determinations for these panels were made by means of a dry type adiabatic calorimeter consisting of a covered brass cup approximately 2-1/2 inches dia. by 2 inches deep. Three thermocouple wells were located in the bottom wall of the cup. The cup was mounted on cork supports which rested in a silver plated copper jacket. The jacket was immersed in a bath of ethylene glycol. The temperature of the bath was maintained at the temperature of the cup by means of a 1000 watt nichrome wire heater and a copper cooling coil immersed in the liquid. Chilled water was used to cool the bath below ambient when cold specific heat measurements were made. A double-bladed stirrer maintained uniform bath temperature.

A tubular furnace and a cold box were used to bring the specimens to temperature. By pivoting this equipment on a common post near the calorimeter, the samples could be transferred to a position directly over the calorimeter cup. At this position the specimen was released from a suspension assembly which was externally triggered. Thermocouples located near the specimen indicated specimen temperature.

Table III. Barcol Hardness Data

Sample No.	Barcol Hardness	Sample No.	Barcol Hardness
X-1068	63	CTL 37-9X	42
	63		42
	65		22
	68		54
	66		36
Average	65	Average	39
Shell X-131	63	Selectron 5016 fluted core	64
	63		61
	66		62
	63		56
	62		60
Average	63	Average	61
Asbestos-Phenolic 9526D (light brown finish samples)	14	Shell X-131 fluted core	56
	14		54
	17		59
	10		56
	8		59
Average	13	Average	57
Asbestos-Phenolic 9526D (areas with sanded finish)	[1]	Asbestos-Phenolic 9526D (areas with a resin finish)	55
			55
			58
			60
			56
		Average	57

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[1] Readings did not register on hardness tester.

Table IV. Resin Content Data

Sample	Drying Temp. ° F	Drying Time (hrs.)	Net Sample Weight (grams)	Net Resin Weight (grams)	% Resin Net Resin Wt x 100 / Total Sample Weight
X-1068	1100	6	11.6175	4.1264	34.5
X-131	1100	6	11.6705	4.8649	41.7
Asbestos-Phenolic 9526D	1100	6	8.6521	2.4642	28.5
Selectron 5016	1100	6	8.9881	3.0076	33.5
Shell X-131 Fluted Core	1100	6	9.7486	4.2332	43.4
CTL 37-9X	1100	6	7.3336	2.4287	33.1

Elevated specimen temperatures were maintained by a manual setting of a variable voltage transformer, which controlled the voltage of the furnace. Cold sample temperatures were obtained by filling the cold box with dry ice. Air was blown into the cold box chamber to insure temperature uniformity. The cold box consisted of two concentric cylinders enclosed in an insulated plywood box. The smaller cylinder (3 in. diameter by 16 in. high) was constructed of 1/4 inch mesh hardware cloth. The larger cylinder was made of galvanized sheet metal (15 in. diameter and 16 in. high). The annulus was filled with dry ice.

Three copper-constantan thermocouples, differentially connected between calorimeter cup and jacket, indicated temperature differences between cup and bath. The three thermocouples enabled a difference of 0.03° F to be detected. During the test runs, this difference was maintained to within 0.15° F. Absolute temperature measurements of the cup were determined by means of three thermocouple junctions, series connected, in the bottom of the calorimeter cup. All of the thermocouple readings were taken on a Leeds and Northrup K-2 potentiometer in conjunction with a galvanometer of 0.5 microvolts per mm deflection sensitivity. This setup permitted temperature measurements within 0.01° F.

Data and Results

Calibration of the calorimeter was made by using an electrolytic copper specimen of known specific heat, giving a constant of 0.2654 Btu/° F.

Specimens of the test materials were heated or cooled to the desired temperature, and following a stabilization period, were dropped into the calorimeter cup. Adiabatic conditions were maintained during each test by manually adjusting the cup guard bath temperature.

Determination of the specific heats consisted of measuring the enthalpy of the specimens as a function of the initial specimen temperature. From the equation of the enthalpy-temperature curve, the specific heat equations were derived as a function of temperature. A reference temperature of 85° F for the enthalpy determinations was used, and all enthalpy values were referred to this 85° F base.

The enthalpy of the specimen at any initial temperature is given by:

$$h_t = \frac{K}{W_S} (t_2 - t_1)$$

where K = calorimeter constant — 0.2654 Btu/°F
W_S = sample weight — lbs
t_1 = initial cup temperature — °F
t_2 = final cup temperature — °F

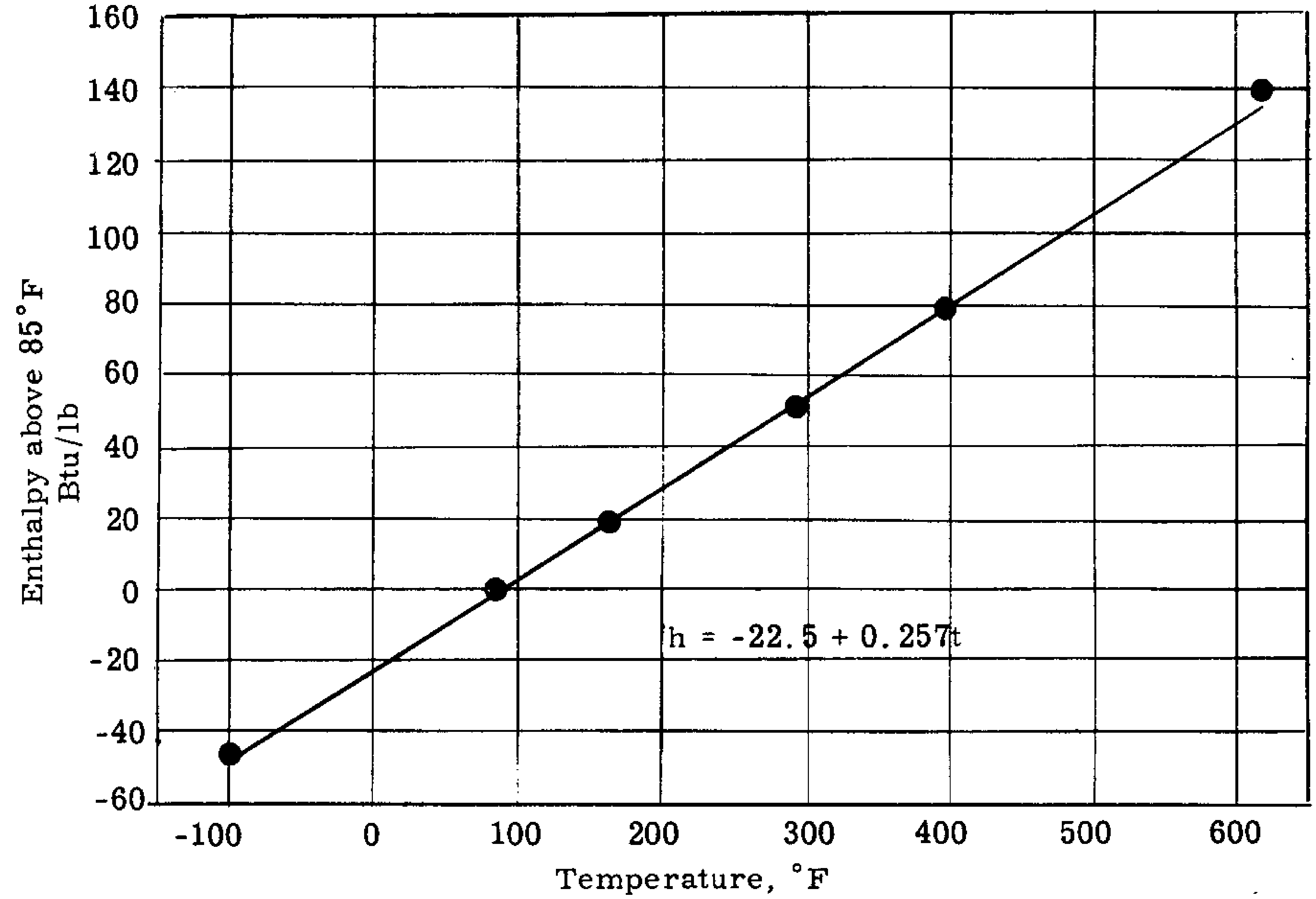

Figure 1. Heat Content Curve for X-1068 Laminate.

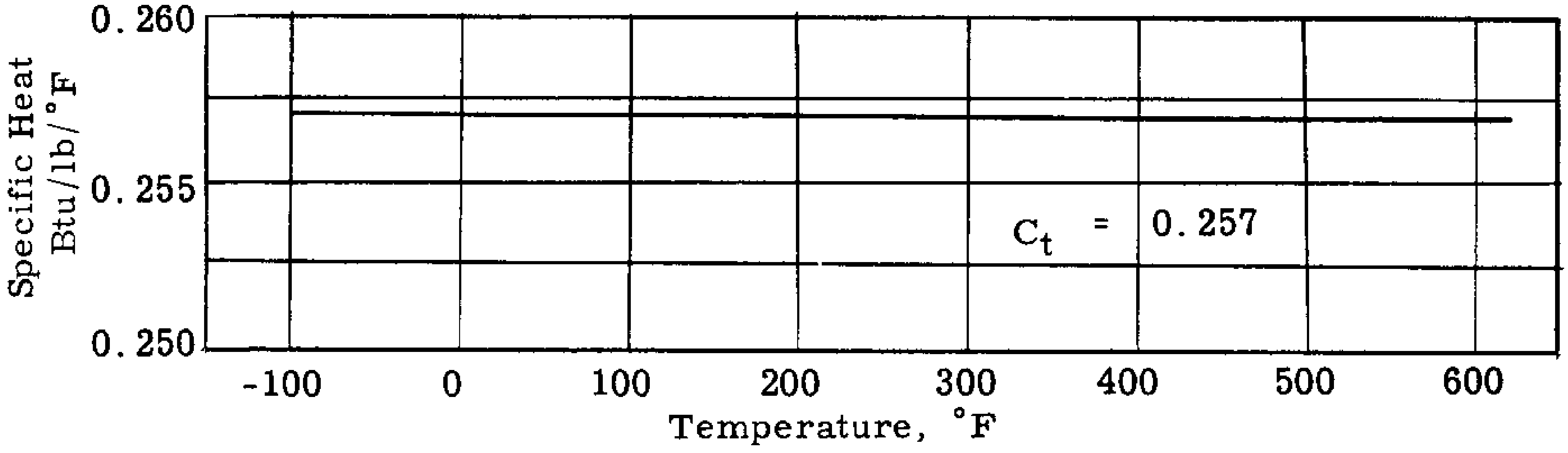

Figure 2. Specific Heat Versus Temperature for X-1068 Laminate.

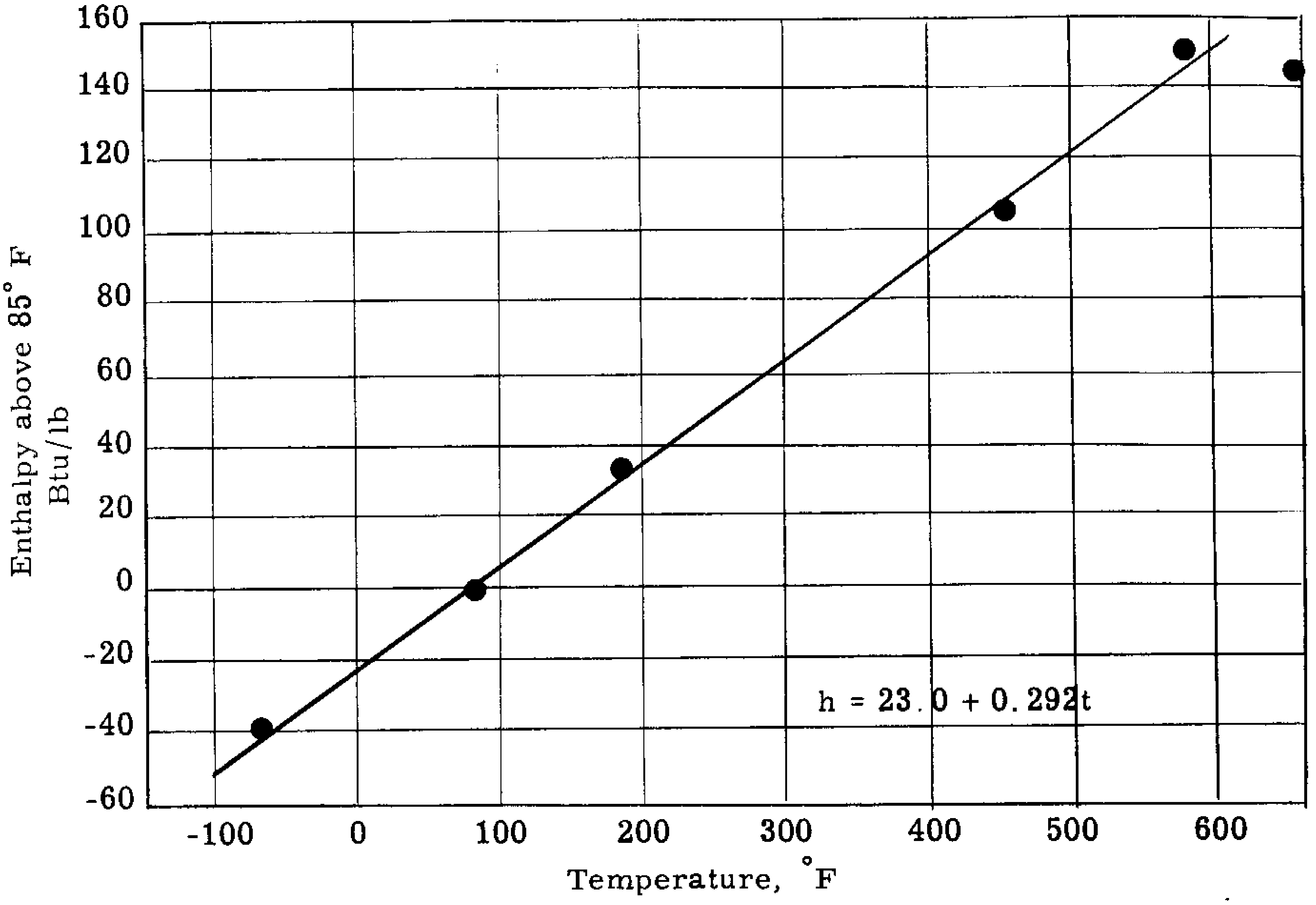

Figure 3. Heat Content Curve for Asbestos-Phenolic 9526D Laminate.

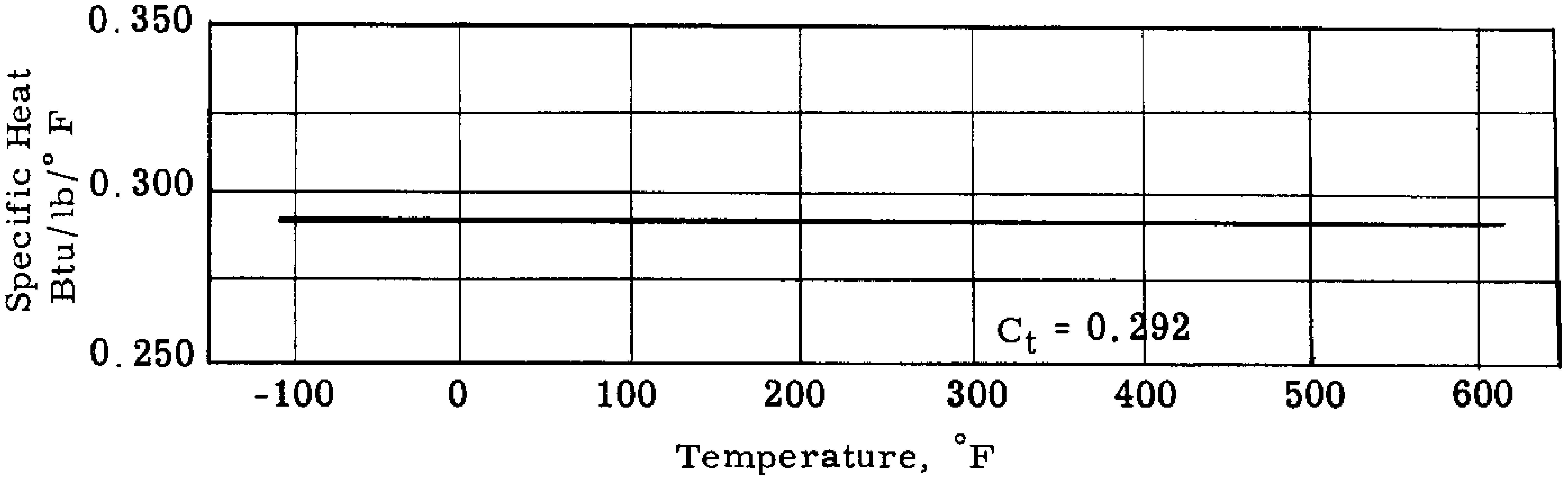

Figure 4. Specific Heat Versus Temperature for Asbestos-Phenolic 9526D Laminate.

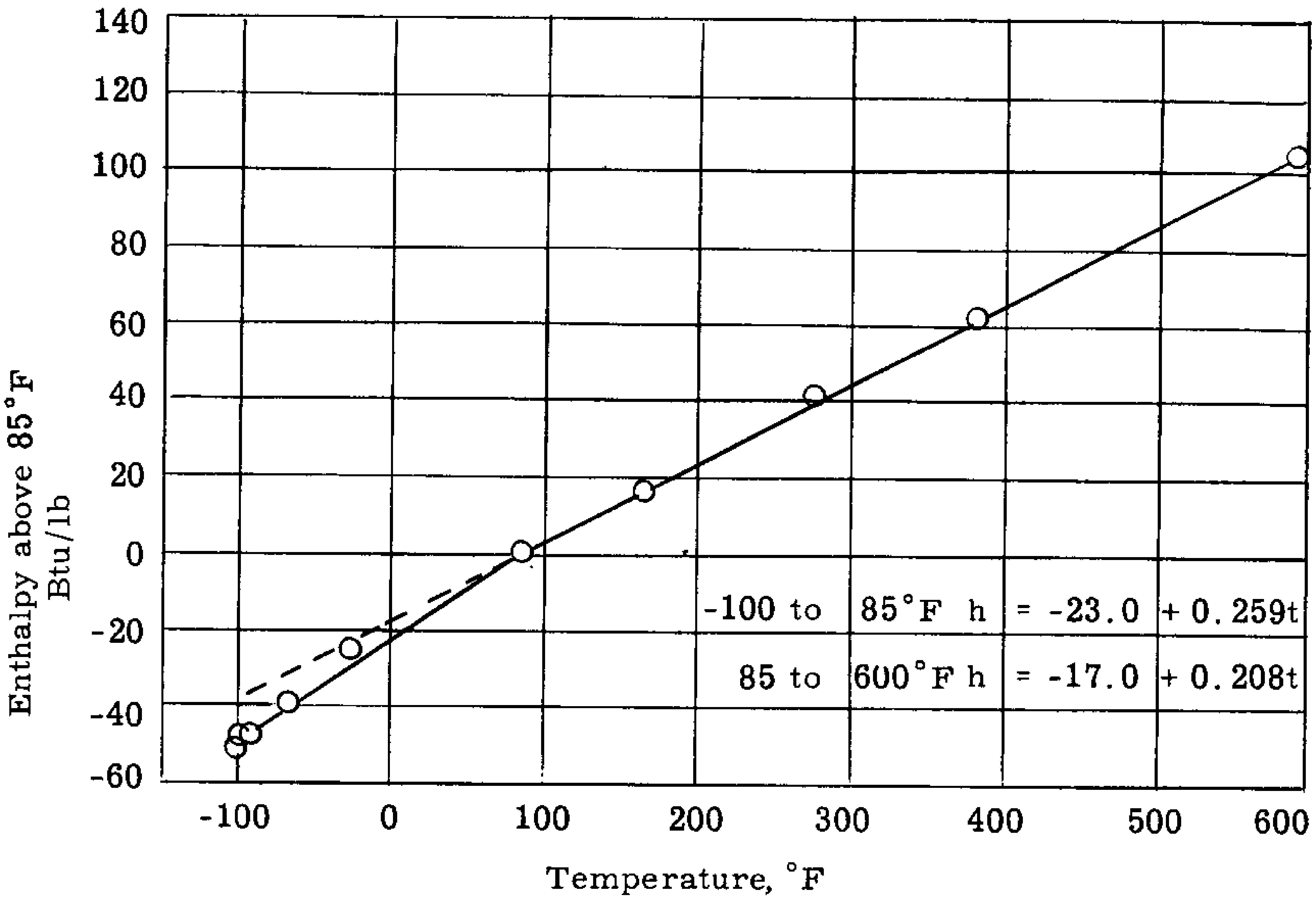

Figure 5. Heat Content Curve for Selectron 5016 Fluted Core Panel.

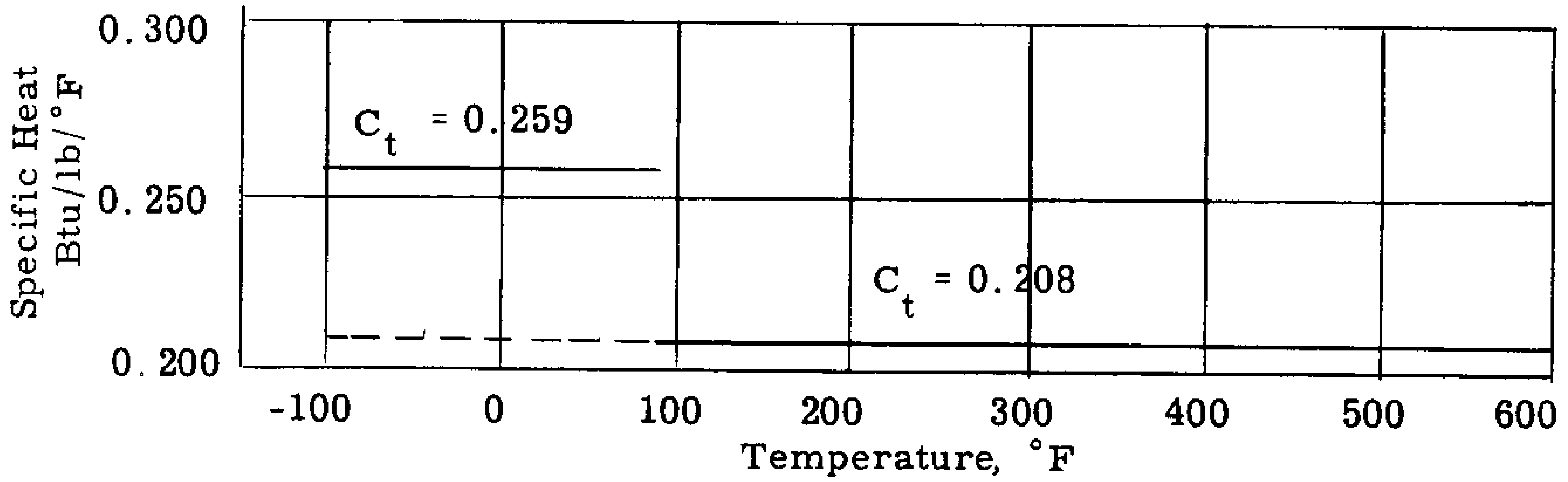

Figure 6. Specific Heat Versus Temperature for Selectron 5016 Fluted Core Panel.

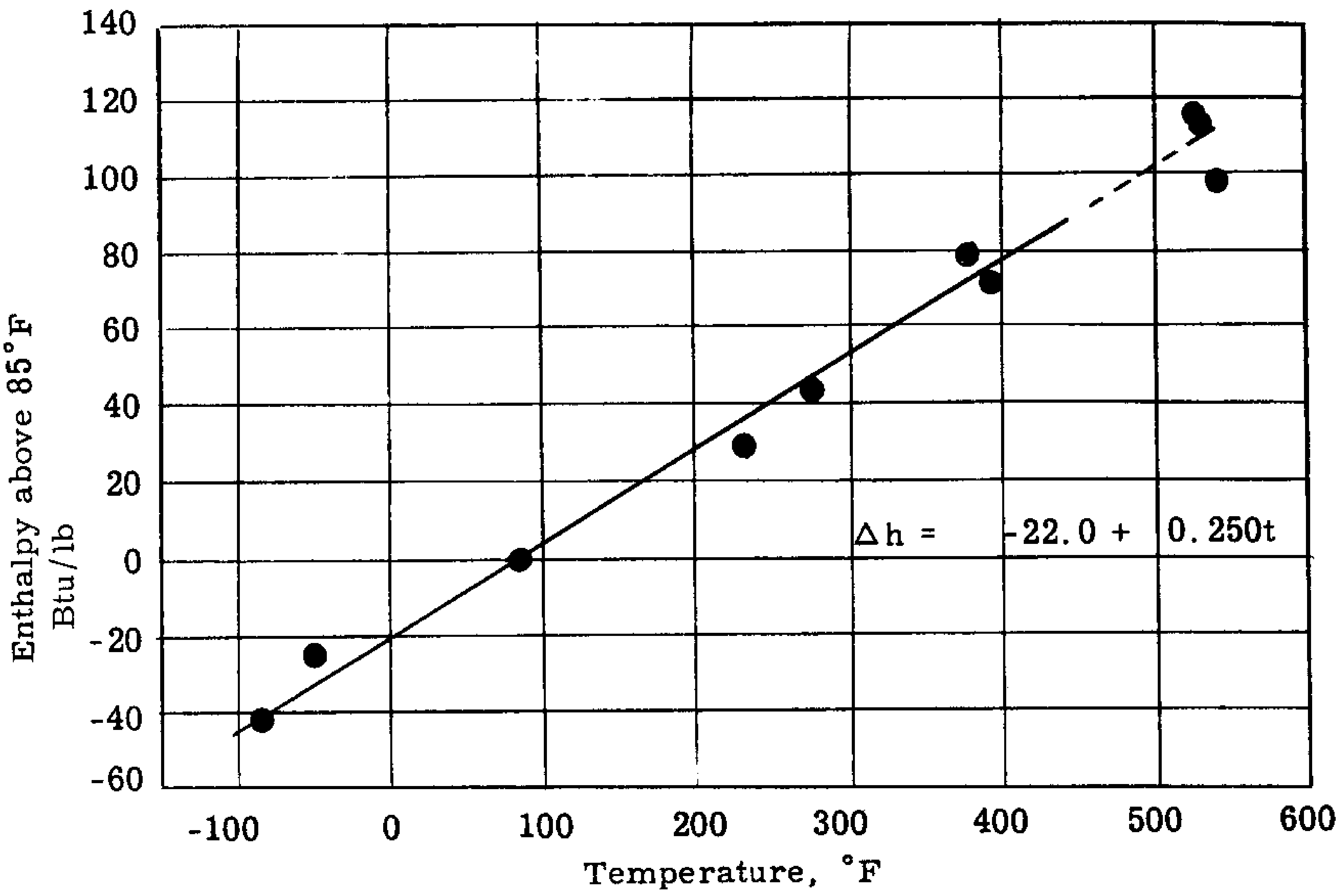

Figure 7. Heat Content Curve for X-131 Laminate.

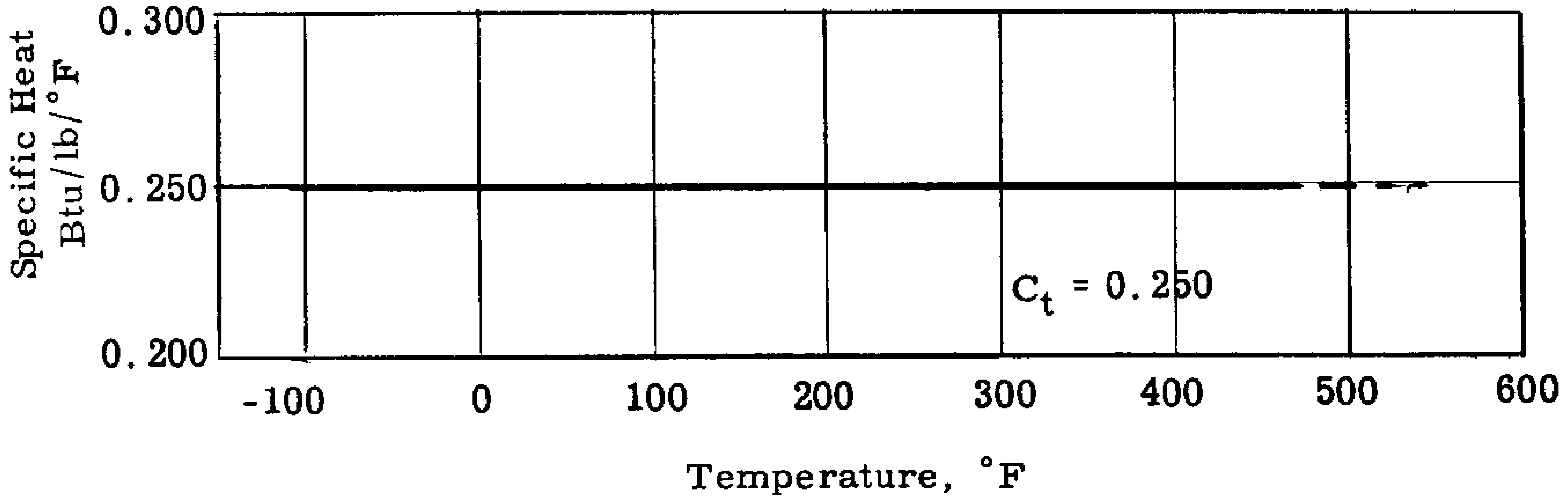

Figure 8. Specific Heat Versus Temperature for X-131 Laminate.

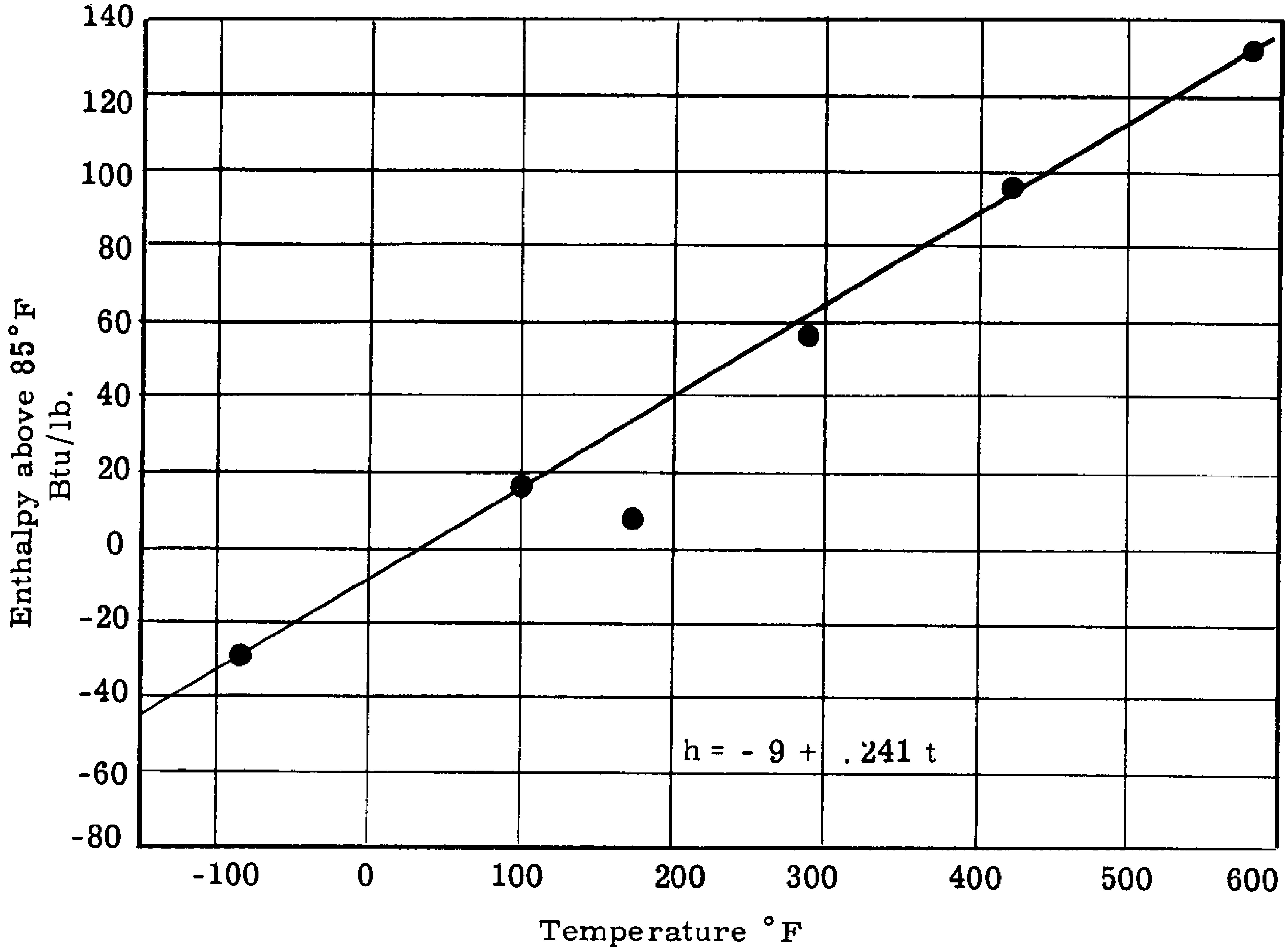

Figure 9. Heat content Curve for Shell X-131 Fluted Core Panel.

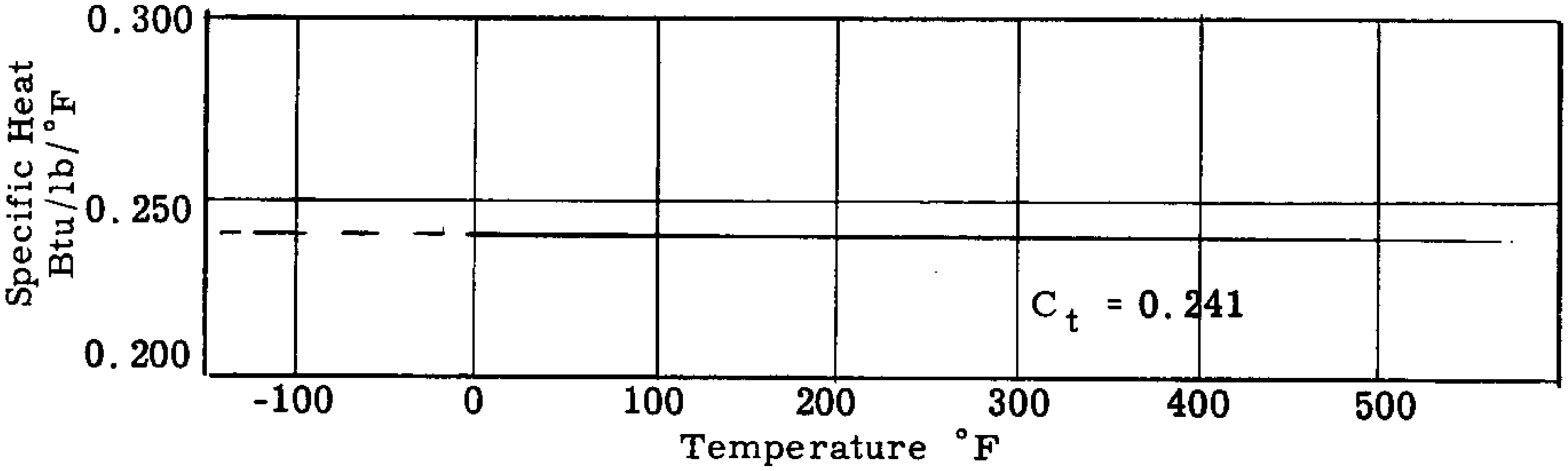

Figure 10. Specific Heat Versus Temperature for Shell X-131 Fluted Core Panel.

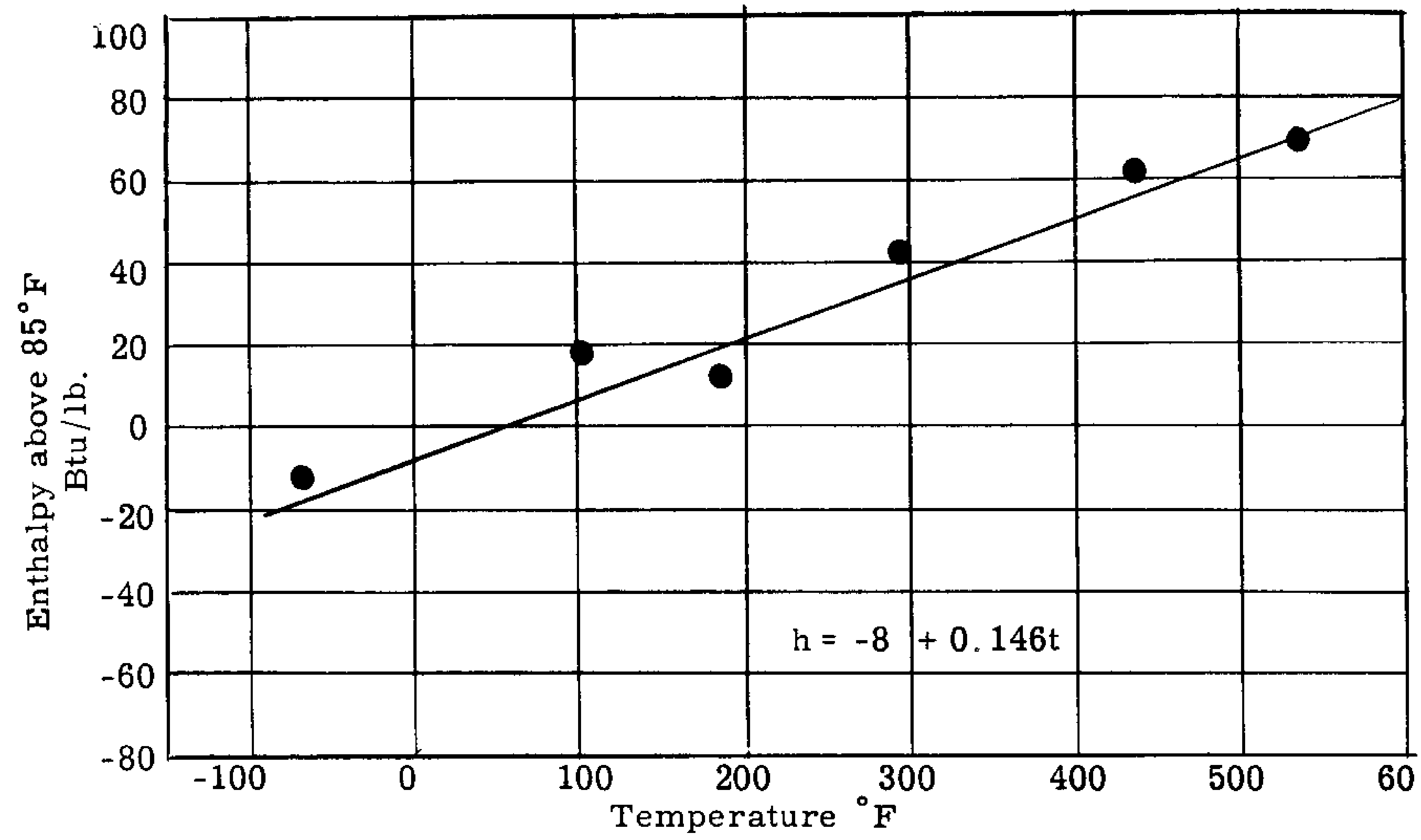

Figure 11. Heat Content Curve for CTL 37-9X Laminate

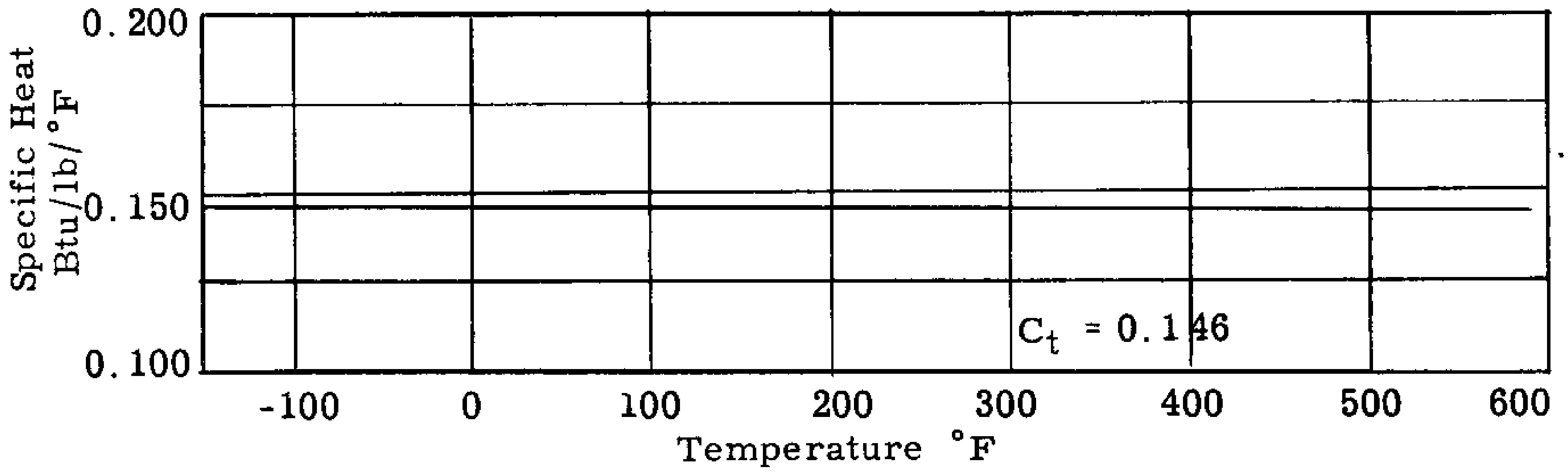

Figure 12. Specific Heat Versus Temperature for CTL 37-9X Laminate.

The enthalpy was referred to the common base temperature of 85° F by:

$$h_{85} = ht \frac{(85 - t_2)}{(t_3 - t_2)}$$

where h_{85} = enthalpy above the reference temperature of 85° F-Btu/lb
t_3 = initial sample temperature — ° F

Where enthalpy curves define a straight line, the equation describing the relationship is:

$$h = A + Bt$$

The values of the constants A and B were determined by the zero-temperature intercept and the slope of the line.

Complete data for the specific-heat determinations are given in Table V in Appendix I. Enthalpy and specific-heat values plotted as functions of temperature are presented in Figures 1 through 12. Enthalpy and specific-heat equations are also included on the corresponding plots.

THERMAL EXPANSION

Apparatus and Procedure

Thermal expansion measurements were made utilizing three quartz tube dilatometers of Bureau of Standards design. The tubes and dial gages were mounted on a single arm to facilitate the testing of three samples simultaneously. The dial gages (B. C. Ames Co., Model 212. 2, shockless, 0 — 10) were graduated in 0. 0001 in. divisions with a total range of 0. 200 in. The manufacturer's stated mechanical accuracy for any given reading is ± 0. 0001 in. at any point in the range.

Expansions of a minimum of two samples of each panel were measured in each of three directions in the plane of the sheet; longitudinal, diagonal, and transverse. Expansions were also made in the thickness direction of each panel (normal to the sheet). The averages of the measurements in each direction are given in Appendix II, Tables I through XII. Plots of thermal expansion as a function of temperature are given in Figures 13 through 24.

The three dilatometers were mounted rigidly to a wall bracket. A plywood cold box (24 in. by 18 in. by 18 in.), containing an insulated bath of trichloroethylene cooled with dry ice was raised to a level that submerged the dilatometer tubes to the specimen height. After reaching -100°F, the box was lowered and the specimens were allowed to return to ambient temperature, readings being made at definite intervals during both the decreasing and increasing portions of the cycle. The entire mounting assembly was then transferred to a second wall bracket located over an oven. The quartz tubes were lowered into the oven and expansion data were taken from ambient temperature to 600°F or until there was visible evidence of deterioration. A thermocouple junction embedded in the specimens was used for temperature measurement. The gages and mounts were kept at room temperature throughout the test by insulating from the bath area and by circulating room temperature air over the gages.

Where the expansion of quartz exceeded 5 percent of the specimen expansion (in the case of the low expansion specimens) the quartz correction factor was applied to the data. This correction was found necessary only on the cold tests, due to the large temperature differentials existing between the quartz tube and the specimen arising as a result of the cold liquid bath. During the hot part of the test cycle, the quartz tube was heated by slowly raising the temperature of the convection air furnace, eliminating this serious temperature lag between the tube and sample.

Data and Results

Each thermal expansion run is indicated by the corresponding legend on the curves, Figures 13 through 24. For the expansion runs made in the plane of the material, all the cold runs were averaged at common temperature levels and the average value plotted. At the high temperature levels, each run was plotted separately. The three curves representing the directions of expansion in the plane of the sheet were plotted adjacently on the same graph for ease in comparison.

The curves representing expansion in the thickness direction are shown plotted in Figures 14, 16, 18, 20, 22, and 24. It was found that the initial run made in the thickness direction differed substantially to our subsequent runs made on the same specimen among all the laminate materials. For the fluted core samples, this condition was not apparent. It is believed that the differences between succeeding runs were attributed to a surface interaction — possibly a bonding action taking place between adjacent disk surfaces during the initial run. Since the fluted core panels were several times thicker than the laminates, fewer fluted core samples were required to make up a given height. Thus, fewer surfaces were involved and the effect was minimized.

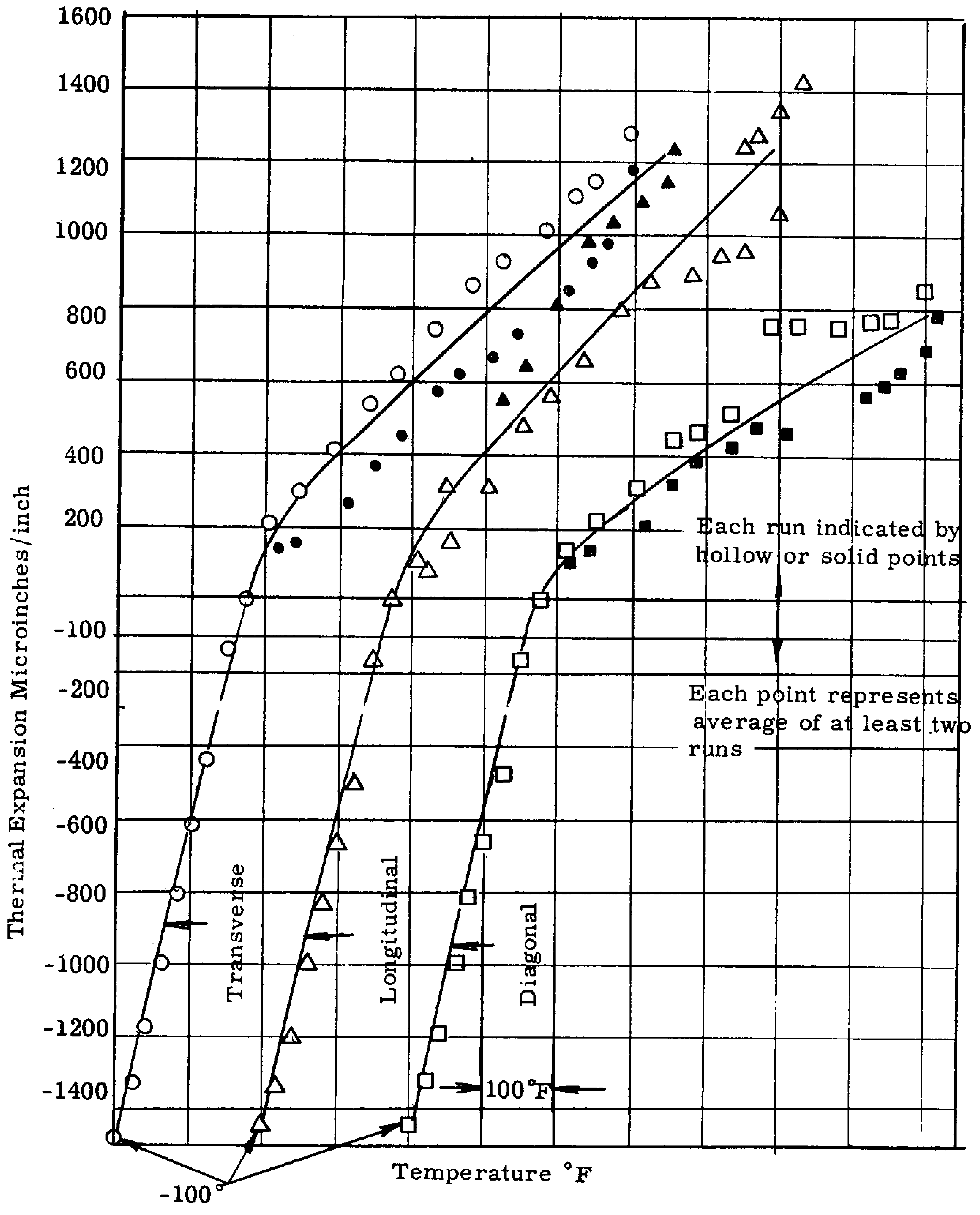

Figure 13. Thermal Expansion of X-1068 Laminate

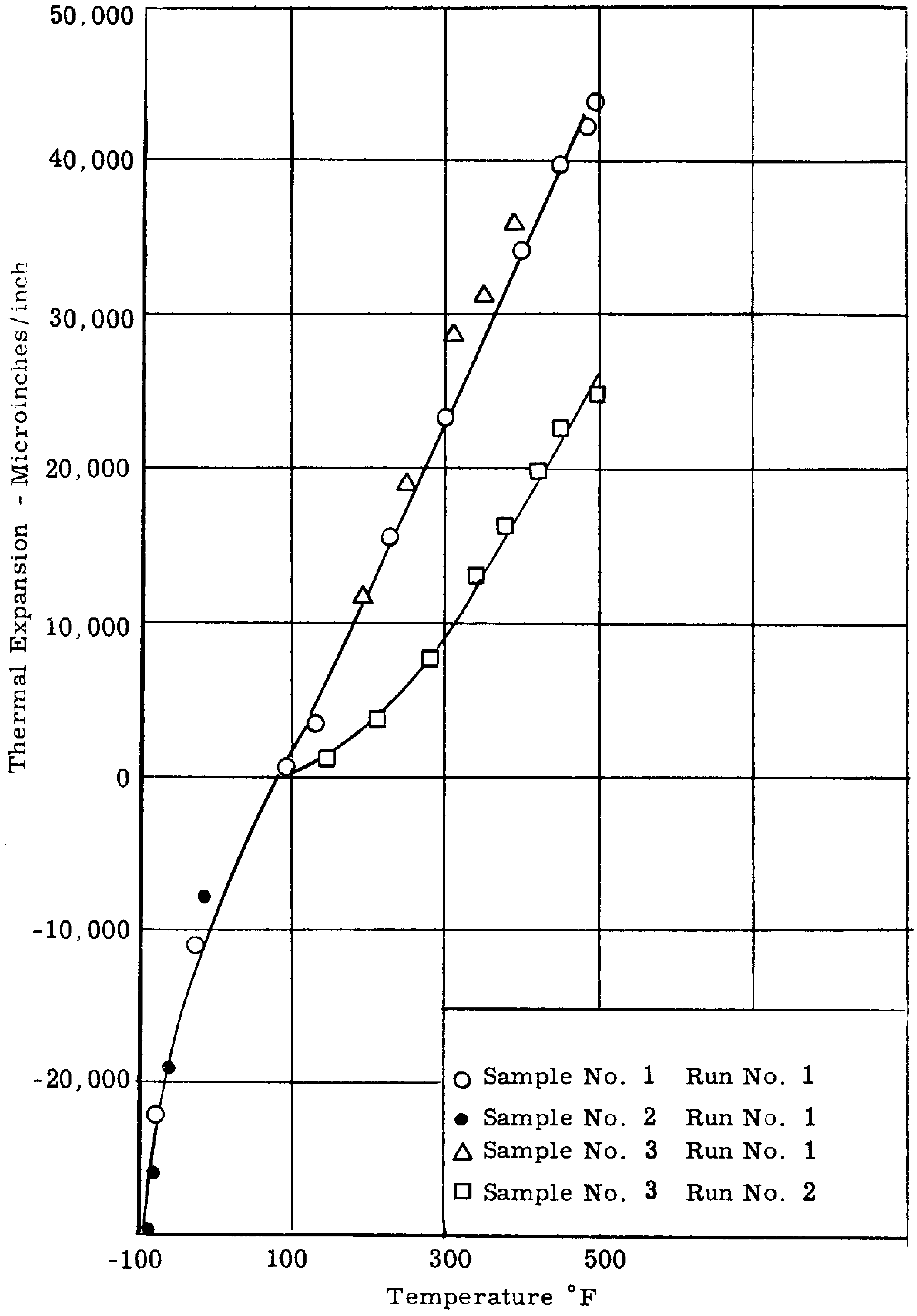

Figure 14. Thermal Expansion through the Thickness Direction of X-1068 Laminate

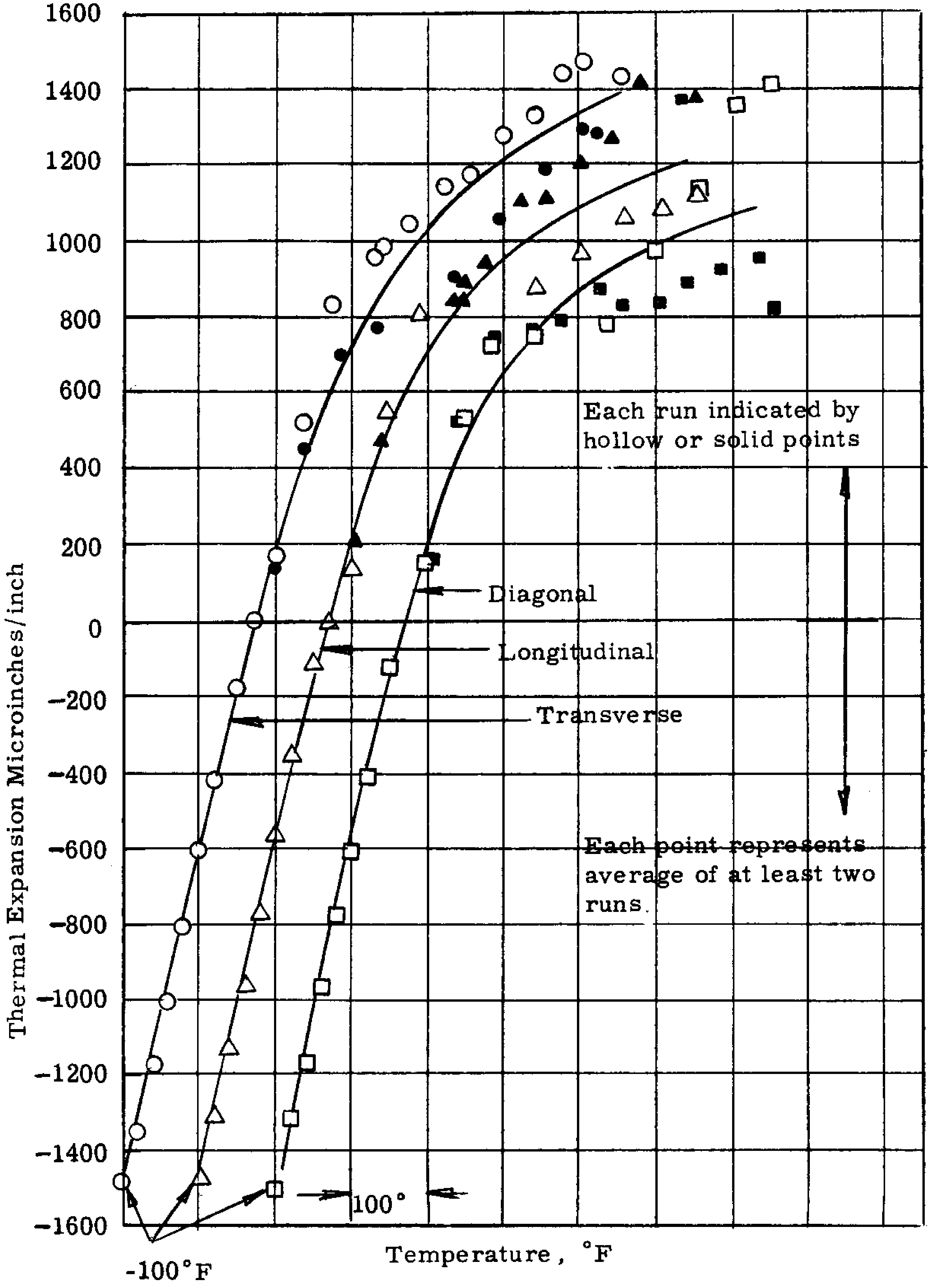

Figure 15. Thermal Expansion of Shell X-131 Laminate.

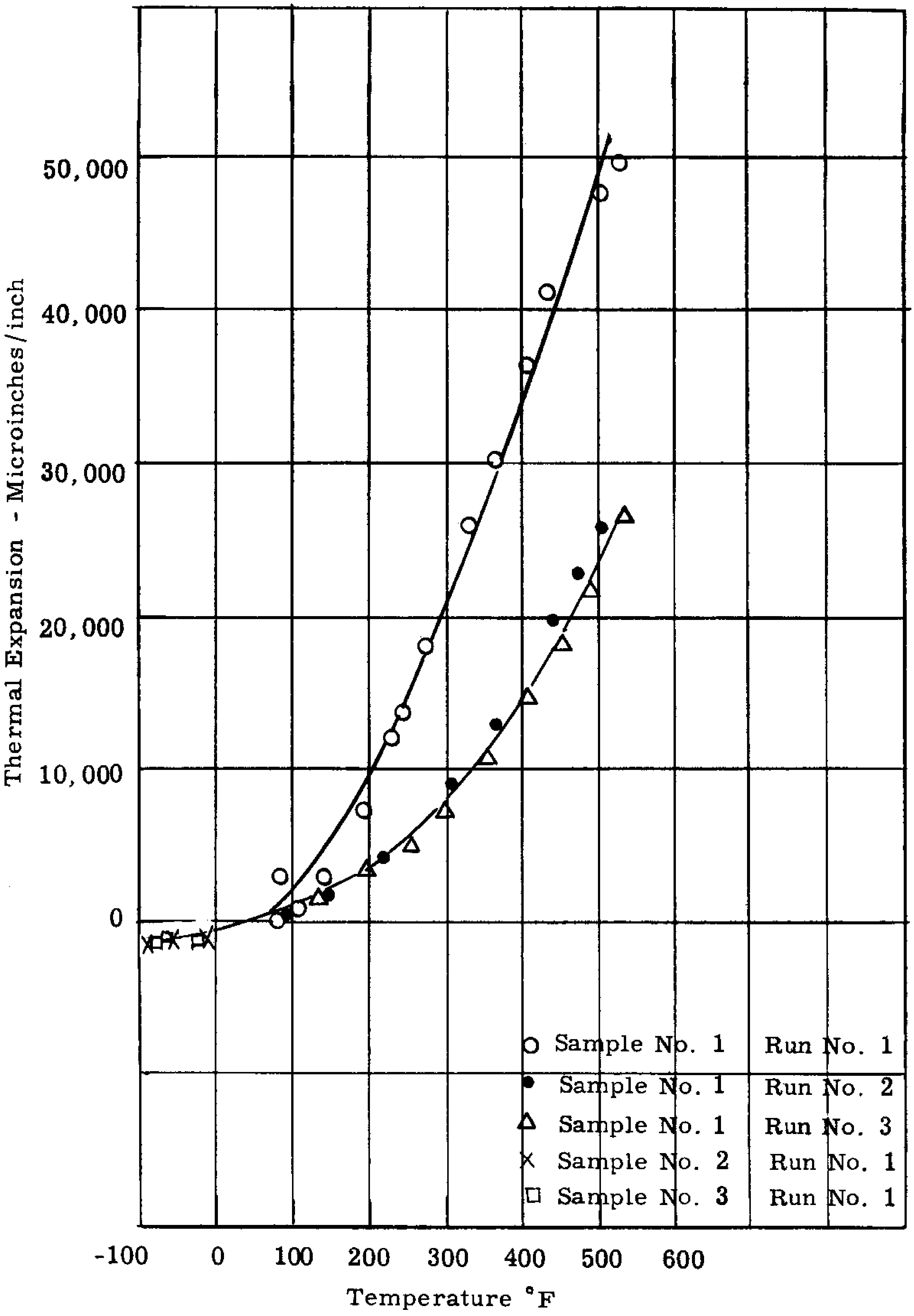

Figure 16. Thermal Expansion through the Thickness Direction of X-131 Laminate

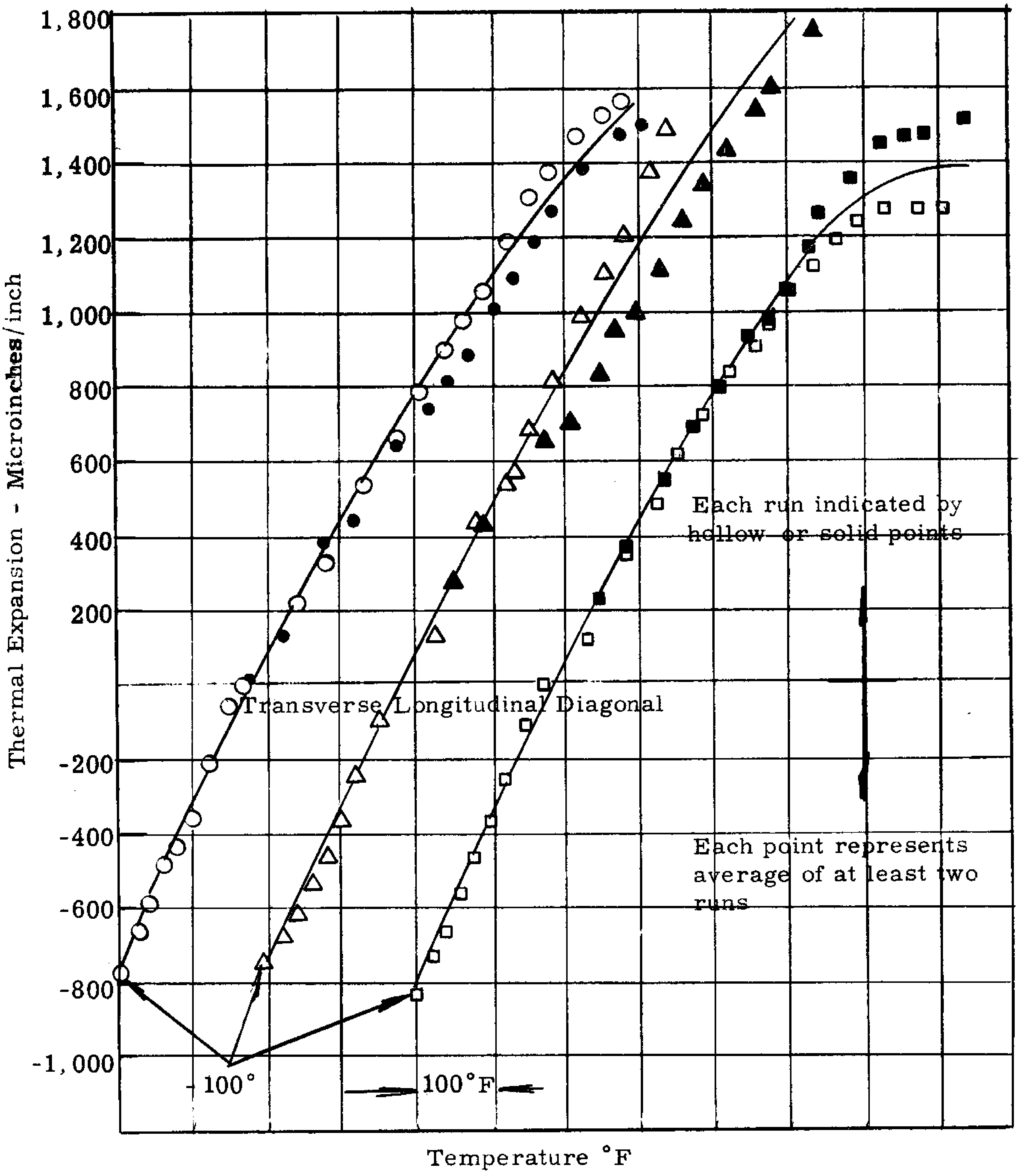

Figure 17. Thermal Expansion of CTL 37-9X Laminate

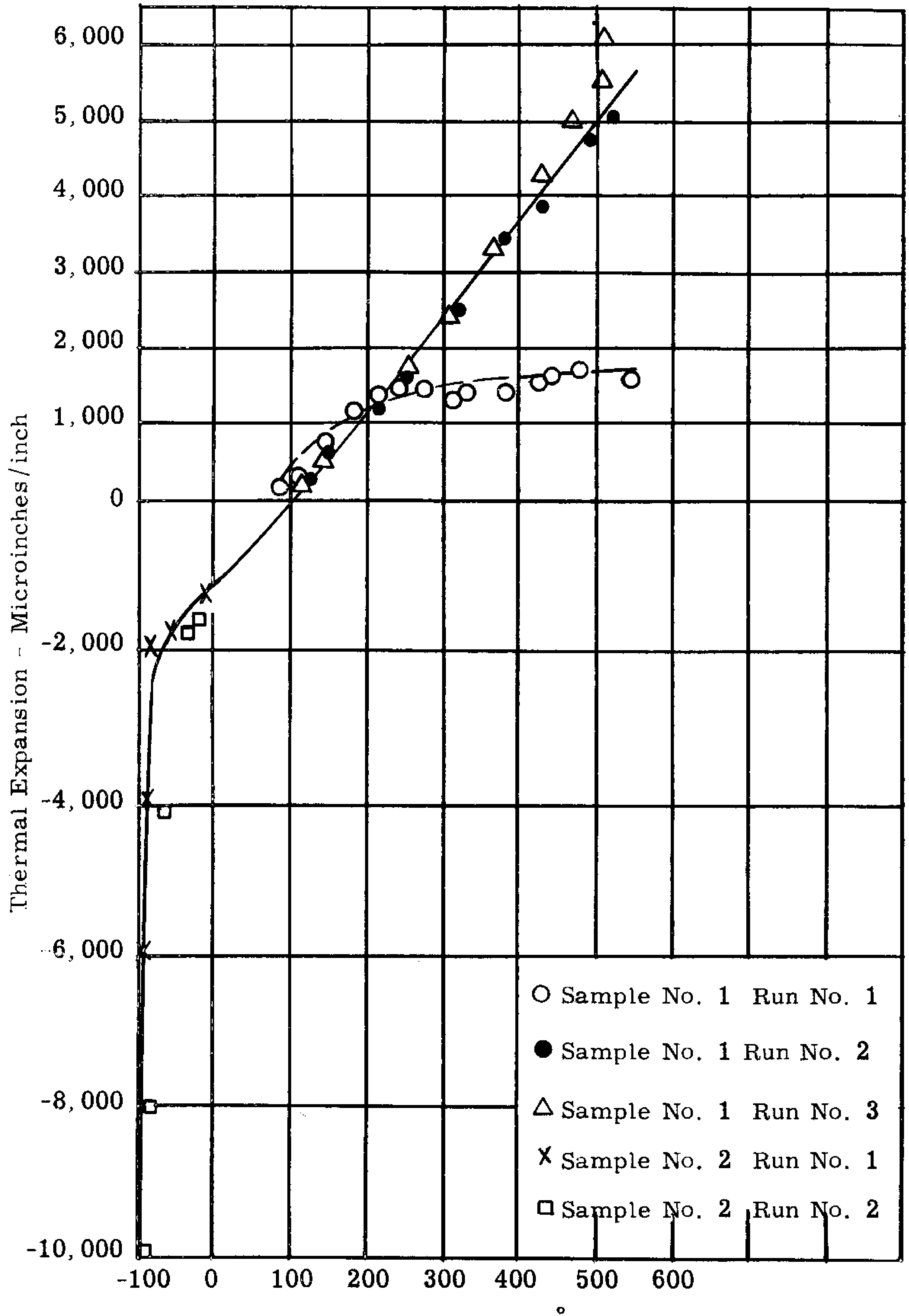

Figure 18. Thermal Expansion Through the Thickness Direction of CTL 37-9X Laminate.

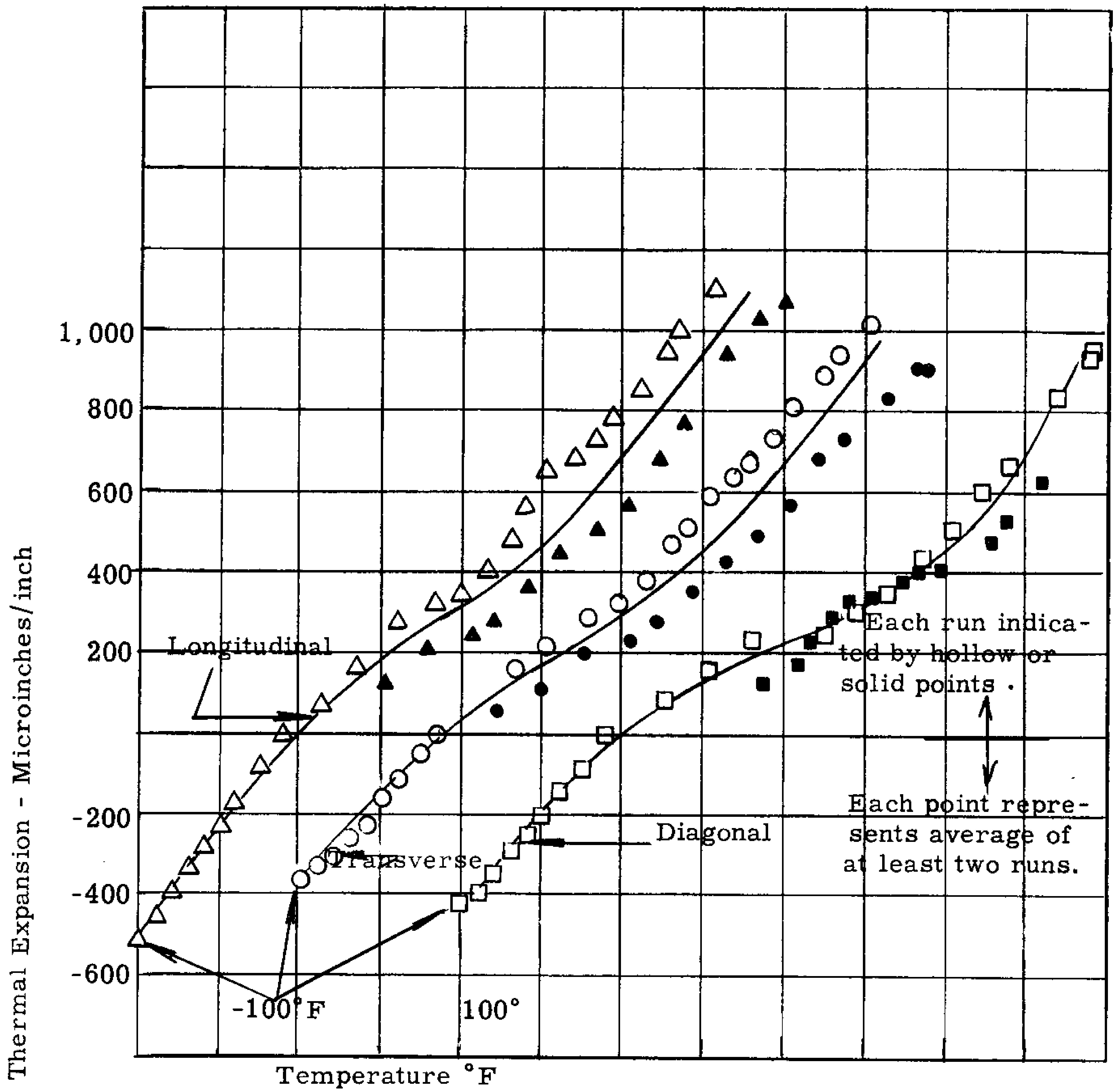

Figure 19. Thermal Expansion of Asbestos-Phenolic 9526D Laminate.

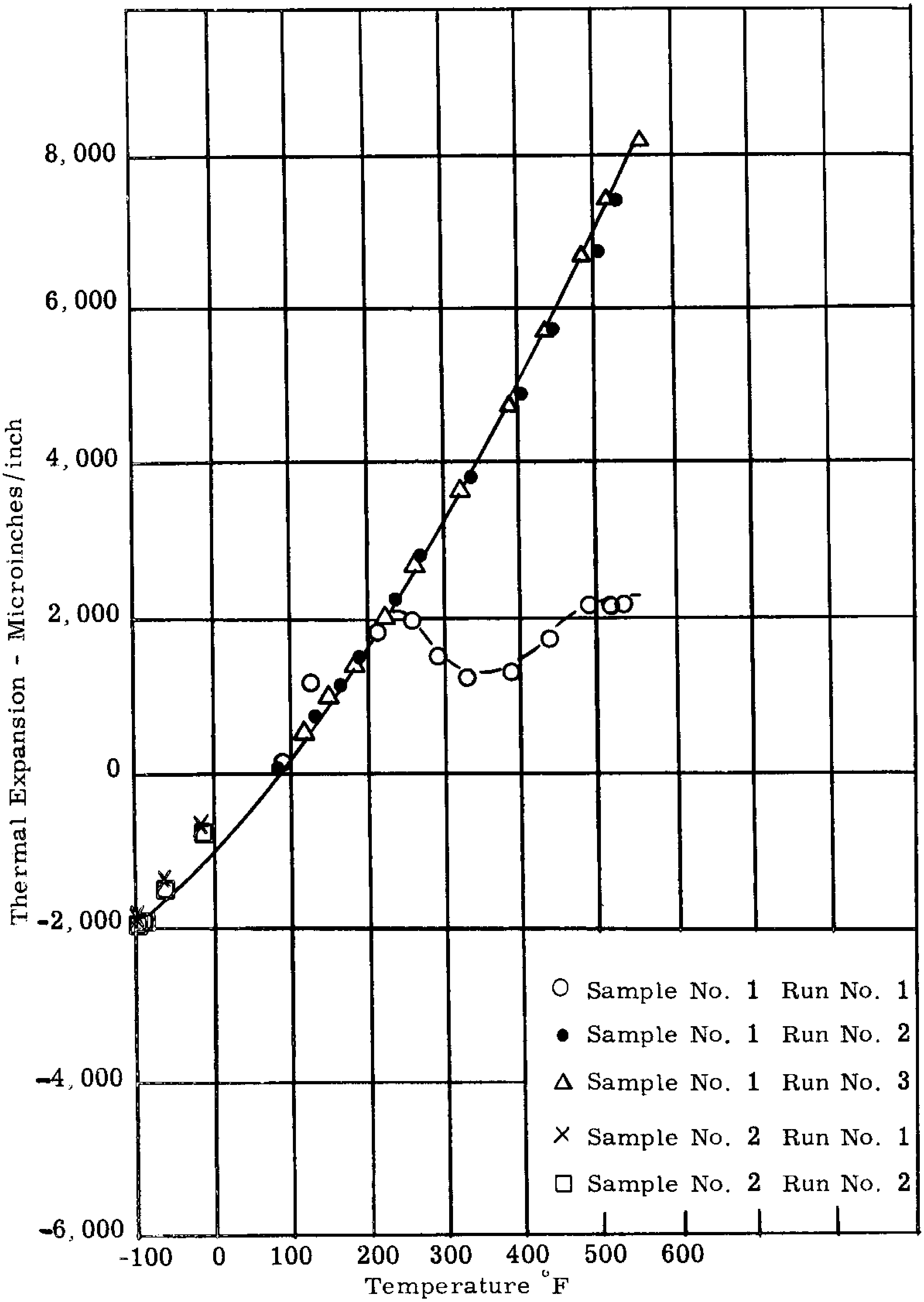

Figure 20. Thermal Expansion Through the Thickness Direction of Asbestos-Phenolic 9526D Laminate.

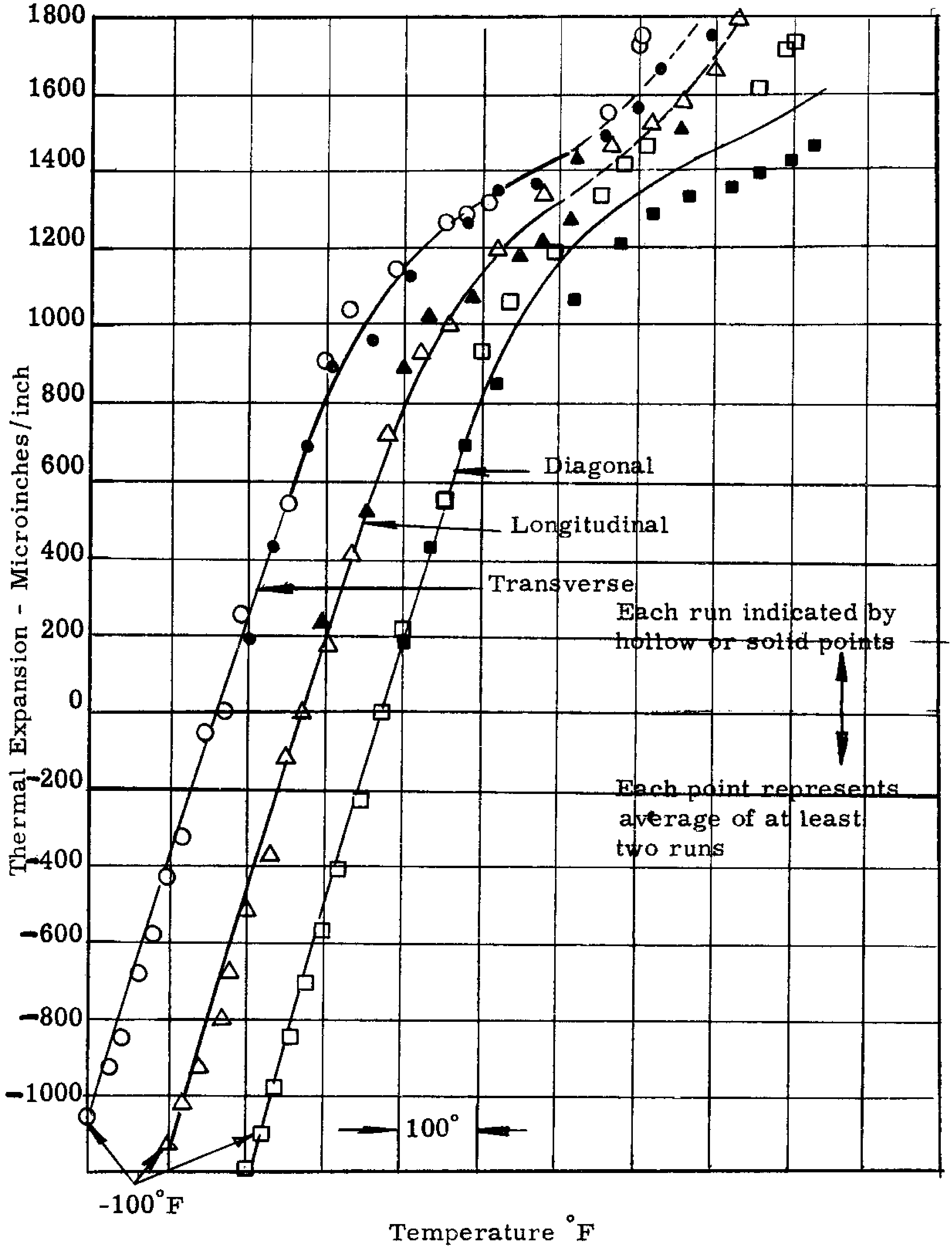

Figure 21. Thermal Expansion of Selectron 5016 Fluted Core Panel

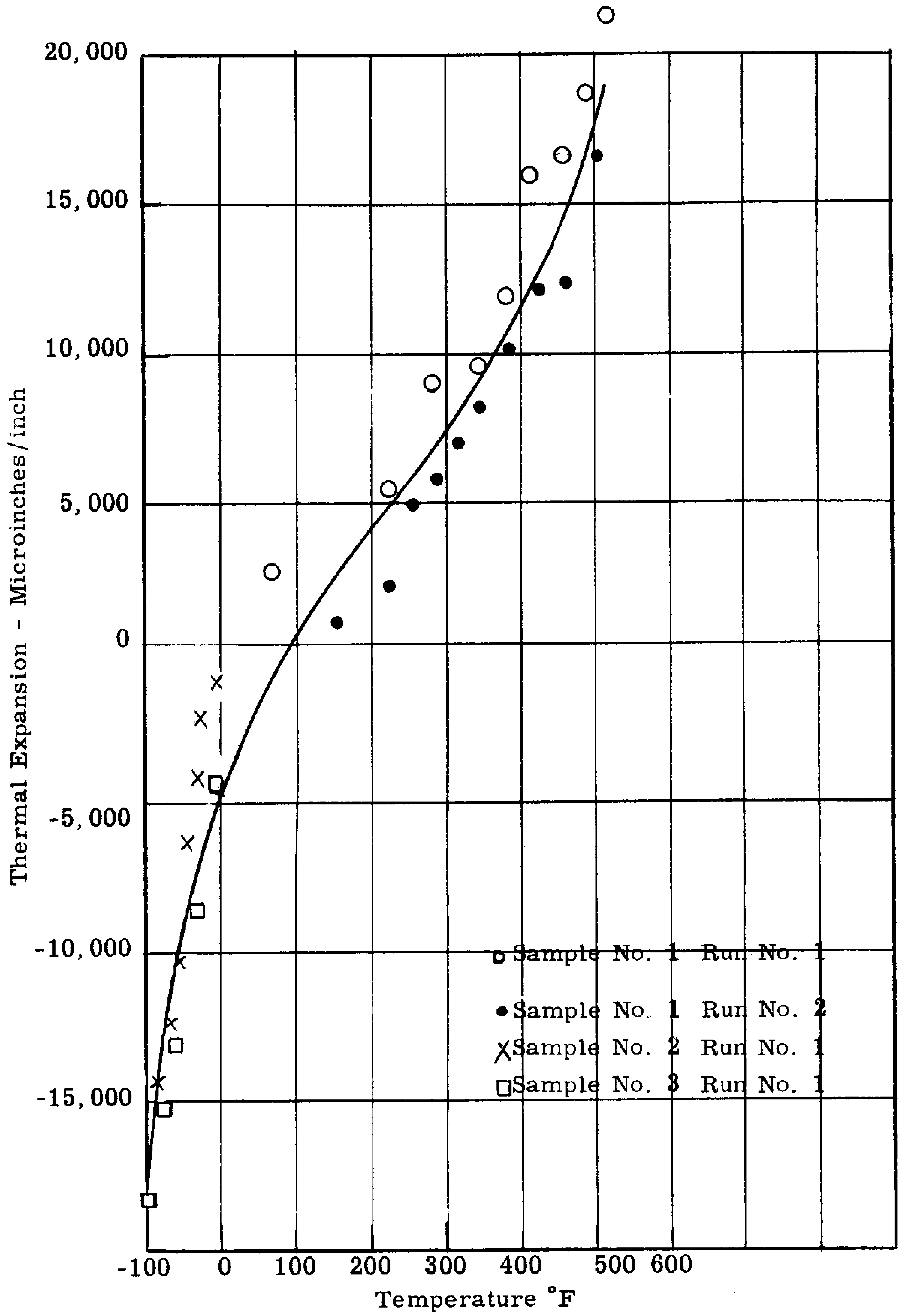

Figure 22. Thermal Expansion Through the Thickness Direction of 5016 Fluted Core Panel

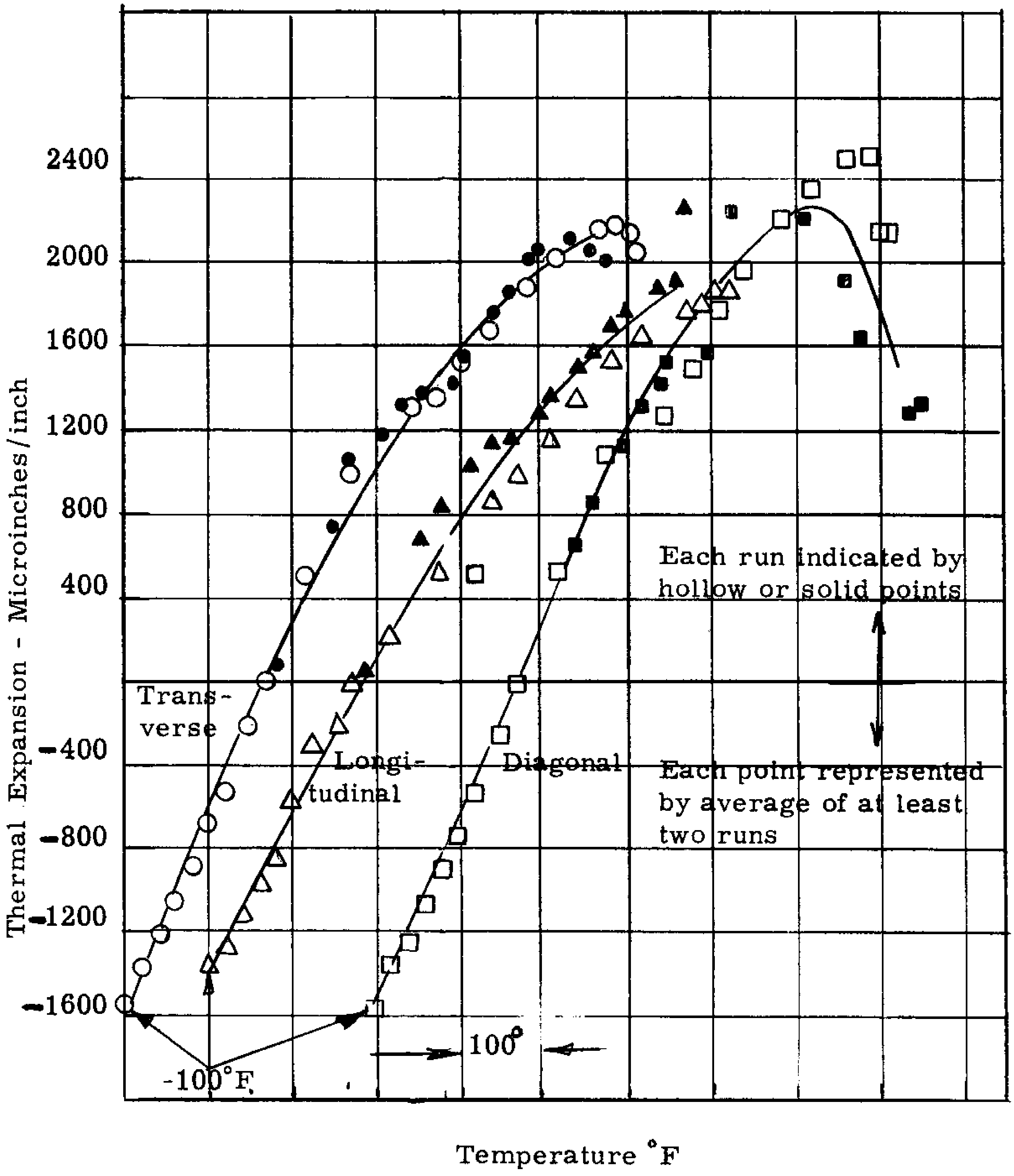

Figure 23. Thermal Expansion of Shell X-131 Fluted Core

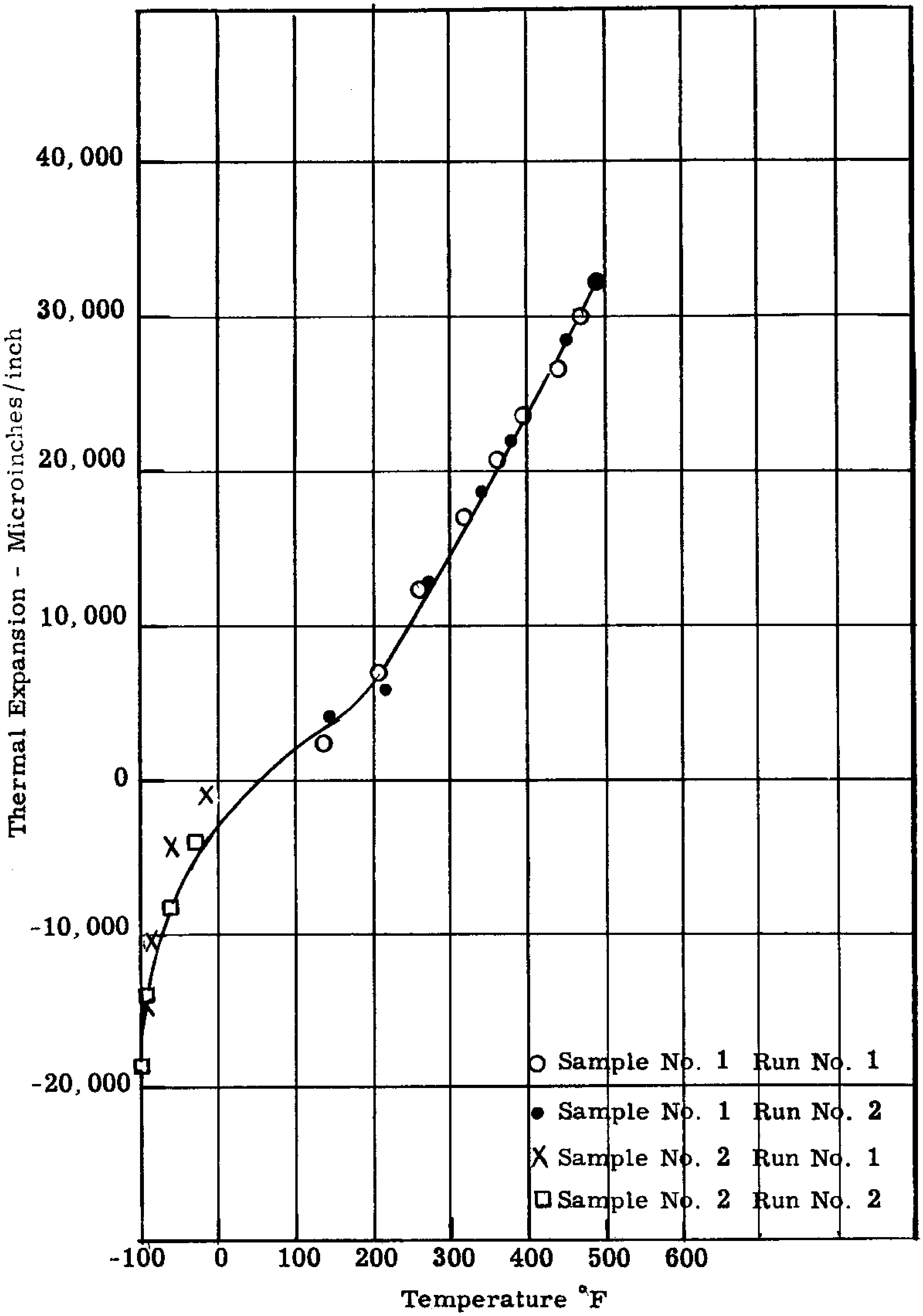

Figure 24. Thermal Expansion Through the Thickness Direction of Shell X-131 Fluted Core Panel

In comparing the expansions in the plane of the sheet, with the exception of the X-1068 laminate, the glass fabric samples exhibited a nearly linear expansion curve up to the breakdown temperature of the resin. The expansion curve for the X-1068 resin sharply reduced its slope at room temperature but continued at the new slope linearly throughout the remainder of the test temperature range. The phenolic impregnated asbestos material indicated the lowest thermal expansion coefficient of all the materials.

In considering the effects of the three directions — transverse, longitudinal, and diagonal — on the expansion coefficient, no definite pattern was established. In some materials, the expansions were greatest for the transverse direction. In others, expansion in the transverse direction was lower, or equal to the other two directions.

Expansion rates in the thickness direction varied from 4 to 28 times the expansion rate in the plane of the sheet, with no apparent systematic relation to resin content, or number of plies of fabric. Probably, the expansion in the thickness direction should be purely a function of the expansion coefficient of the resin alone, whereas the expansion in the plane of the sheet constitutes almost totally a function of the glass fabric.

THERMAL CONDUCTIVITY

Apparatus and Procedure

Thermal conductivity tests were made with a guarded hot plate which was a slight modification of the standard ASTM C 177-45 design.

The apparatus consisted of a central heater plate surrounded by a guard heater, each separately controlled. The guard ring was maintained at the same temperature as the central heater so that all of the heat flow from the central heater was normal to the test surfaces. The temperature difference between the guard and central sections was measured by means of eight differential—thermocouple junctions connected in series. The plate containing the two heaters was sandwiched between layers of insulation, copper plates, test panels, another copper and insulation sheet, and finally a cold source to dissipate the heat. The cold source consisted of a copper coil enclosed in an aluminum box. Sample temperatures were measured by means of five thermocouples located in the 14-inch square copper plates and projecting through the plates to the surface of the sample. In order to protect the copper plates from high temperature corrosion, they were nickel plated.

To maintain good contact pressure, a screw loading device held the entire sandwich assembly pressed firmly together. Sample pressure was indicated by a calibrated strain gage load cell. The entire assembly was insulated by enclosing it in a box filled with vermiculite.

To obtain mean sample temperatures above room temperature, water was circulated through the copper tubing of the cold plates. For mean sample temperatures below room temperature, cold trichloroethylene was pumped through the copper tubing. This coolant was chilled by circulating it through copper coils in a trichloroethylene dry ice bath. Equilibrium conditions were certified before readings were taken.

Coefficients of thermal conductivity were calculated from the expression:

$$K = \frac{ql}{A \Sigma \Delta T}$$

where l = thickness of one specimen — inches
A = area of central heater section — square feet
q = total heat flow Btu/hr
ΔT = sum of temperature drops across each sample —°F

Theoretically, q, the heat input, should split, with exactly half of the input flowing through each sample. The temperature drops, however, rarely indicate that this condition exists. Instead there is a slight unbalance in the heat flow. The above formula then yields an arithmetic average for the two test panels.

Data and Results

Table XVIII contains the primary data and the conductivity factors for the six test materials. Plotted data, presenting thermal conductivity as a function of temperature appear in Figures 25, 26, and 27.

An inspection of the three figures will show that the thermal conductivity values for the six materials covered a range of 0.5 to 1.75. Within this range, the materials displaying the lowest conductivity values were the CTL 37-9X and the phenolic laminate. These materials also produced the flattest curves in the maximum temperature range indicating a resistance to breakdown at the higher temperatures. An inspection of the spent samples revealed that these samples were the least discolored of the six materials tested. It is interesting to see that the conductivity of the materials varies roughly with the density — the higher the conductivity, the greater the density. Note also that the addition of flutes to the X-131 laminate fails to alter the conductivity factors for this material.

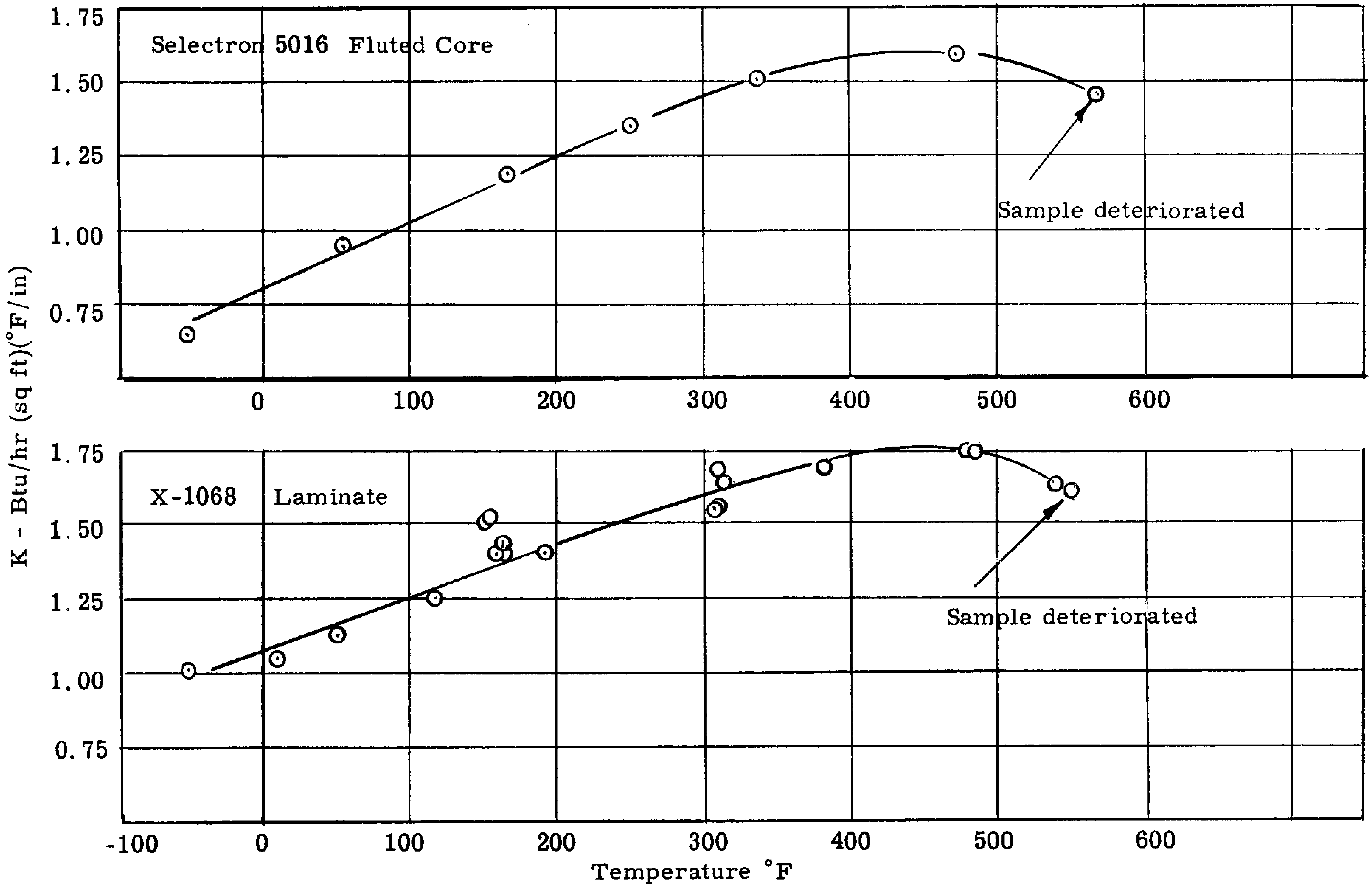

Figure 25. Thermal Conductivity vs Temperature of X-1068 Laminate and Selectron 5016 Fluted Core Panels.

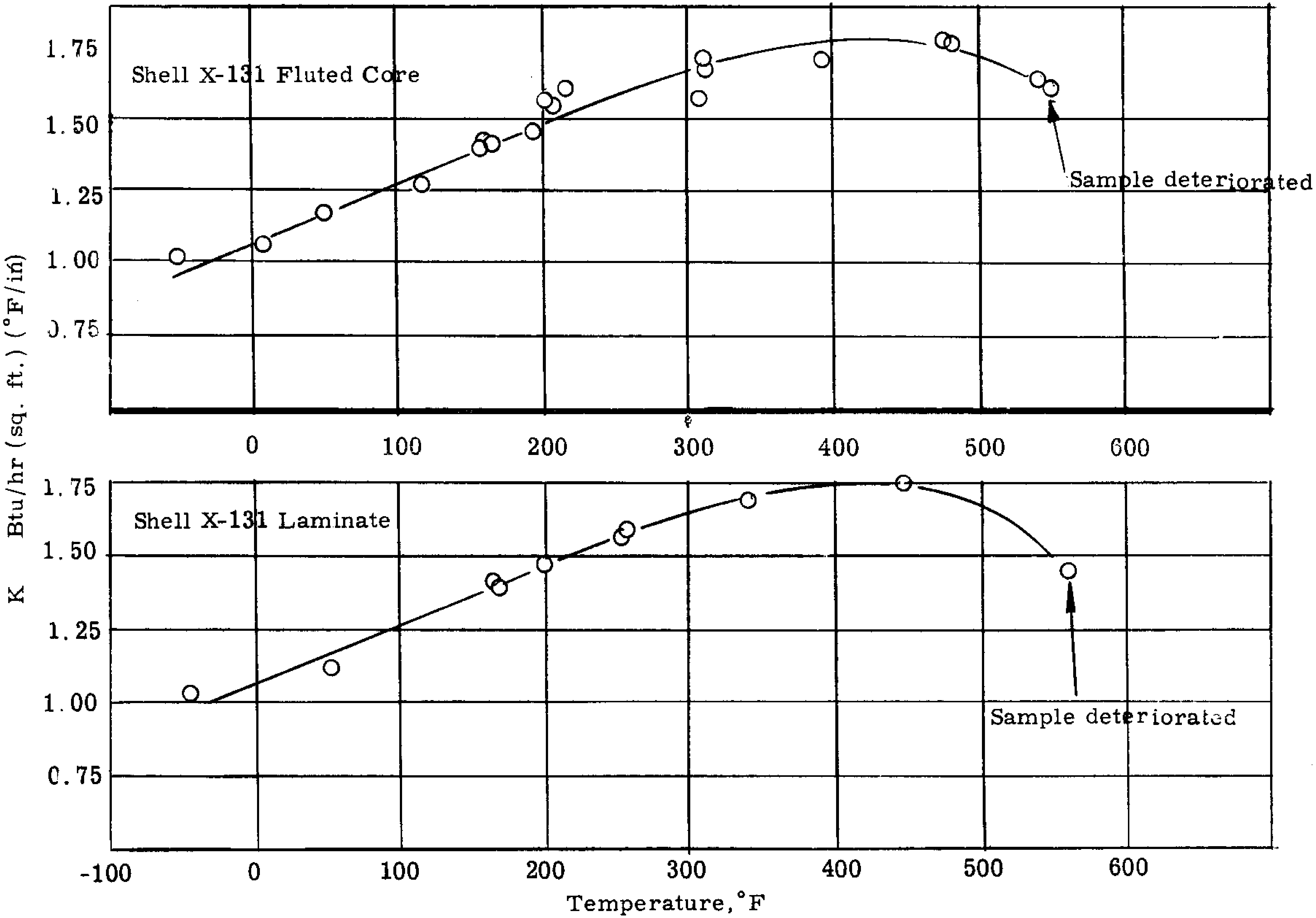

Figure 26. Thermal Conductivity vs. Temperature of Shell X-131 Laminate and Fluted Core Panels.

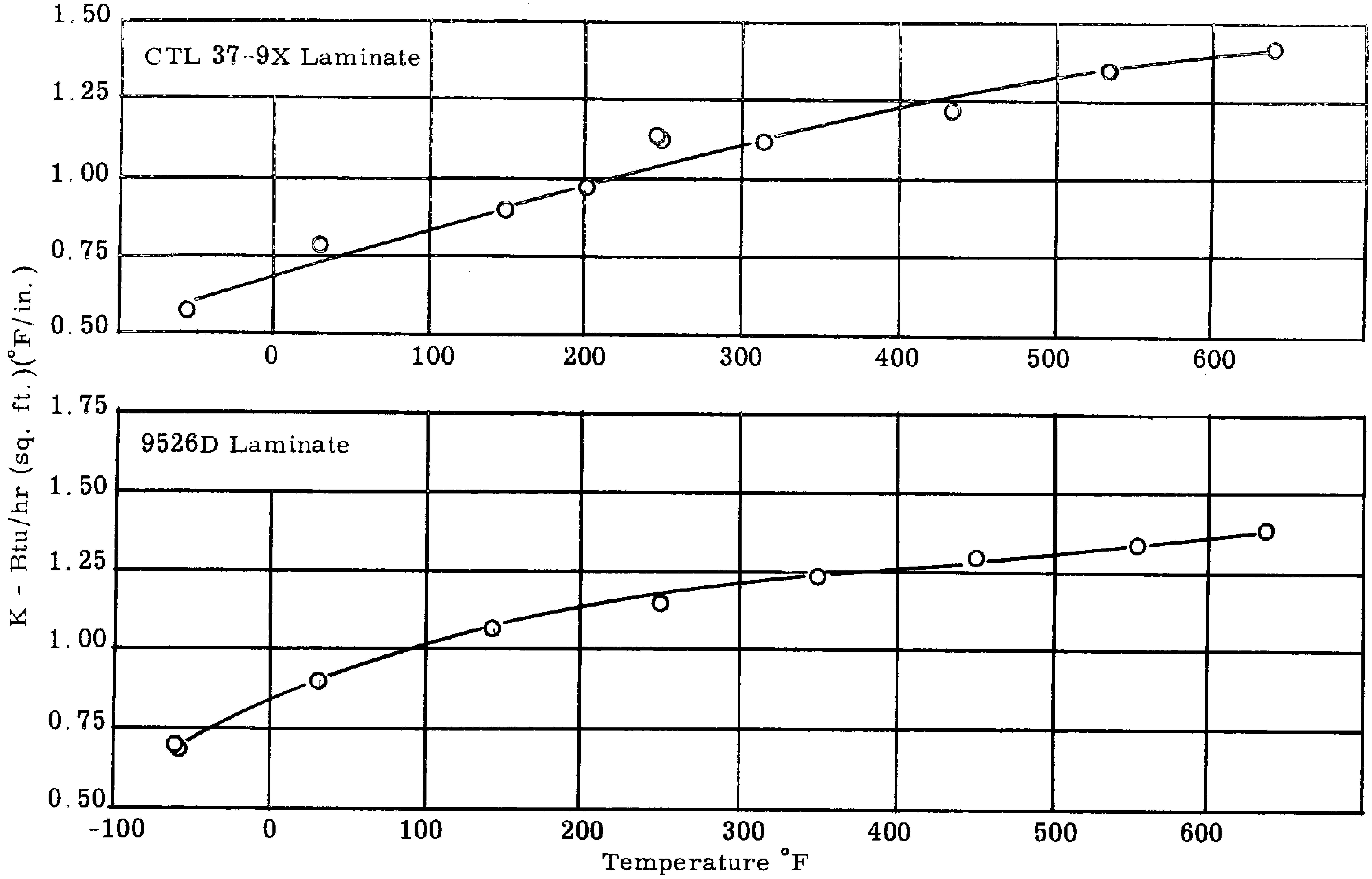

Figure 27. Thermal Conductivity vs. Temperature for Asbestos-Phenolic 9526D Laminate and CTL 37-9X Laminates.

Appendix I

Table V. Specific Heat Data

Run No.	Cal. Constant Btu/°F	Final Cup Temp t_2 °F	Change in Cup Temp $t_2 - t_1$ °F	Initial Sample Temp °F	Initial Wt of Sample (g)	Final Wt of Sample (g)	$h = \frac{K}{W_s}(t_2-t_1)$ Btu/lb	Enthalpy above 85°F Ref Btu/lb
(X-1068 Laminate)								
1	0.2654	74.27	2.05	164.3	11.8702	11.8527	20.84	18.36
2	0.2654	81.43	5.08	295.0	11.7770	11.7409	52.13	51.26
3	0.2654	80.41	7.79	398.7	11.7416	11.6692	80.44	79.28
4	0.2654	92.78	11.83	619.0	11.6062	10.3464	137.77	139.81
5	0.2654	71.68	4.22	-99.7	11.5232	11.5232	-44.13	-47.56
(Phenolic, 9526D								
1	0.2654	86.69	2.19	189.3	8.0928	8.0191	32.90	33.46
2	0.2654	75.44	7.44	455.2	8.1812	8.1345	110.20	107.43
3	0.2654	82.31	8.85	655.4	8.5150	7.1830	148.45	147.75
4	0.2654	85.38	9.33	583.0	8.0655	7.3700	152.53	152.65
5	0.2654	69.60	2.40	-61.4	8.2767	8.2767	-34.94	-39.05
(Selectron 5016 Fluted Core)								
1	0.2654	81.35	1.30	165.2	9.3939	9.2320	16.97	16.23
2	0.2654	85.33	3.20	277.4	9.4868	9.4434	40.83	40.90
3	0.2654	88.52	4.72	381.5	9.4078	9.2597	61.42	62.16
4	0.2654	90.70	6.25	592.3	9.0808	7.2543	103.81	104.99
5	0.2654	73.50	3.42	-90.2	9.0695	9.0695	-45.43	-48.62
6	0.2654	70.97	2.73	-65.1	9.0695	9.0695	-36.26	-40.00
7	0.2654	73.25	3.68	-100.7	9.0695	9.0695	-48.89	-52.19
8	0.2654	71.30	3.40	-97.1	9.0695	9.0695	-45.17	-48.85
9	0.2654	70.14	1.68	-23.1	9.0695	9.0695	-22.32	-25.88

Appendix I

Table V. Specific Heat Data (continued)

Run No.	Cal. Constant Btu/° F	Final Cup Temp t_2 ° F	Change in Cup Temp $t_2 - t_1$ ° F	Initial Sample Temp ° F	Initial Wt of Sample (g)	Final Wt of Sample (g)	h = $\frac{K}{W_S}(t_2 - t_1)$ Btu/lb	Enthalpy above 85° F Ref Btu/lb
	(X-131 Laminate)							
1	0. 2654	77. 47	3. 07	232. 3	11. 8873	11. 8631	31. 18	29. 66
2	0. 2654	83. 88	7. 83	379. 9	11. 6706	11. 6358	81. 08	80. 77
3	0 2654	86. 86	10. 91	532. 4	11. 8813	11. 6747	112. 59	113. 06
4	0. 2654	87. 12	9. 02	544. 1	11. 7835	11. 0046	98. 76	99. 22
5	0 2654	82. 40	4. 35	273. 8	11. 5663	11. 5451	45. 32	44. 70
6	0. 2654	82. 65	7. 15	393. 1	11. 6911	11. 6540	73. 92	73. 36
7	0. 2654	87. 65	10. 54	528. 9	11. 6785	10. 9962	115. 49	116. 18
8	0. 2654	73. 37	2. 08	-49. 3	11. 3167	11. 3175	-22. 15	-24. 25
9	0. 2654	75. 00	3. 70	-81. 6	11. 3161	11. 3181	-39. 89	-41. 91
	(Shell X-131 Fluted Core)							
1	0. 2654	74. 20	0. 70	173. 6	9. 4293	9. 4002	8. 95	7. 75
2	0. 2654	85. 08	7. 81	421. 6	10. 0925	9. 9117	95. 20	95. 20
3	0. 2654	108. 60	10. 30	583. 6	10. 2163	9. 8635	126. 20	132. 48
4	0. 2654	83. 60	4. 50	285. 0	9. 6895	9. 6345	56. 10	56. 04
5	0. 2654	70. 50	2. 80	100. 2	10. 1061	10. 0929	33. 40	17. 10
6	0. 2654	67. 95	-2. 96	-85. 0	10. 0690	10. 0690	-33. 40	-29. 67
	(CTL 37-9X Laminate)							
1	0. 2654	76. 20	0. 70	185. 0	7. 2709	7. 2428	11. 65	10. 61
2	0. 2654	86. 20	3. 50	435. 0	7. 0651	7. 0185	60. 30	60. 00
3	0. 2654	103. 60	4. 30	533. 6	7. 2365	7. 1648	72. 60	69. 46
4	0. 2654	82. 10	2. 60	287. 1	7. 1080	7. 0786	44. 30	43. 67
5	0. 2654	66. 95	2. 45	100. 3	7. 2790	7. 2788	40. 70	18. 60
6	0. 2654	64. 60	0. 76	-70. 0	7. 3135	7. 3135	-12. 50	-10. 60

Appendix II

Average Thermal Expansion Data

Table VI. Thermal Expansion Data for X-1068 Laminate

Transverse Direction		Longitudinal Direction		Diagonal Direction	
Temp ° F	Avg Expansion μ in/in	Temp ° F	Avg Expansion μ in/in	Temp ° F	Avg Expansion μ in/in
70	0	50	-163	50	-160
50	-145	20	-506	20	-495
20	-450	0	-680	0	-672
0	-637	-20	-844	-20	-837
-20	-825	-40	-1007	-40	-1015
-40	-1014	-60	-1205	-60	-1200
-60	-1189	-80	-1348	-80	-1344
-80	-1342	-100	-1455	-100	-1450
-100	-1485	107	100	109	128
105	200	151	157	150	200
145	285	201	300	203	300
194	400	251	473	253	428
243	528	281	543	285	458
277	613	329	644	332	500
328	728	380	787	383	744
378	857	419	858	420	744
417	913	477	872	477	744
478	1000	516	930	516	757
515	1100	550	944	548	757
546	1140	594	1058	594	843
591	1270	118	714	116	100
115	128	146	300	141	129
138	143	220	543	219	200
215	257	256	643	252	314
249	357	289	800	289	386
284	444	334	973	335	415
332	557	367	1030	367	472
364	614	408	1085	410	457
407	658	441	1128	409	457
443	714	450	1230	517	558
515	842	547	1230	542	585
542	914	560	1260	565	613
561	970	597	1330	600	685
599	1170	628	1410	633	772
623	1200				

Table VII. Thermal Expansion Data for X-131 Laminate

Transverse Direction		Longitudinal Direction		Diagonal Direction	
Temp °F	Avg Expansion µ in/in	Temp °F	Avg Expansion µ in/in	Temp °F	Avg Expansion µ in/in
50	-180	50	-110	50	-120
20	-420	20	-350	20	-410
0	-605	0	-560	0	-610
-20	-805	-20	-770	-20	-785
-40	-1002	-40	-960	-40	-970
-60	-1169	-60	-1130	-60	-1164
-80	-1352	-80	-1306	-80	-1317
-100	-1480	-100	-1470	-100	-1450
75		80		80	
100	171	100	169	97	164
135	520	145	564	145	532
175	828	188	808	182	737
230	948	242	836	242	750
240	994	340	887	338	785
272	1040	400	973	399	974
320	1140	453	1060	454	1150
352	1175	507	1083	508	1362
400	1270	553	1118	553	1412
440	1333	78		78	
480	1422	103	207	103	179
505	1476	140	578	140	522
557	1435	182	827	177	755
79		232	846	232	760
100	1464	245	887	246	760
138	457	274	945	275	793
183	700	325	1102	323	873
233	768	354	1112	353	828
334	903	402	1200	402	837
397	1060	440	1262	440	887
452	1190	480	1420	483	926
505	1296	533	1365	533	961
520	1280	555	1265	558	814

Table VIII. Thermal Expansion Data for CTL 37-9X Laminate

Longitudinal Direction		Transverse Direction		Diagonal Direction	
Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in
50	95	50	57	50	104
20	239	20	215	20	247
0	365	0	357	0	372
-20	462	-20	428	-20	470
-40	536	-40	478	-40	568
-60	611	-60	587	-60	664
-80	688	-80	658	-80	737
-100	744	-100	772	-100	772
84		71		83	
125	143	84	143	124	114
185	415	141	214	182	357
226	542	179	329	224	485
253	685	230	528	253	615
289	814	267	658	286	715
323	985	302	772	320	828
353	1100	343	900	353	900
373	1200	366	970	372	958
413	1370	392	1050	409	1050
437	1485	427	1180	435	1112
465	2900	454	1300	464	1185
490	3160	484	1370	491	1228
529	3330	517	1470	530	1270
579	3460	551	1520	579	1270
607	3530	579	1560	607	1270
73		635	2350	72	
91	285	84		89	285
150	285	122	128	145	228
189	428	178	386	184	371
236	570	218	443	234	555
272	657	248	587	271	684
307	715	282	643	306	798
347	828	317	744	347	928
368	958	349	813	367	970
397	985	372	885	394	1055
429	1110	408	1000	430	1170
462	1240	434	1085	443	1265
487	1340	464	1185	485	1350
520	1430	488	1270	523	1440
558	1540	527	1385	558	1458
581	1600	579	1470	583	1458
637	1760	607	1500	640	1510

Table IX. Thermal Expansion Data for Asbestos-Phenolic 9526D Laminate

Longitudinal Direction		Transverse Direction		Diagonal Direction	
Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in
50	-80	50	-53	50	90
20	-166	20	-115	20	147
0	-226	0	-161	0	200
-20	-286	-20	-215	-20	250
-40	-336	-40	-261	-40	296
-60	-397	-60	-310	-60	351
-80	-454	-80	-335	-80	396
-100	-508	-100	-360	-100	420
83		81		73	
124	714	116	427	107	143
170	186	165	157	150	857
214	272	207	214	206	157
261	314	256	285	259	228
300	343	291	329	346	242
329	400	326	385	386	300
359	486	356	470	422	357
378	572	375	513	468	428
402	628	401	585	504	500
435	687	435	629	543	600
461	728	457	670	579	670
487	786	488	728	635	828
518	857	513	800	675	928
551	943	547	885	683	958
567	1000	565	928	82	
613	1100	608	1010	121	
73		73		172	128
105		204	143	214	186
150	572	148	572	329	228
205	114	198	114		243
258	214	252	200	333	257
312	242	310	229	359	285
343	286	341	286	377	343
386	372	383	358	405	343
423	428	422	414	440	286
468	514	468	486	465	400
504	572	501	558	494	414
542	685	539	643	526	414
573	772	571	728	558	485
627	943	627	830	573	542
664	1025	662	900	617	628
698	1058	673	900		

Table X. Thermal Expansion Data for Fluted Core 5016

Longitudinal Direction		Diagonal Direction		Transverse Direction	
Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in
50	120	50	215	50	-55
20	382	20	406	20	-322
0	520	0	568	0	-435
-20	678	-20	703	-20	-575
-40	803	-40	842	-40	-686
-60	935	-60	979	-60	-847
-80	1038	-80	1097	-80	-915
-100	1135	-100	1200	-100	-1050
77		72		67	
110	172	101	214	98	255
139	400	157	546	158	543
187	713	205	942	203	908
227	928	240	1060	237	1042
268	1000	297	1200	297	1140
328	1200	358	1340	358	1260
387	1340	387	1422	387	1285
428	1430	418	1470	417	1326
478	1472	565	1620	572	1555
526	1560	602	1722	608	1735
565	1580	608	1728	613	1758
605	1667	77	185	82	
637	1800	107	428	103	186
101	223	140	693	135	422
157	514	185	853	181	692
204	892	227	885	222	886
237	1020	270	885	265	956
295	1072	326	1072	322	1130
357	1182	387	1210	387	1262
387	1215	428	1290	428	1345
417	1260	477	1328	478	1366
566	1515	528	1360	528	1435
603	1745	563	1400	565	1500
608	1775	603	1433	605	1578
		633	1464	637	1676

Table XI. Thermal Expansion Data for Shell X-131 Fluted Core

Transverse Direction		Longitudinal Direction		Diagonal Direction	
Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in	Temp °F	Avg Expansion μ in/in
50	-210	50	-210	50	-230
20	-520	20	-300	20	-559
0	-698	0	-565	0	-730
-20	-880	-20	-820	-20	-915
-40	-1045	-40	-962	-40	-1063
-60	-1208	-60	-1110	-60	-1230
-80	-1380	-80	-1250	-80	-1374
-100	-1530	-100	-1360	-100	-1530
67		67		101	
117	500	119	230	118	515
173	1000	175	540	175	1100
243	1300	234	850	246	1285
271	1344	270	990	275	1500
302	1540	304	1170	307	1765
335	1685	338	1360	335	1950
381	1868	383	1540	383	2200
415	2010	414	1640	415	2370
467	2150	463	1740	463	2490
487	2155	487	1760	490	2490
503	2115	503	1860	503	2150
512	2050	506	1860	508	2150
68		68		68	
80	672	82	672	80	357
150	787	152	713	140	672
168	1040	177	873	160	855
207	1182	212	1054	195	1145
235	1305	240	1122	222	1320
257	1388	260	1162	245	1415
293	1412	297	1275	297	1535
307	1568	308	1325	376	2270
343	1795	344	1508	413	2210
360	1875	364	1580	462	1922
387	2010	381	1710	481	1628
398	2060	397	1782	515	1455
438	2110	435	1868	538	1285
458	2060	458	1885	550	1265
478	2020	467	2270		

Table XII. Thermal Expansion Data in the Thickness Direction of X-1068 Laminate

Temperature °F	Expansion μ in/in
Run on 3-15/16 in. Sample	
86	915
120	3,690
158	8,330
221	15,650
295	23,300
396	34,200
448	39,700
480	42,300
487	43,800
Consecutive Runs on 3-1/2 in. Sample	
123	4,230
189	11,920
243	19,200
302	28,700
344	31,000
383	35,900
97	286
140	1,312
201	3,970
272	7,780
333	13,100
369	16,400
415	19,900
444	22,500
493	24,700

Temperature °F	Expansion μ in/in
Consecutive Runs on 2-7/8 in. Sample	
-7	-1,665
-35	-11,050
-69	-18,420
-85	-22,100
-21	-7,560
-61	-18,600
-89	-26,000
-98	-29,700

Table XIII. Thermal Expansion Data in the Thickness Direction of X-131 Laminate

Temperature °F	Expansion µ in/in	Temperature °F	Expansion µ in/in
Consecutive Runs on 7-3/16 in. Sample			
86	279	-11	863
102	974	-63	1,183
142	2,910	-98	1,410
192	7,100		
230	12,220	65	
242	13,980	-23	892
277	19,000	-61	1,170
330	26,000	-85	1,310
365	30,200	-96	1,322
409	36,300		
435	41,100		
501	48,500		
523	49,800		
95	404		
145	1,924		
213	4,420		
305	9,030		
367	13,120		
446	19,880		
475	22,900		
506	26,100		
134	1,517		
196	3,340		
259	5,000		
290	7,280		
347	10,620		
408	14,700		
450	18,150		
487	21,800		
529	26,300		

Table XIV. Thermal Expansion Data in the Thickness Direction of CTL 37-9X Laminate

Temperature °F	Expansion μ in/in
Consecutive Runs on 7-1/4 in. Sample	
85	152
107	331
148	758
181	1,145
213	1,395
246	1,463
280	1,463
312	1,350
327	1,380
383	1,410
415	1,517
438	1,575
478	1,700
576	1,545
85	13.8
123	278
150	648
222	1,230
253	1,628
320	2,540
385	3,450
433	3,910
493	4,770
522	5,070
111	262
142	538
210	1,298
253	1,720
305	2,440
363	3,300
422	4,290
467	5,020
503	5,530
506	6,130
Consecutive Runs on 5-1/4 in. Sample	
-11	-1,275
-55	-1,715
-80	-1,905
-95	-3,990
-98	-5,910
-21	-1,542
-36	-1,732
-74	-4,020
-90	-7,980
-98	-9,880

Table XV. Thermal Expansion Data in the Thickness Direction of Asbestos-Phenolic 9526D Laminate

Temperature °F	Expansion μ in/in	Temperature °F	Expansion μ in/in
Consecutive Runs on 7-1/8 in. Sample			
90	155	119	548
127	1,138	155	1,050
213	1,812	182	1,447
253	1,980	223	2,020
292	1,572	262	2,750
325	1,208	323	3,690
380	1,332	383	4,760
435	1,785	441	5,850
487	2,150	483	6,670
512	2,120	518	7,420
522	2,160	552	8,180
85	98.3	Consecutive Runs on 5-1/4 in. Sample	
133	717		
163	1,137		
190	1,518	-19	-610
242	2,270	-65	-1,333
274	2,810	-93	-1,810
338	3,870	-101	-1,945
402	4,920		
444	5,720	-14	-705
470	6,210	-62	-1,467
503	6,780	-98	-1,885
529	7,380	-103	-5,750

Table XVI. Thermal Expansion Data in the Thickness Direction of 5016 Fluted Core Panel

Temperature °F	Expansion μ in/in	Temperature °F	Expansion μ in/in
Consecutive Runs on 5-3/8 in. Sample		Run on 5-1/8 in. Sample	
69	2,710	-8	4,300
226	5,480	-34	8,550
286	9,080	-60	13,060
347	9,640	-73	15,220
380	11,850	-99	17,800
416	16,000		
456	16,880		
488	18,700		
514	21,100		
107	316		
156	1,097		
254	2,380		
258	5,000		
290	5,930		
320	7,020		
347	8,330		
389	10,130		
428	12,200		
461	12,360		
505	16,620		
Run on 5-7/16 in. Sample			
-7	940		
-24	2,050		
-30	4,270		
-44	6,280		
-59	10,300		
-70	12,350		
-91	14,400		

Table XVII. Thermal Expansion Data in the Thickness Direction of X-131 Fluted Core

Temperature ° F	Expansion μ in/in	Temperature ° F	Expansion μ in/in
Consecutive Runs on 5-1/4 in. Sample		Consecutive Runs on 5-1/8 in Sample	
138	2,440	-7	-1,190
210	6,770	-65	-4,320
264	12,200	-82	-10,580
321	17,100	-98	-14,650
364	20,500		
400	23,500	-30	-3,910
446	26,400	-59	-8,260
475	30,000	-95	-14,430
		-102	-18,500
104	457		
146	4,100		
215	5,750		
279	12,620		
345	18,500		
383	22,000		
456	28,600		
497	32,200		

Appendix III

Table XVIII. Thermal Conductivity Data

Temperature °F	ΔT, °F	[1]Volts	[1]Amps	Watts	Thickness, in.	Area, sq in.	K, Btu/hr/sq ft/in/° F
			Selectron 5016 Fluted Core				
-52	57.9	27.0	0.412	11.1	.444	64	0.65
+52	203.2	60.0	0.950	57.0	.444	64	0.95
+164	159.2	59.0	0.937	55.3	.444	64	1.18
+249	157.3	80.2	1.29	103.3	.444	64	1.35
+335	341.6	98.1	1.56	153.0	.444	64	1.52
+470	468.0	117.0	1.85	217.0	.444	64	1.58
+565	635.5	131.3	2.06	272.0	.444	64	1.45
			X-1068 Laminate				
-51	23.7	39.9	0.635	25.3	.128	64	1.04
6	78.2	73.0	1.15	84.0	.128	64	1.05
50	110.3	90.5	1.43	129.0	.128	64	1.17
117	65.6	73.0	1.16	84.3	.128	64	1.26
151	14.8	29.9	0.762	22.8	.128	64	1.51
153	14.6	29.9	0.760	22.7	.128	64	1.52
158	106.0	97.5	1.54	150.0	.128	64	1.41
164	109.2	98.7	1.55	152.5	.128	64	1.40
164	104.5	98.5	1.55	152.5	.128	64	1.43
191	148.0	117.0	1.81	211.0	.128	64	1.41
201	21.7	36.7	0.94	34.5	.128	64	1.56

Appendix III

Table XVIII. Thermal Conductivity Data (continued)

Temperature °F	ΔT, °F	[1]Volts	[1]Amps	Watts	Thickness, in.	Area, sq in.	K, Btu/hr/sq ft/in./° F
X-1068 Laminate (continued)							
215	23.8	39.1	0.995	38.9	.128	64	1.59
308	248.8	158.0	2.53	395.0	.128	64	1.55
308	248.8	158.0	2.53	395.0	.128	64	1.55
311	36.5	49.7	1.26	62.7	.128	64	1.69
313	37.5	49.8	1.26	62.9	.128	64	1.64
381	50.6	59.0	1.47	86.9	.128	64	1.68
476	59.8	65.1	1.67	108.5	.128	64	1.76
480	60.5	65.2	1.67	108.5	.128	64	1.74
540	80.2	72.6	1.83	132.6	.128	64	1.62
548	81.5	72.6	1.83	132.6	.128	64	1.60
Shell X-131 Fluted Core							
-45	83.0	28.5	0.445	12.7	.668	64	0.78
+69	279.5	60.0	0.990	59.4	.668	64	1.1
221	277.9	75.0	1.21	90.3	.668	64	1.66
360	426.3	99.2	1.56	155.0	.668	64	1.85
439	514.2	110.2	1.73	192.0	.668	64	1.88
525	613.0	125.0	1.98	247.0	.668	64	1.9

Appendix III

Table XVIII. Thermal Conductivity Data (continued)

Temperature °F	ΔT, °F	^{1}Volts	^{1}Amps	Watts	Thickness, in.	Area, sq in.	K, Btu/hr/sq ft/in./° F
Shell X-131 Laminate							
-47	14.7	30.0	0.488	14.7	.135	64	1.02
51	48.9	57.4	0.900	51.7	.135	64	1.11
165	43.2	60.5	0.975	59.0	.135	64	1.42
165	43.2	60.2	0.975	58.8	.135	64	1.41
197	55.2	70.0	1.11	77.8	.135	64	1.46
253	75.2	85.0	1.34	113.6	.135	64	1.57
257	74.8	85.0	1.34	113.6	.135	64	1.58
339	105.8	104.8	1.65	173.0	.135	64	1.69
444	139.9	122.2	1.93	235.0	.135	64	1.74
558	224.1	141.2	2.21	312.0	.135	64	1.44
CTL 37-9X							
-55	24.8	30.0	0.450	13.5	.138	64	0.575
30.2	74.8	59.9	0.940	56.2	.138	64	0.787
150	65.9	60.0	0.930	55.8	.138	64	0.898
201	91.3	72.0	1.16	83.5	.138	64	0.97
245	109.8	87.0	1.34	116.0	.138	64	1.12
249	116.8	87.0	1.40	122.0	.138	64	1.11
315	149.3	99.0	1.58	156.0	.138	64	1.11
433	203.4	122.0	1.94	236.0	.138	64	1.23
535	242.0	140.0	2.20	308.0	.138	64	1.35
640	280.0	154.0	2.45	377.0	.138	64	1.42

Appendix III

Table XVIII. Thermal Conductivity Data (continued)

Temperature °F	ΔT, °F	[1]Volts	[1]Amps	Watts	Thickness, in.	Area, sq in.	K, Btu/hr/sq ft/in./° F
			Asbestos-Phenolic 9526D Laminate				
-60	19.4	28.4	0.500	14.2	.126	64	0.71
-57	20.7	28.5	0.500	14.2	.126	64	0.665
32	64.0	61.0	0.975	59.5	.126	64	0.92
143	49.6	58.9	0.925	54.5	.126	64	1.07
252	102.9	88.0	1.40	12.3	.126	64	1.16
352	147.6	109.0	1.71	18.6	.126	64	1.24
453	190.3	127.0	1.98	251.5	.126	64	1.29
554	230.5	142.5	2.24	318.0	.126	64	1.34
556	230.5	143.0	2.23	319.0	.126	64	1.34
636	256.4	152.5	2.43	360.6	.126	64	1.40

[1] Different meters used to cover range.