# EFFECT OF THERMAL GRADIENTS ON THE STRENGTH OF PHENOLIC AND SILICONE REINFORCED PLASTIC LAMINATES

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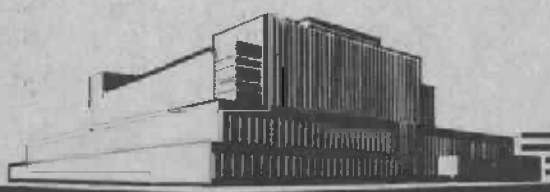

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FOREST SERVICE
In Cooperation with the University of Wisconsin

# EFFECT OF THERMAL GRADIENTS ON THE STRENGTH PROPERTIES OF PHENOLIC AND SILICONE REINFORCED PLASTIC LAMINATES[1]

By

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## Abstract

Phenolic and silicone laminates 1/8 inch thick were investigated to determine: (1) The thermal gradient present when various conditions of boundary temperatures were maintained, (2) the time required to reach this steady-state thermal gradient, and (3) the effect of the thermal gradient on the compressive strength properties of the laminates.

Data on the three phases of the study are presented in tables and figures. In general, it was found that (1) for all practical purposes, the thermal gradient is a straightline relationship between the boundary temperatures; (2) the time required to reach a steady-state thermal gradient can be a matter of seconds in 1/8-inch-thick phenolic or silicone glass laminates, depending on the boundary conditions and intensity of heating media; and (3) compressive strength decreases as the difference in boundary temperatures is increased. The compression tests were all made parallel to the warp and after a 10-minute soak at a given test temperature

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[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

Report No. 1878

Approximately 200 thermal gradient and compression tests were made during the study. An analysis of the thermal strains in a member subjected to a thermal gradient is presented.

## Introduction

The increasing speeds of modern flight vehicles and the corresponding increases in temperature that occur in their structural components require knowledge of the resistance of materials to these elevated temperatures and of their strength properties under various thermal gradient conditions. Data on strength values at various elevated temperatures for different periods of exposure have been obtained at the Forest Products Laboratory in a cooperative program with Wright Air Development Division. Reports on a phenolic laminate[3], on a phenolic asbestos laminate[4], and on a silicone laminate[5] have been published. Other materials, including an epoxy laminate, are being investigated.

Since a thermal gradient as well as a constant temperature condition may exist in plastic laminates used in flight vehicles, it is important that information on the strength properties under different surface temperature conditions be acquired. This study was undertaken in order to provide design criteria over the useful range in elevated temperatures for phenolic and silicone glass-fabric laminates. These laminates were selected because, at 500° F., they represent materials with approximately the lowest and highest rates of thermal conductivity according to figure 7-2 of the Military Handbook 17, "Plastics for Flight Vehicles," Part I.

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[3] Boller, K. H. Strength Properties of Reinforced Plastic Laminates at Elevated Temperatures (CTL-91LD Resin with 181-A1100 Glass Fabric). WADC Technical Report 59-569, July 1959.

[4] Boller, K. H. Strength Properties of Reinforced Plastic Laminates at Elevated Temperatures (Phenolic-Asbestos, R/M Pyrotex Felt Style 41-RPD). WADD Technical Report 60-177, Part I, in press.

[5] Boller, K. H., and Kimball, K. E. Strength Properties of Reinforced Plastic Laminates at Elevated Temperatures (DC 2106 Resin and 181 Heat-Cleaned Glass Fabric). WADC Technical Report 59-229, September 1959.

The scope of the study included:

(1) Determination of the internal thermal gradient of the laminate under various conditions of boundary temperatures.

(2) Determination of the time required to reach a steady-state condition under various boundary temperatures.

(3) Determination, by compression tests, of the stress-strain relationship and strength values when a steady-state condition of thermal gradient is maintained.

The temperature for these laminates varies from 100° F. on the "cold" side to 1,000° F. on the "hot" side, depending on the material and the boundary conditions desired.

Available data on typical laminates show that compressive and flexural properties vary more with temperature and time at a given temperature than do tensile properties. Therefore, effects of thermal gradients can be studied most effectively from compression or flexure tests. The compression tests appeared to be the more suitable for several reasons, including: (1) Compressive data are generally more useful for design purposes than flexural data; and (2) compression specimens are stressed to reasonably the same extent over the entire cross section instead of a complex stress distribution such as occurs in a flexure test.

## Test Material

The laminates used in these thermal gradient studies were from the same or comparable lots of material that had been supplied for the previously reported elevated temperature studies.[3, 5] The phenolic-glass-fabric material was furnished by Cincinnati Testing and Research Laboratories, Inc., and was fabricated by American Reinforced Sales. The general fabrication and postcuring information was furnished by the supplier; average values of resin content, Barcol hardness, and specific gravity were obtained at the Forest Products Laboratory. The information on the phenolic laminate is as follows:

Resin: CTL-91LD.

Catalyst: None.

Fabric: 181-A1100 glass fabric, parallel laminated back to back.

Number of plies: 14.

Method of impregnation: "B" stage "prepreg" cloth used; material from standard production run which is impregnated on a Waldron-type treater, using dip pan, metered squeeze rolls, drying oven, cooling zone, and windup.

Initial resin content: 40 ±2 percent, including volatiles.

Precure: None.

Cauls and parting films: Steel cauls with a No. 8 mirror finish; 600 PT cellophane as a releasing film.

Curing cycle: 200 pounds per square inch at 265° to 275° F. for 40 to 50 minutes.

Removal from press: Cooled under pressure.

Postcure: 24 hours each at 250°, 300°, and 350° F.

Resin content: 37.3 percent (determined from burnoff tests).

Barcol hardness: 86.

Specific gravity: 1.79.

Nominal size of panels: 1/8 by 36 by 36 inches.

The silicone-impregnated glass cloth was impregnated by the U.S. Polymeric Company and supplied to the Laboratory by the Dow-Corning Company. One 1/8- by 36- by 36- inch panel was fabricated at the

Laboratory by methods prescribed by the supplier. The following general information on the material was either from the supplier or obtained by tests at the Forest Products Laboratory.

Resin: DC 2106.

Catalyst: XY-15.

Fabric: 181 glass fabric, heat-cleaned, parallel laminated.

Number of plies: 13.

Curing cycle: 100 pounds per square inch at 175° C. (350° F.) for approximately 30 minutes.

Postcure: 48 hours at 250° C. (482° F.).

Resin content (estimated)[6]: 34.5 percent.

Barcol hardness: 32 (before postcure).

Specific gravity: 1.80.

Nominal size of panel: 1/8 by 36 by 36 inches.

Laminates of both the phenolic and silicone resins had to be specially fabricated to 1/8 by 1 by 3 inches for the thermal gradient studies. These small laminates were made from material comparable to that used in the panels from which the compression specimens were cut.

The material for these laminates was supplied by the respective companies, and the same procedures of fabrication were followed in making these special small panels as were used for the large test panels.

In order to measure the temperature gradient in these small laminates, thermocouples were placed in the laminates during fabrication (fig. 1). The thermocouples were made of 0.005-inch-diameter chromel and alumel wire that was fused to make the junction and were placed on the faces and between the plies of 181 glass fabric. So that the thermocouple junctions would not be concentrated in one location,

[6] Assuming the fabric weight to be 8.90 ounces per square yard.

they were spaced approximately 1/8 inch apart throughout the longitudinal center and in the transverse center of the piece.

## Test Methods

Since rapid heating and accurate control of the boundary temperatures were of vital importance in these tests, the heating and cooling procedures were somewhat complex. Two types of heating devices, a specially built electric oven and a battery of infrared lamps, were tried as heating media with little or no success. Both required extended periods (as much as 10 minutes) to heat one side of the specimen to 500° F. Since faster heating was desired, a third type was tried. It consisted of a specially wound, 1/2-inch-wide by 2-inch-long, nichrome-ribbon coil of 2-1/2-ohm resistance. The heat output of this coil could be varied with a powerstat and transformer unit. The powerstat was connected to a 220-volt line and, in turn, to the transformer, which was wired so that it delivered 16 volts and 22 amperes when the powerstat was set at 100 percent of capacity. The nichrome-ribbon coil delivered uniform heat output over its length, which meant that the specimen surface would be uniformly heated throughout the test area. The flow of current to the heater was controlled by a thermocouple mounted on the surface of the specimen and connected to an electronic recorder-controller and relay system.

The other surface of the test specimen was cooled by flowing air over it. This was made possible by redesigning one portion of the compression jig described in Method 1021.1 of Federal Specification L-P-406b, "Plastics, Organic: General Specification, Test Methods." This side of the jig had lateral slots cut across the face next to the specimen. These slots were connected to a distribution chamber on the back of the jig by drilling holes through the jig; through these holes a uniform supply of air flowed. This distribution chamber, in turn, was connected to a 75-pound air supply line with a manually operated needle valve to control the air flow.

Under extreme thermal-gradient conditions, the cooling effect of room-temperature air was not great enough to maintain the cold surface temperature desired, so the compressed air had to be cooled below room temperature. This was accomplished by passing the air through cylinders filled with dry ice before it entered the distribution

chamber on the jig. In this manner, the air leaving the jig could be cooled to -40° F. before it contacted the surface of the specimen. The cold surface temperatures were maintained at the desired levels by regulating the flow of air with the needle valve. A thermocouple on the face of the specimen and a recording potentiometer were used to indicate when the air flow valve was correctly set to give the cold face the temperature desired. Figure 2 shows the compression jig with the air slots connected to the air distribution chamber and the air supply line. The compression jig described was used in all of the tests to support the specimen during loading to prevent buckling as well as the control surface temperatures.

All test specimens were normal conditioned in an atmosphere of 73° F. and 50 percent relative humidity for at least 2 weeks before test.

## Thermal-Gradient Determinations

The special laminates with the embedded thermocouples were mounted in the compression jig with the nichrome-ribbon coil on one face and the cooling portion of the jig on the other. A thin sheet of copper (16 gage, B&S) was placed on each face of the specimen in order to distribute more evenly the heat and the cool air over the respective faces. A dummy specimen 1/8 inch thick, made of the material under test, was placed between the heater and the jig to retard heat losses through the metal jig. The thermocouple leads on the high-temperature surface of the specimen were then connected to the electronic recorder-controller that operated the "on" and "off" control of the heating coil. The thermocouple leads on the low-temperature surface of the specimen were connected to the recording potentiometer to show the temperatures being maintained on that surface. The other themocouple leads were connected to a jackbox. By means of a portable potentiometer, temperatures could be readily determined at each of the internal locations. These temperatures were read at different time intervals to determine when a steady state of thermal gradient was reached and also the form of the gradient through the 1/8-inch laminate.

Thermal gradient tests were made while different combinations of surface temperatures were maintained on the special laminates. The rates of heating were governed by the powerstat setting. In none of the tests was the powerstat set to its full capacity, because the

cold surface temperatures, which were controlled manually, could be adjusted more accurately at the lower rates of heating.

## Compression Tests

The compression tests were designed to show the effect of exposure to different levels of surface temperatures on the strength properties of the material. The specimens used for these tests were necked-down from strips 1/8 by 3/4 by 3-1/8 inches to a net section 1/2 inch wide and 1-1/4 inches long with an arc of 2-inch radius in the transition portions. The bearing ends of these specimens were ground smooth, parallel to each other, and perpendicular to the longitudinal axis. These compression specimens did not have any surface or embedded thermocouples.

The setup (fig. 3) was put in place in the jig in the following order:

(1) The portion of the jig that was fastened to the "L"-shaped support was considered as the base of the setup. This was also the hot side of the jig during test.

(2) A dummy specimen about 2-3/4 inches long was installed to retard excessive heat losses from the coil to the metal jig.

(3) The nichrome-ribbon coil covered on each side with a thin layer of mica was attached.

(4) A thin piece of copper (16 gage, B&S) the same size as the coil was installed.

(5) A chromel-alumel thermocouple junction of 36 gage (B&S) wire was attached.

(6) The test specimen was put in place.

(7) An iron-constantan thermocouple junction of 30 gage (B&S) wire was installed.

(8) Another piece of thin copper the same size as the coil was attached.

(9) The slotted portion of the compression jig was then put in place and the whole setup held together with four bolts. These bolts were

drawn up sufficiently tight to prevent buckling of the specimen during loading but not tight enough to restrain the compressive deformations.

A compressometer (fig. 4) for measuring compression strains was also fastened to the "L" base. It consisted of two lever arms, each of which was in part a frame that encompassed the specimen and jig. At one end the lever arms were supported on pivots and columns to the base. By use of the frame, the lever arms were attached to the specimen by another set of pivot points situated exactly 1 inch apart. At twice the distance from the base pivot points to the specimen pivot points, cables were attached that extended to the lever arms of the microformer unit. Both lever arms of the microformer unit were weighted to keep tension on the cables (fig. 5).

The recorder used in connection with the microformer unit had three magnifications; the high and medium settings, however, were most commonly used where 1.0 inch on the recorder graph represents 0.00166- and 0.0033-inch movement, respectively, at the pivot points on the specimen. Load-deformation data were automatically recorded so that the modulus of elasticity, proportional limit, and maximum stress could be computed.

The thermocouple on the heated face of the specimen was connected to the electronic recorder-controller, while the one on the cold face was connected to the recording potentiometer.

Figure 6 gives an overall view of the equipment used in conducting the compression tests of the specimens subjected to a thermal gradient.

In some of the compression tests, both faces of the specimen were kept at the same elevated temperature, with no temperature gradient. In these tests, a nichrome-ribbon heating coil of 2-1/2-ohm resistance was placed on each broad side of the specimen. With this setup the specimen was uniformly heated on both faces. These setups served for control purposes and yielded data for comparison with results of other studies in which different heating methods and periods of exposure had been used.

In the constant or uniform temperature tests, heat was controlled on one face only. Since the resistance of the two coils was balanced, the heat output of each was also balanced. The recording potentiometer was, however, connected to the face opposite the control unit to verify that the face temperatures were the same.

In all of the compression tests, the required temperature levels were held for 10 minutes before starting the test. The compression test required 2 to 4 minutes after loading was started.

## Presentation of Data

### Thermal Gradients

Typical data showing the temperature that existed through the thickness of the phenolic and silicone laminates after various soak periods are presented in tables 1 and 2.

Plots of the temperature gradients in both types of laminates are shown in figures 7 and 8. Curves showing the gradients at various surface temperatures are presented. The values plotted represent the average temperature of readings taken after five different time intervals. Data presented in table 1, for example, are represented by one of the curves in figure 7.

### Compression Tests

Values of modulus of elasticity, proportional limit, and maximum compressive stress for the two different laminates are presented in tables 3 and 4. Properties under various conditions of temperature are shown and grouped according to the average test temperature.

The specific values in figures 9 and 10 show the percentage of maximum stress at room temperature that was retained by the material when it was subjected to different temperature gradients. By interpolation between the points, contour lines have been drawn to give an approximate empirical percentage of room temperature strength that might be expected from similar material at temperature levels other than those tried.

### Comparative Values of Maximum Compressive Stress

Table 5 is a tabulation of values of compressive strength obtained during this and previous investigations.[3,4] Material from the same

or comparable lots was used in all studies, so similar strength properties might be expected. In reviewing the data of table 5, it must be kept in mind that, (1) two different methods of heating were employed and (2) the periods of soak were different.

## Discussion of Results

The procedures followed in establishing and maintaining constant temperature gradients in a steady state proved to be satisfactory. The desired temperatures could be established in a short period and maintained throughout the 10-minute soak and the following test period.

### Thermal Gradients

The series of tests made on the special laminates with the embedded thermocouples provided data of the type desired. Continuous readings on interior thermocouples showed that the thermal gradient desired was reached at approximately the same time that the surface temperature were attained, usually within 1/2 to 1-1/2 minutes.

Data presented in tables 1 and 2 represent temperatures taken at 5-, 10-,15-, 20-, and 30-minute intervals after the desired temperature was reached on the hot face. In general, the temperature gradient for the respective surface conditions was about the same for the different soak periods. Some variation in temperature is to be expected because of the on-off action of the hot face control unit. Furthermore, the rate of air flow over the cold surface was not changed during the test. It is quite possible that the cooling effect of the air flow might change during the test, expecially when dry ice was used in the system. This would account for the change in the cold-side temperature noted in table 1.

The heating element on the hot face was operated by means of an electronic controller that caused a relay to be in the "on" or "off" position. The heating element was never "on" continuously after the hot face of the specimen reached control conditions. Despite the fact that the controller sensitivity was set at its optimun control point, which was just short of the point that caused the relay to chatter, there was quite a pronounced cyclic action present. This

cyclic action sometimes caused the individual readings at any one thermocouple location to vary by a substantial amount. Approximately 2 minutes were required to read the temperatures at 15 locations in the laminates. During this period the heater may have been on and off 10 or 20 times, depending on the surface conditions being maintained. Therefore, to offset the effects of the cyclic heating action, the curves shown in figures 7 and 8 are plotted from data that are averages of the readings taken after 5, 10, 15, 20, and 30 minutes of heating.

The results of these tests show that, for practical purposes, the temperature gradient in a 1/8-inch-thick phenolic or silicone laminate can be considered as a straightline relationship.

It would have been possible to change the time required to reach the desired temperatures on the hot face by further adjusting the powerstat, but moderate changes would probably not have affected the gradient. An attempt was made to adjust the setting so that the hot surface temperature would be reached in about 3/4 minute. The actual time required varied, however, depending upon the surface temperatures. Typical times required to reach control conditions on the silicone laminate were as follows:

| Hot surface °F. | Cold surface °F. | Time Sec. |
|---|---|---|
| 400 | 200 | 25 |
| 600 | 200 | 35 |
| 800 | 200 | 60 |
| 1,000 | 200 | 90 |

When the silicone specimens were heated to uniform temperatures throughout, with heating coils on both faces, temperatures as high as 1,000° F. were reached in approximately 45 seconds. This rate of heating was also controlled by the setting on the powerstat and could have been accelerated.

## Compression Tests

Phenolic laminates.--Data from compression tests of phenolic laminates are presented in table 3 and figure 9. These data show that, with a 10-minute soak at uniform temperatures of 300° F. and higher,

there is a marked reduction in compressive strength from room temperature values. As the level of temperature is increased, less compressive strength is retained. On the basis of the strength at room temperature, the strength retention is 73 percent when the temperature through the piece is 300° F., 54 percent at 400° F., 35 percent at 500° F., and 29 percent at 600° F.

Compressive strength values of the phenolic laminate also show further tendencies to decrease when thermal gradients are introduced. This is clearly shown in table 3. For example: Consider an average temperature of 300° F. in the laminate. When a uniform temperature was maintained, 73 percent of the compressive strength at room temperature was retained. When a thermal gradient of 200° F. was present, the retention in strength was 66 percent; and at a thermal gradient of 400° F., the strength retention was 55 percent. Percentage retentions of compressive strength at other uniform and gradient temperature levels are also shown in table 3.

If the cold side of a specimen is maintained at a set temperature and the hot side is heated further, the percentage retention of room temperature compressive strength decreases. For example, when both the cold and hot sides are at 300° F., 73 percent of the compressive strength is retained. However, when the hot side is raised to 500° F., the amount retained drops to 40 percent; and when the hot side is at 700° F. only 32 percent of the strength is retained.

When the hot side of a specimen is maintained at a constant temperature and that of the cold side is decreased, there is usually a slight increase in strength. The increase does not always occur, however, as is evident from the empirical contour lines of figure 9. Vertical contour lines would indicate no change in strength with a change in only the cold-face temperature.

Table 3 also shows that the modulus of elasticity of the phenolic laminate is lowered as the constant temperature is raised. The lowest value is about 77 percent of the room temperature value. The presence of a thermal gradient generally had little effect on the modulus of elasticity but was evident in the group having an average temperature of 300° F. At average temperatures of 400°, 500°, and 600° F. the average modulus of elasticity was about the same irrespective of the temperature or the thermal gradient.

The proportional limit values at constant temperatures do not show a definite trend; however, within groups at the same average temperature there is a tendency toward a lower proportional limit as the temperature gradient is increased.

The percentage of room temperature compressive strength values that might be expected from a phenolic laminate soaked for 10 minutes at various intermediate temperature levels can be estimated from figure 9.

Table 5 shows comparative values of compressive strength at constant temperature as obtained with oven heat in a previous study[3] and with conduction heating in this study. The 10-minute soaking period with conduction heating appears to cause greater reduction in compressive strength than 30 minutes of oven heating. This is true to 600° F., which was the highest uniform temperature maintained with conduction heating. Even for soaking periods of 100 hours, convection heating at 300° and 400° F. did not reduce the compressive strength as much as the 10-minute soak with conduction heating.

Other data indicate that this difference is primarily an effect of time at temperature rather than an effect of the heating media; the strength after 1/2 hour of conduction heating is likely to be higher than that after 10 minutes of conduction heating.

Silicone laminate.--Data from compression tests are presented in table 4 and figure 10. These data show the effects of uniform elevated temperatures and thermal gradients at different levels of temperature on the compressive strength of the laminate after a 10-minute soak period. Under these conditions, there is a marked reduction of compressive strength from room temperature values as the temperature on either one or both faces is increased to 300° F. or more. The percentage of compressive strength retained, on the basis of room temperature strength, showed the following: 60 percent retained at 300° F.; 54 percent at 400° F., 44 percent at 500° and 600° F., and 35 percent at 700° and 800° F.

Table 4 has the various temperature gradient tests grouped as average temperatures in the test specimens. The data show that the introduction of a gradient at 300° F. or any higher temperature level tends to reduce the amount of strength retained by the material. However, if the gradient at any average temperature is increased, the strength is only slightly changed.

Data show that if the hot-face temperature is kept constant but that of the cold face is changed so that there is a different gradient present, the change in retention of compressive strength is less that 5 percent of the room temperature strength. However, if the cold-face temperature is kept constant and that of the hot face is raised, the percentage of compressive strength retained is reduced considerably.

Table 4 shows that the modulus of elasticity of the silicone laminate is lowered slightly when the material is heated above room temperature. Additional heat or the introduction of thermal gradients to the material does not tend to affect the modulus of elasticity by any appreciable amount nor in any definite pattern.

The proportional limit values of the silicone laminates at constant elevated temperatures generally decreased with increasing temperature. The introduction of a gradient at an average temperature level further decreased the proportional limit values. An increase in the gradient, however, did not always produce a decrease in the proportional limit.

Percentages of room temperature compressive strength values that might be expected from a silicone laminate subjected to a 10-minute soak at temperature gradient levels that have not been tested can be extimated from figure 10. For practical purposes, the lines could probably be considered as being vertical, which would indicate that strength is not affected by the cold-side temperature.

The compressive strength values found in this study and a previous study[4] on silicone laminates are shown in table 5. Two different heating media and various soak periods were used in the two studies. The results show that the differences in strength are minor when comparing values after a 30-minute soak with convection heating and a 10-minute soak with conduction heating at different constant temperature levels.

## Theoretical Approach

A flat, unrestrained specimen will increase in length with an increase in average temperature whether or not a thermal gradient is present. If this linear expansion does not affect results, it may be ignored. The existence of a thermal gradient, however, results in unequal expansion of the hot and cold faces, hence curvature of the specimen.

A restraining jig will keep it flat while being heated. Or a curved specimen can be returned to its initially flat condition by applying a suitable bending moment. In either case, a flat specimen having a thermal gradient will be under compressive stress on the hot face and tensile stress on the cold face.

In the work described in this report, specimens were placed in the compression jig before they were heated. When the specimen was subsequently heated and a thermal gradient developed, the hot face was stressed in compression. The application of a direct external force increased the compressive stress. Values of maximum stress recorded in the tables are based on the external force divided by the cross-sectional area.

Appendix I presents an analysis of the thermal strains in a member subjected to a thermal gradient. The analysis was applied to the phenolic laminates tested under this program, but the correlation between predicted and observed values was not good. The strain due to the thermal gradient was generally of a small magnitude when compared with the strain at failure. Thermal strains would, however, increase in magnitude with an increase in thickness or thermal gradient.

## Conclusions

From the data here reported on 1/8-inch-thick phenolic and silicone laminates the following conclusions are drawn:

(1) The temperature gradient in the laminates is essentially a straightline relationship between the temperatures of opposite forces.

(2) Conduction heating with the nichrome-ribbon coil proved to be a satisfactory method of bringing specimens rapidly to the desired temperatures. Temperatures and temperature conditions were attained in 1-1/2 minutes or less and the rate of heating could have been accelerated.

(3) The compressive strength of the material after 10 minutes at uniform temperature decreases substantially with increasing temperature. At 300° and 600° F., the phenolic laminate retained 73 and 29 percent of its strength at room temperature, respectively. The silicone laminate at 300° F. and 800° F. retained 60 and 35 percent of its strength at room temperature, respectively. Modulus of elasticity and stress at proportional limit also generally decrease with an increase in temperature, but the decrease is not so pronounced as compressive strength.

(4) Maintaining the same average temperature but introducing a thermal gradient tends to reduce the stress at proportional limit and the compressive strength. The gradient, however, generally has little effect on the modulus of elasticity.

(5) An analysis of the thermal strains in a member subjected to a thermal gradient was developed but was not applicable to these limited data.

## APPENDIX I

### Analysis of the Thermal Strains In A Member Subjected to a Temperature Gradient[7]

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Consider an initially straight, rectangular, homogeneous specimen. When subjected to a temperature gradient, the unrestrained specimen will bend as shown in figure 11.

Position will be expressed as the distance $x$, measured from the concave side. Let the initial temperature at every point be $T_o$, and $T_c$ the cold side temperature after the gradient is established. If $L_o$ is the initial length, the length of any longitudinal element after a temperature change is

$$L = L_o \left[ 1 + \alpha_o (T - T_o) \right] \tag{1}$$

where $\alpha_o$ is the coefficient of linear thermal expansion. The length of the colder side of the specimen, from (1), is

$$L_c = L_o \left[ 1 + \alpha_o (T_c - T_o) \right] \tag{2}$$

The length of any longitudinal element may be written as a function of the cold side length.

$$L = L_c \left[ 1 + \alpha_c (T - T_c) \right] \tag{3}$$

By differentiation of equations (1) and (3),

$$\frac{dL}{dT} = L_o \alpha_o = L_c \alpha_c \tag{4}$$

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[7] This derivation was prepared by C. B. Norris and R. L. Ethington of the Forest Products Laboratory.

The relationship between the coefficients may be gotten by substituting (2) into (4) and solving for $\alpha_c$.

$$\alpha_c = \frac{\alpha_o}{1 + \alpha_o (T_c - T_o)} \tag{5}$$

For the usual small values of $\alpha_o$, a very good approximation is

$$\alpha_c = \alpha_o \tag{6}$$

In the following analysis, the subscript will be omitted from the coefficient. If the temperature gradient is assumed constant, then

$$T = T_c + kx \tag{7}$$

where $k$ is the temperature gradient. Then the length of any element, from equations (3) and (7), is

$$L = L_c (1 + \alpha k x) \tag{8}$$

The thermal unit strain in any longitudinal element is

$$\epsilon_T = \frac{L - L_c}{L_c} \tag{9}$$

by substitution of equation (8) into (9),

$$\epsilon_T = \alpha k x \tag{10}$$

This indicates that the thermal strain is a linear function of position, and the specimen can take the unrestrained shape shown in figure 11 without developing stresses. Now assume that the specimen is straightened by applying moments to the ends. The length of all elements becomes $L_a$, the length of the neutral surface. The unit strain in any element due to bending is

$$\epsilon_b = \frac{L_a - L}{L} \tag{11}$$

From equations (8) and (11),

$$\epsilon_b = \frac{\alpha k (a - x)}{1 + \alpha k x} \tag{12}$$

Equation (12) is the strain equation of conventional curved beam analysis with the curvature caused by a temperature gradient. When the term $\alpha kx$ is small compared with unity, it may be neglected. This amounts to neglecting a small curvature of the beam in the subsequent determination of the stress and strain distributions. Then

$$\epsilon_b = \alpha k (a - x) \tag{13}$$

It is assumed that the modulus of elasticity varies linearly with temperature. Then

$$E = E_c - b (T - T_c) \tag{14}$$

from equations (7) and (14),

$$E = E_c - bkx \tag{15}$$

Equations (13) and (15) may be combined according to Hooke's law to give the stress at any point in the cross section.

$$\sigma = \alpha k (a - x) (E_c - bkx) \tag{16}$$

The condition of longitudinal equilibrium requires that

$$\int_o^t \sigma \, dx = 0 \tag{17}$$

If equation (16) is substituted into (17) and the integration performed, it is found that

$$a = 2t \left[ \frac{\frac{E_c}{2} - \frac{tbk}{3}}{2E_c - tbk} \right] \tag{18}$$

From equations (13) and (18), the bending strain any place in the specimen is

$$\epsilon_b = \alpha k \left[ 2t \left( \frac{\frac{E_c}{2} - \frac{tbk}{3}}{2E_c - tbk} \right) - x \right] \tag{19}$$

The corresponding stress, from equations (16) and (18), is

$$\sigma = \alpha k \left[ E_c - bkx \right] \left[ 2t \left( \frac{\frac{E_c}{2} - \frac{tbk}{3}}{2E_c - tbk} \right) - x \right] \tag{20}$$

The outer fiber strain on the hot side is given by

$$\epsilon_b = - \frac{atk \left( E_c - \frac{tbk}{3} \right)}{2E_c - tbk} \tag{21}$$

The corresponding fiber stress is

$$\sigma = - \frac{atk \left( E_c - tbk \right) \left( E_c - \frac{tbk}{3} \right)}{2E_c - tbk} \tag{22}$$

## List of Symbols

$a$ = distance from concave side to neutral surface

$b$ = absolute value of the slope of the modulus of elasticity-temperature curve

$E_c$ = modulus of elasticity at the cold side temperature

$k$ = constant temperature gradient

$L_o$ = length of specimen at initial temperature

$L_a$ = length of neutral surface

$L_c$ = length of cold side

$T_o$ = initial temperature

$T_c$ = temperature of cold side

$t$ = thickness of specimen

$x$ = position coordinate measured from concave side

$\epsilon_T$ = unit strain due to temperature gradient

$\epsilon_b$ = unit strain due to bending

$\alpha$ = coefficient of linear thermal expansion

$\alpha_o$ = coefficient of linear thermal expansion bases on initial length

$\sigma$ = unit stress

Table 1.--Typical temperature gradient data taken at different intervals of time through a 1/8-inch thick phenolic laminate reinforced with 14 plies of 181 glass fabric 0.0085 inch thick. Powerstat set at 90. Room temperature during test, 75° F.

| Thermocouple No. and location[1] | Temperature after-- 5 minutes | 10 minutes | 15 minutes | 20 minutes | 30 minutes | Average temperature |
|---|---|---|---|---|---|---|
| | °F. | °F. | °F. | °F. | °F. | °F. |
| 1 (hot face)[2] | 700 | 700 | 700 | 700 | 700 | 700 |
| 2 | 650 | 640 | 660 | 655 | 645 | 650 |
| 3 | 620 | 620 | 630 | 625 | 630 | 625 |
| 4 | 560 | 570 | 605 | 510 | 595 | 590 |
| 5 | 535 | 535 | 570 | 575 | 570 | 560 |
| 6 | 515 | 525 | 495 | 505 | 510 | 510 |
| 7 | 510 | 520 | 445 | 460 | 460 | 480 |
| 8 | 435 | 430 | 410 | 425 | 420 | 425 |
| 9 | 405 | 400 | 380 | 395 | 385 | 395 |
| [3]10 | ..... | ..... | ..... | ..... | ..... | ..... |
| 11 | 320 | 315 | 290 | 285 | 295 | 300 |
| 12 | 280 | 270 | 260 | 245 | 260 | 265 |
| 13 | 170 | 165 | 170 | 170 | 185 | 170 |
| 14 | 145 | 135 | 145 | 160 | 170 | 150 |
| 15 (cold face)[4] | 100 | 110 | 115 | 120 | 155 | 120 |

[1] Thermocouples 1 and 15 were on opposite faces of the laminate. Other thermocouples were between the plies of fabric as No. 2--between plies 1 and 2; No. 3--between 2 and 3; etc.

[2] Time to reach 700° F. was 80 seconds.

[3] No. 10 thermocouple lead broken.

[4] Air to cold face passed over dry ice--supply of dry ice nearly exhausted when No. 15 was recorded after 30 minutes.

Table 2.--Typical temperature gradient data taken at different intervals of time through a 1/8-inch thick silicone laminate reinforced with 14 plies of 181 glass fabric 0.0085 inch thick. Powerstat set at 75. Room temperature during test 79° F.

| Thermocouple No. and location[1] | Temperature after-- 5 minutes | 10 minutes | 15 minutes | 20 minutes | 30 minutes | Average temperature |
|---|---|---|---|---|---|---|
| | °F. | °F. | °F. | °F. | °F. | °F. |
| 1 (hot face)[2] | 600 | 600 | 600 | 600 | 600 | 600 |
| 2 | 565 | 560 | 560 | 560 | 565 | 560 |
| 3 | 525 | 520 | 520 | 530 | 520 | 525 |
| 4 | 500 | 495 | 495 | 500 | 495 | 495 |
| 5 | 465 | 465 | 465 | 470 | 465 | 465 |
| 6 | 440 | 435 | 440 | 445 | 440 | 440 |
| 7 | 405 | 410 | 410 | 410 | 410 | 410 |
| 8 | 390 | 395 | 400 | 400 | 395 | 395 |
| 9 | 365 | 370 | 375 | 370 | 370 | 370 |
| 10 | 335 | 340 | 345 | 340 | 340 | 340 |
| 11 | 300 | 300 | 305 | 300 | 305 | 305 |
| 12 | 260 | 265 | 270 | 260 | 265 | 265 |
| 13 | 225 | 230 | 230 | 230 | 230 | 230 |
| 14 | 220 | 220 | 230 | 220 | 220 | 220 |
| 15 (cold face)[3] | 190 | 200 | 210 | 190 | 200 | 200 |

[1] Thermocouples 1 and 15 were on opposite faces of the laminate. Other thermocouples were between the plies of fabric as No. 2--between plies 1 and 2; No. 3--between 2 and 3; etc.

[2] Time to reach 600° F. was 70 seconds.

[3] Air to cold face was 75° F. compressed air.

Table 3.--Compressive values[1] at constant and thermal gradient temperature conditions[2] on 1/8-inch-thick specimens of phenolic resin and 181-A1100 glass-fabric base laminates

| Hot face temperature | Cold face temperature | Modulus of elasticity | Proportional limit | Maximum stress | | |
|---|---|---|---|---|---|---|
| | | | | Value | Percent of room temperature value | Percent of uniform temperature value |
| °F. | °F. | 1,000 p.s.i. | P.s.i. | P.s.i. | Percent | Percent |
| 70-75 | 70-75 | 3,580 | 28,800 | 66,600 | 100 | 100 |
| 300 | 300 | 3,370 | 15,300 | 48,400 | 72.7 | 100 |
| 400 | 200 | 3,170 | 25,300 | 44,300 | 66.5 | 91.5 |
| 500 | 100 | 2,930 | 18,900 | 30,100 | 45.2 | 62.2 |
| 400 | 400 | 2,820 | 20,100 | 36,200 | 54.4 | 100 |
| 500 | 300 | 2,800 | 15,600 | 27,000 | 40.5 | 74.6 |
| 600 | 200 | 2,840 | 16,100 | 25,700 | 38.6 | 71.0 |
| 700 | 100 | 2,880 | 11,800 | 25,800 | 38.7 | 71.3 |
| 500 | 500 | 2,750 | 15,600 | 23,600 | 35.4 | 100 |
| 600 | 400 | 2,950 | 13,800 | 24,200 | 36.3 | 102.5 |
| 700 | 300 | 2,690 | 9,500 | 21,000 | 31.5 | 89.0 |
| 600 | 600 | 2,790 | 13,900 | 19,500 | 29.3 | 100 |
| 700 | 500 | 2,740 | 12,600 | 19,000 | 28.5 | 97.4 |

[1] Average values of five test specimens.

[2] All temperature conditions were held for a 10-minute soak period prior to test.

Table 4.--Compressive values[1] at constant and thermal gradient temperature conditions[2] on 1/8-inch-thick specimens of silicone resin and 181-heat-cleaned glass-fabric base laminates

| Hot face temperature | Cold face temperature | Modulus of elasticity | Proportional limit | Maximum stress | | |
|---|---|---|---|---|---|---|
| | | | | Value | Percent of room temperature value | Percent of uniform temperature value |
| °F. | °F. | 1,000 p.s.i. | P.s.i. | P.s.i. | Percent | Percent |
| 70-75 | 70-75 | 2,490 | 11,100 | 20,900 | 100 | 100 |
| 300 | 300 | 2,130 | 9,200 | 12,600 | 60.3 | 100 |
| 400 | 200 | 2,190 | 7,700 | 11,500 | 55.0 | 91.3 |
| 500 | 100 | 2,200 | 6,300 | 9,500 | 45.4 | 75.4 |
| 400 | 400 | 1,880 | 8,400 | 11,300 | 54.1 | 100 |
| 500 | 300 | 1,900 | 6,400 | 8,600 | 41.1 | 76.1 |
| 600 | 200 | 2,030 | 7,000 | 8,300 | 39.7 | 73.4 |
| 700 | 100 | 1,980 | 6,500 | 8,000 | 38.3 | 70.8 |
| 500 | 500 | 2,240 | 8,100 | 9,100 | 43.5 | 100 |
| 600 | 400 | 2,120 | 5,300 | 8,000 | 38.3 | 87.9 |
| 700 | 300 | 2,140 | 4,600 | 7,100 | 34.0 | 78.0 |
| 800 | 200 | 2,090 | 5,000 | 6,800 | 32.5 | 74.7 |
| 900 | 100 | 1,780 | 5,900 | 6,400 | 30.6 | 70.3 |
| 600 | 600 | 2,030 | 5,900 | 9,100 | 43.5 | 100 |
| 700 | 500 | 2,040 | 4,500 | 7,000 | 33.5 | 76.9 |
| 800 | 400 | 1,990 | 5,400 | 7,000 | 33.5 | 76.9 |
| 900 | 300 | 2,020 | 5,100 | 6,600 | 31.6 | 72.5 |
| 1,000 | 200 | 2,160 | 4,800 | 6,700 | 32.1 | 73.6 |
| 700 | 700 | 1,970 | ..... | 7,300 | 34.9 | 100 |
| 900 | 500 | 2,180 | 3,500 | 6,400 | 30.6 | 87.7 |
| 1,000 | 400 | 1,940 | ..... | 6,700 | 32.1 | 91.8 |
| 800 | 800 | 2,130 | 6,500 | 7,400 | 35.4 | 100 |
| 1,000 | 600 | 2,400 | 5,600 | 7,000 | 33.5 | 94.6 |

[1] Average values of five test specimens.

[2] All temperature conditions were held for a 10-minute soak period prior to test.

Table 5.--Comparative values of maximum compressive stress at various temperature levels and heating periods. Different heating media were used[1]

| Reference | Soaking[2] period | Maximum stress[3] at-- | | | | | |
|---|---|---|---|---|---|---|---|
| | | Room temperature[4] | 300° F. | 400° F. | 500° F. | 600° F. | 700° F. | 800° F. |
| | Hr. | P.s.i. | P.s.i. | P.s.i. | P.s.i. | P.s.i. | P.s.i. | P.s.i. |
| **Phenolic Resin and 14 Plies of 181-A1100 Glass Fabric** | | | | | | | | |
| WADC-TR-59-569 | | 65,800 | | | | | | |
| WADC-TR-59-569 | 0.5 | | 61,600 | 47,500 | 34,600 | 27,700 | 22,800 | 15,200 |
| WADC-TR-59-569 | 24 | | 62,200 | 51,400 | | 7,100 | 0 | |
| WADC-TR-59-569 | 1,000 | | 56,300 | 44,500 | 2,800 | | | |
| Present study | | 66,600 | | | | | | |
| Present study | 1/6 | | 48,400 | 36,200 | 23,600 | 19,500 | | |
| **Silicone Resin and 13 Plies of 181-Heat Cleaned Glass Fabric** | | | | | | | | |
| WADC-TR 59-229 | | 20,800 | | | | | | |
| WADC-TR 59-229 | 0.5 | | 13,100 | 11,600 | 9,200 | 7,800 | 7,200 | 6,500 |
| WADC-TR 59-229 | 24 | | | 9,900 | 9,200 | 8,300 | | |
| WADC-TR 59-229 | 1,000 | | 11,700 | 10,200 | 8,400 | | | |
| Present study | | 20,900 | | | | | | |
| Present study | 1/6 | | 12,600 | 11,300 | 9,100 | 9,100 | 7,300 | 7,400 |

[1] Tests reported in the WADC Technical Reports were made on specimens heated in an oven. Specimens in present study were heated with a specially designed resistance heater.

[2] Period that the specimens were exposed to the respective temperatures before starting the test. Specimens tested at soak temperature. Test period required 2 to 4 minutes depending on magnitude of load applied.

[3] Values are average of five specimens.

[4] Tested after conditioning at 73° F. and 50 percent relative humidity.

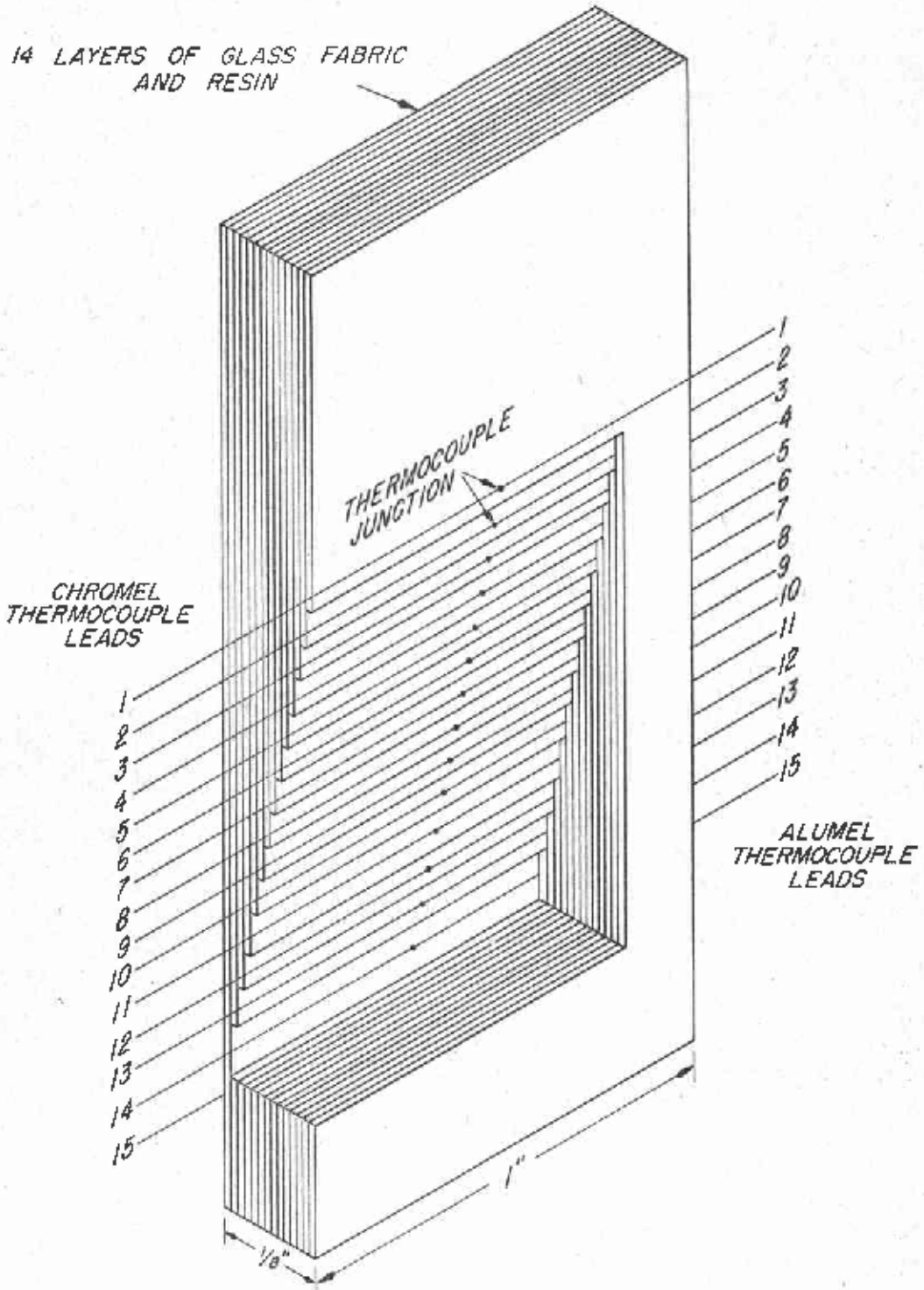


Figure 1.--Sketch of a special 1/8- by 1- by 3-inch laminate showing the location of the thermocouples. These thermocouples were spaced 1/8 inch apart through the longitudinal center in the transverse center of the piece. They were each separated by a single layer of 181 glass fabric through the thickness.

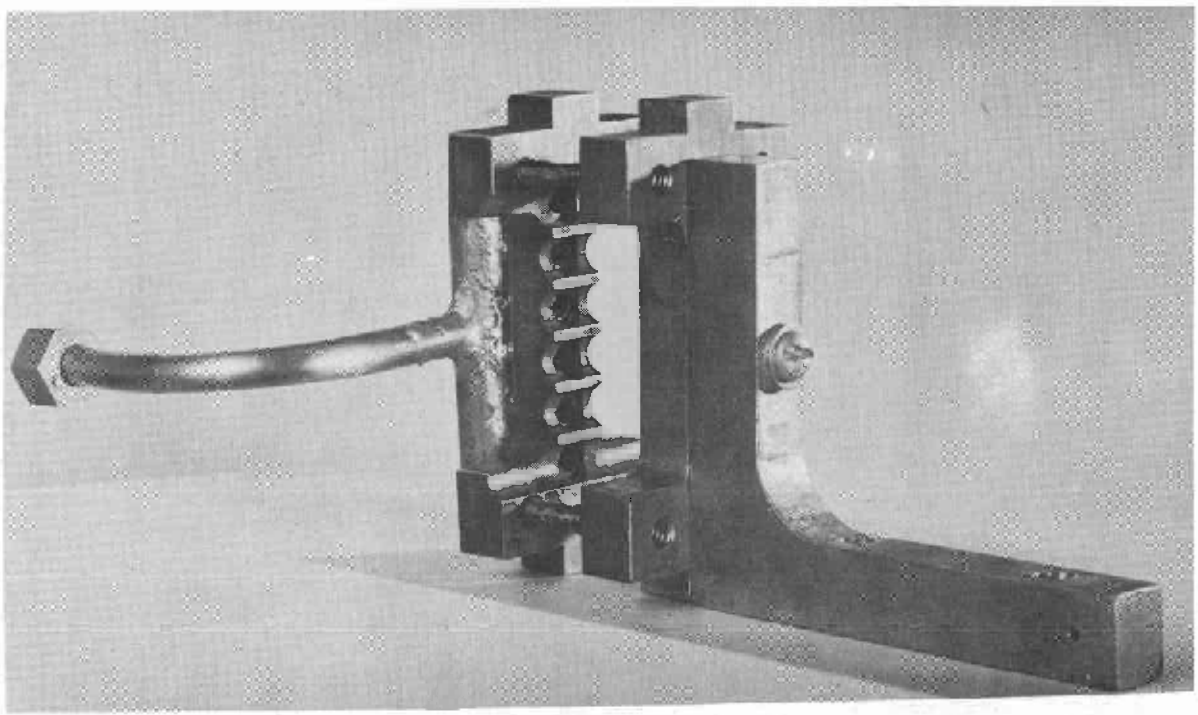

Figure 2.--Compression jig. Shown are lateral slots for air movement, air ports, air distribution chamber, and air supply line on the cold-surface side of the jig.

ZM 117 055

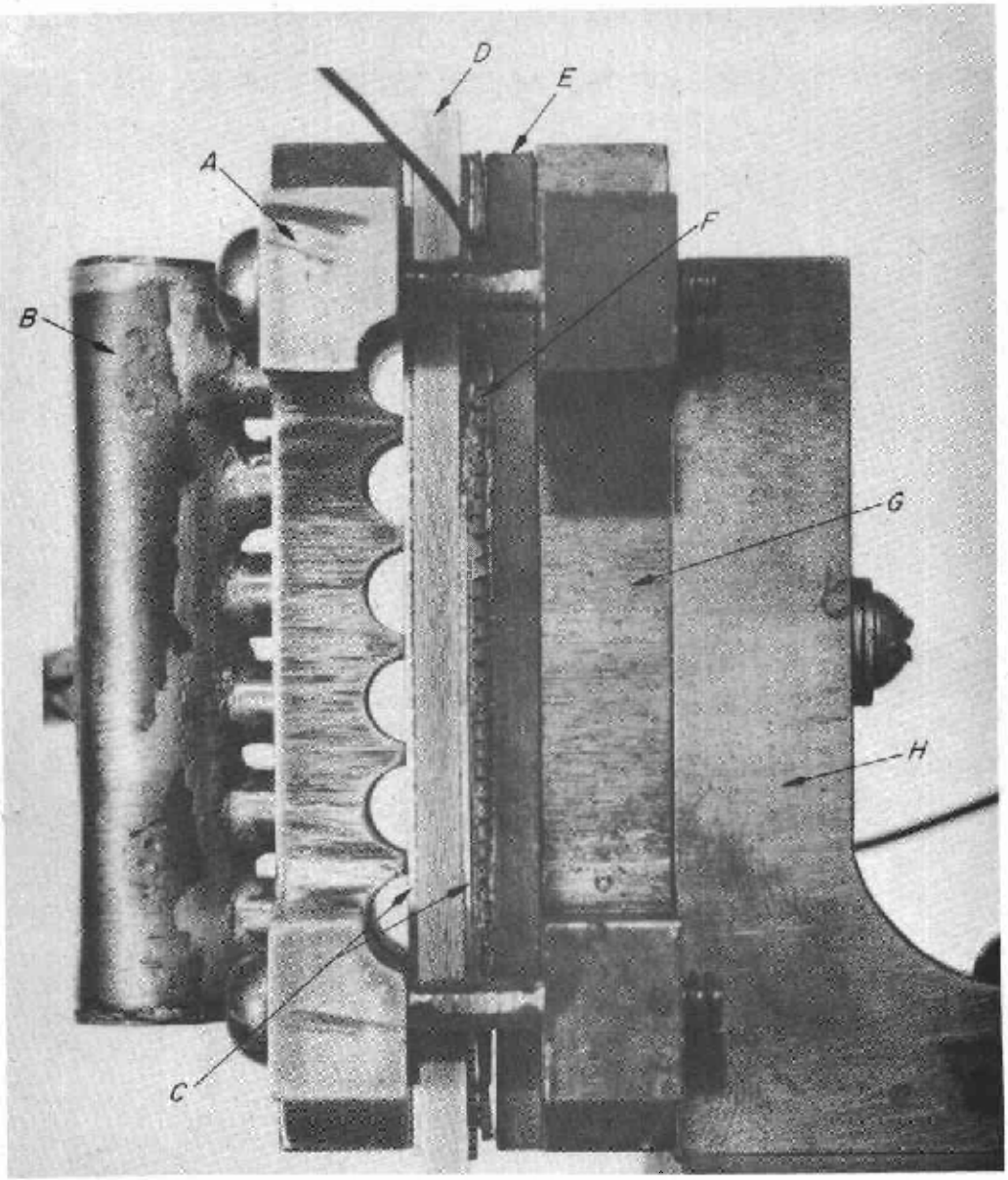


Figure 3.--Enlargement showing specially designed compression jig and arrangement of various components during test. A, Cold side of jig; B, air distribution chamber; C, 16-gage copper strips; D, specimen; E, insulating material; F, nichrome-ribbon heating coil; G, hot side of jig; H, "L" support for jig. Thermocouple used to control and record temperatures on hot side was located between the specimen and copper strip. Thermocouple used to record temperature on cold side was located directly opposite hot-side thermocouple.

ZM 117 464

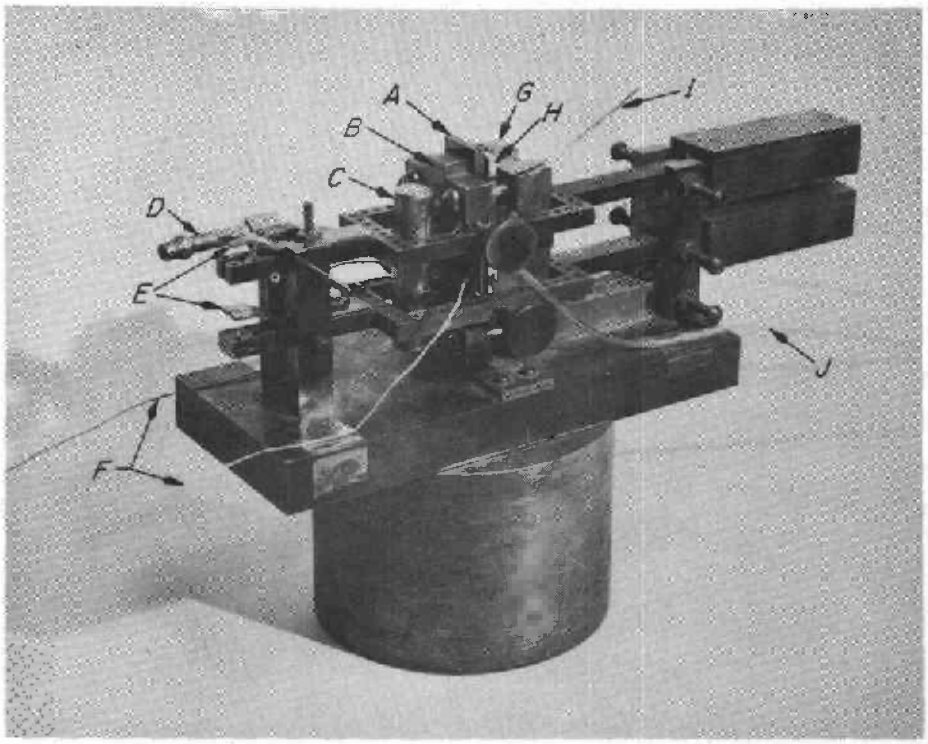


Figure 4.--Compression test setup showing specimen, supporting jig, compressometer and other component parts. Principal parts are: A, test specimen; B, cold face of jig; C, air distribution chamber; D, air supply line; E, connection points to microformer unit; F, iron-constantan thermocouple leads; G, hot face of jig; H, insulating material; I, nichrome-ribbon heater lead wire; J, chromel-alumel thermocouple leads.

ZM 116 781

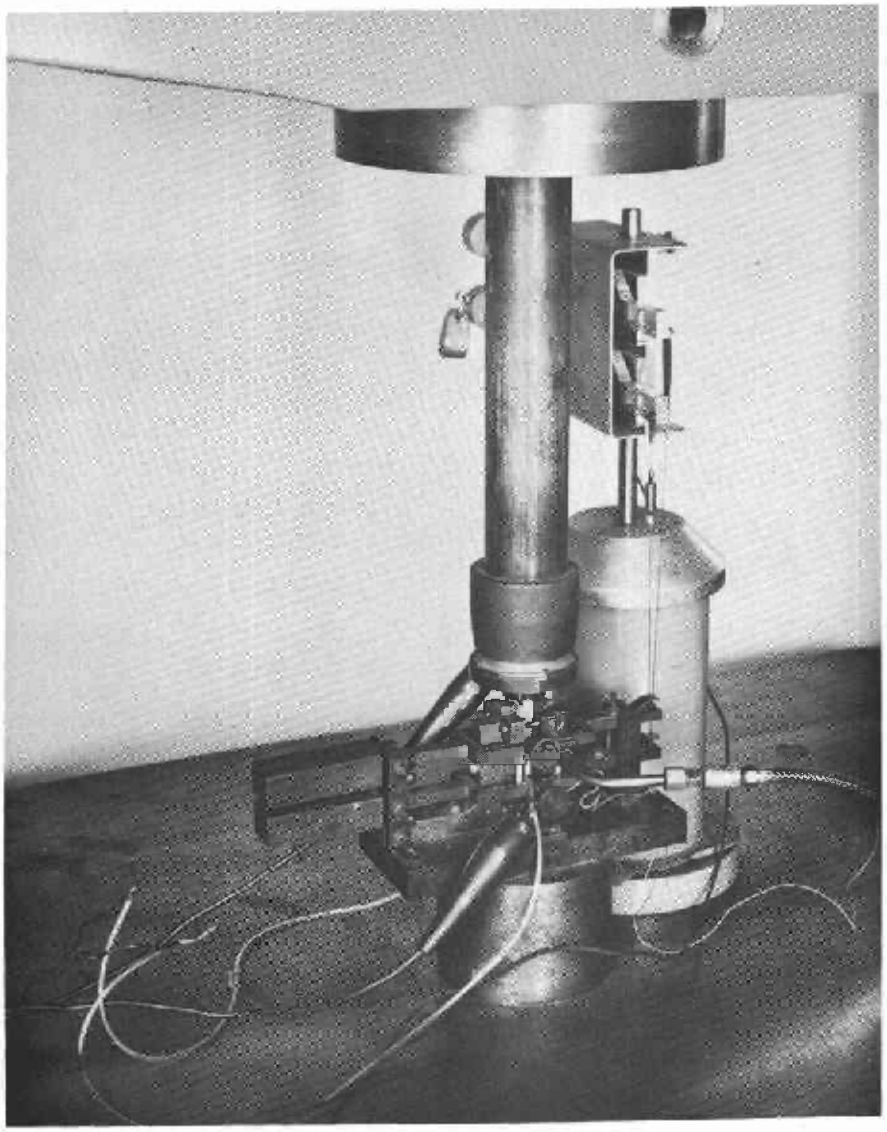

Figure 5.--Compression specimen ready for testing in the specially designed jig for the thermal gradient studies. The relationship between the compressometer and the microformer unit is shown.

ZM 116 773

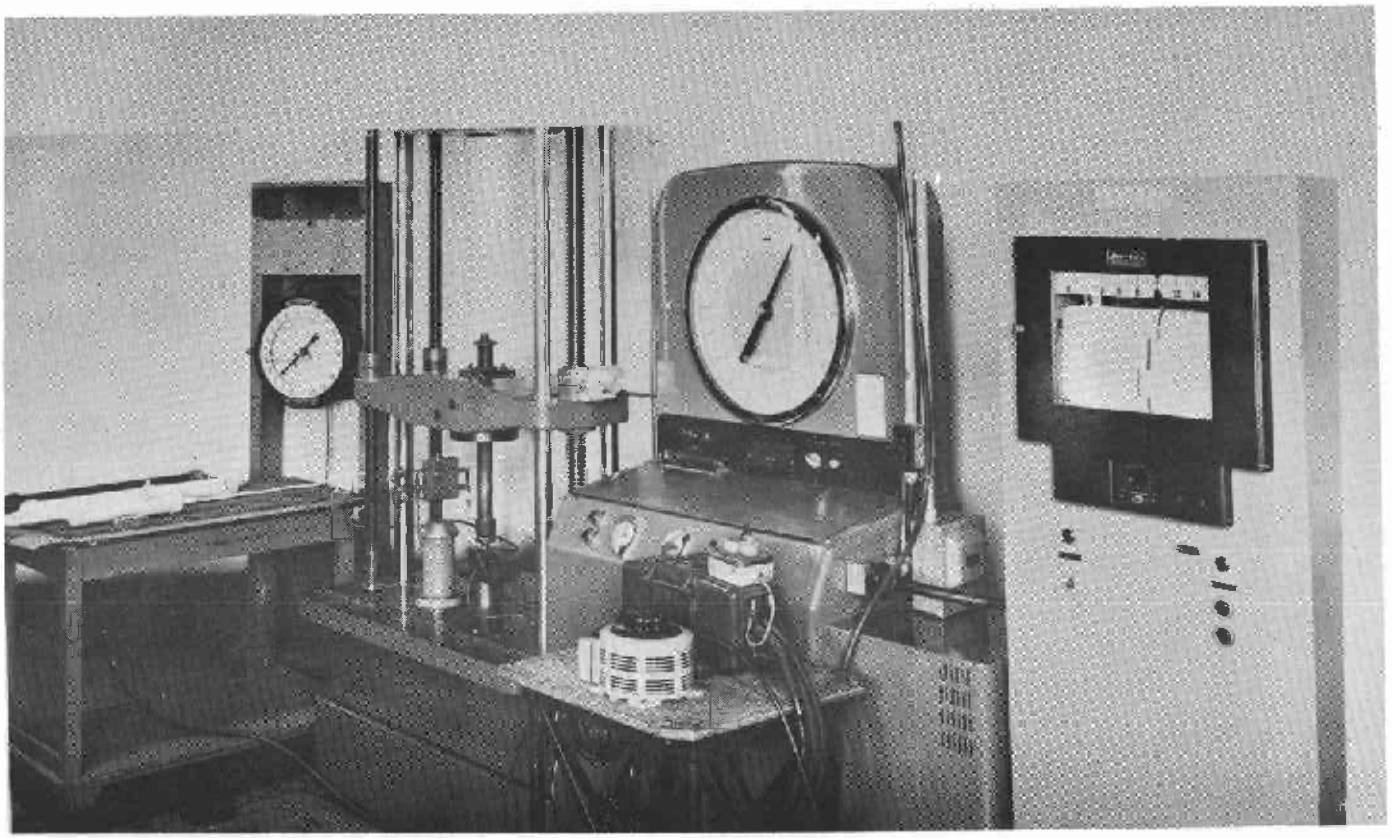

Figure 6.--Overall view of equipment used in compression tests of specimens having a thermal gradient.

ZM 116 778

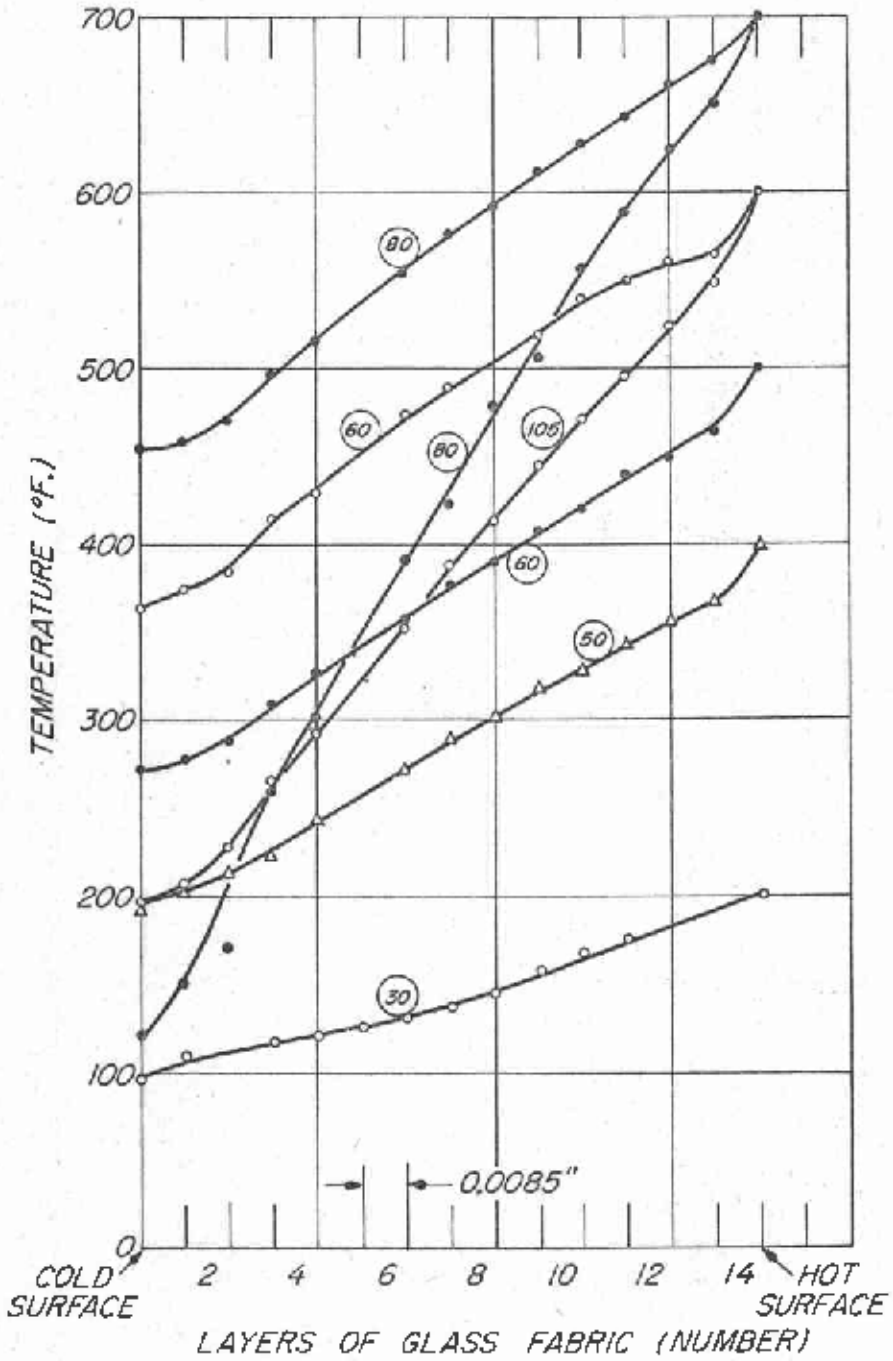


**Figure 7.--Thermal gradients in a phenolic glass-fabric-base plastic laminate (CTL-91LD and 181-A1100 glass fabric). Values plotted are averages of temperatures taken at 5, 10, 15, 20, and 30 minute intervals at steady-state conditions of surface temperatures. Circled number adjacent to each curve shows the time in seconds required to reach the hot face temperature.**

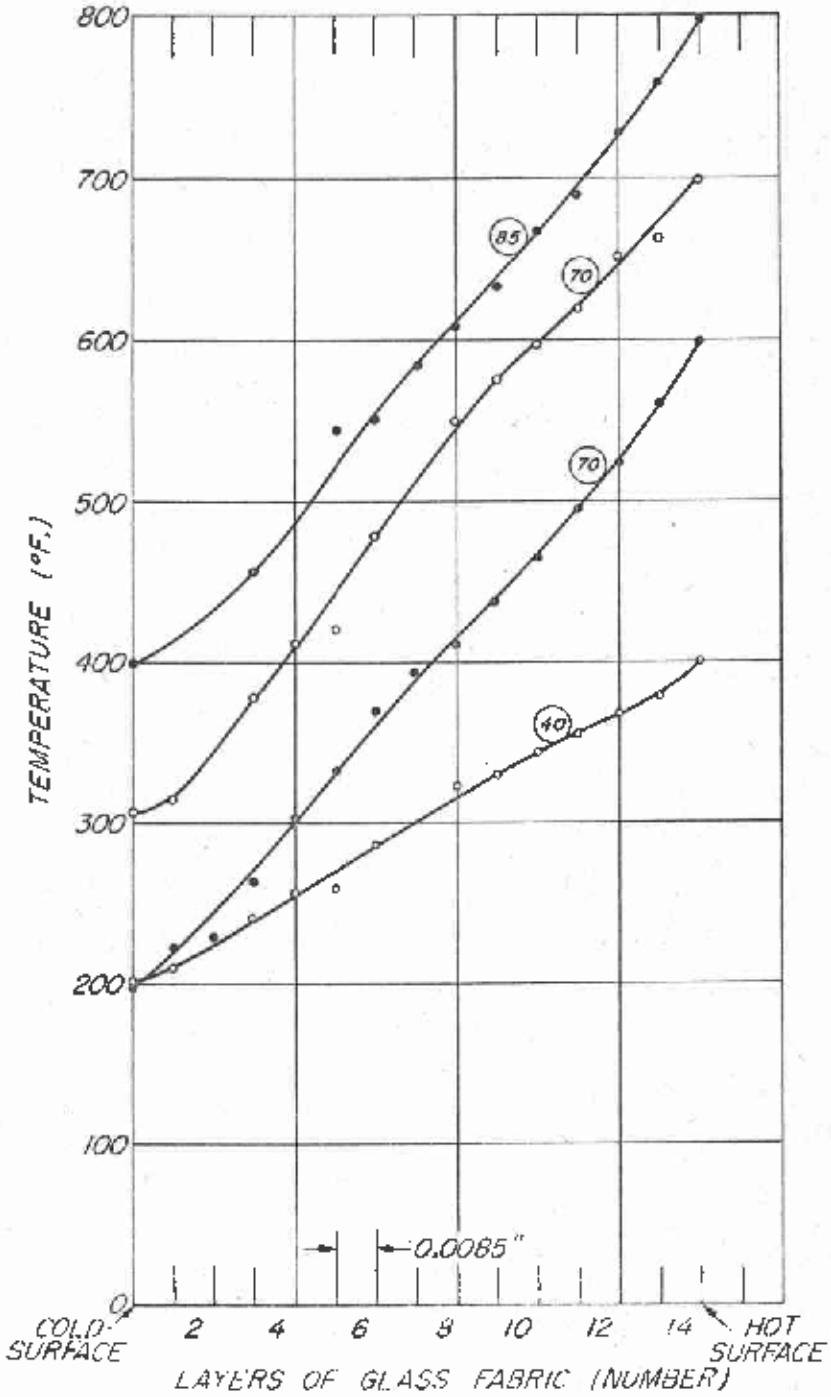


Figure 8.--Thermal gradients in a silicone glass-fabric-base plastic laminate (DC 2106 and 181-heat cleaned glass fabric. Values plotted are averages of temperatures taken at 5, 10, 15, 20, and 30 minute intervals at steady-state conditions of surface temperatures. Circled number adjacent to each curve shows the time in seconds required to reach the hot face temperature.

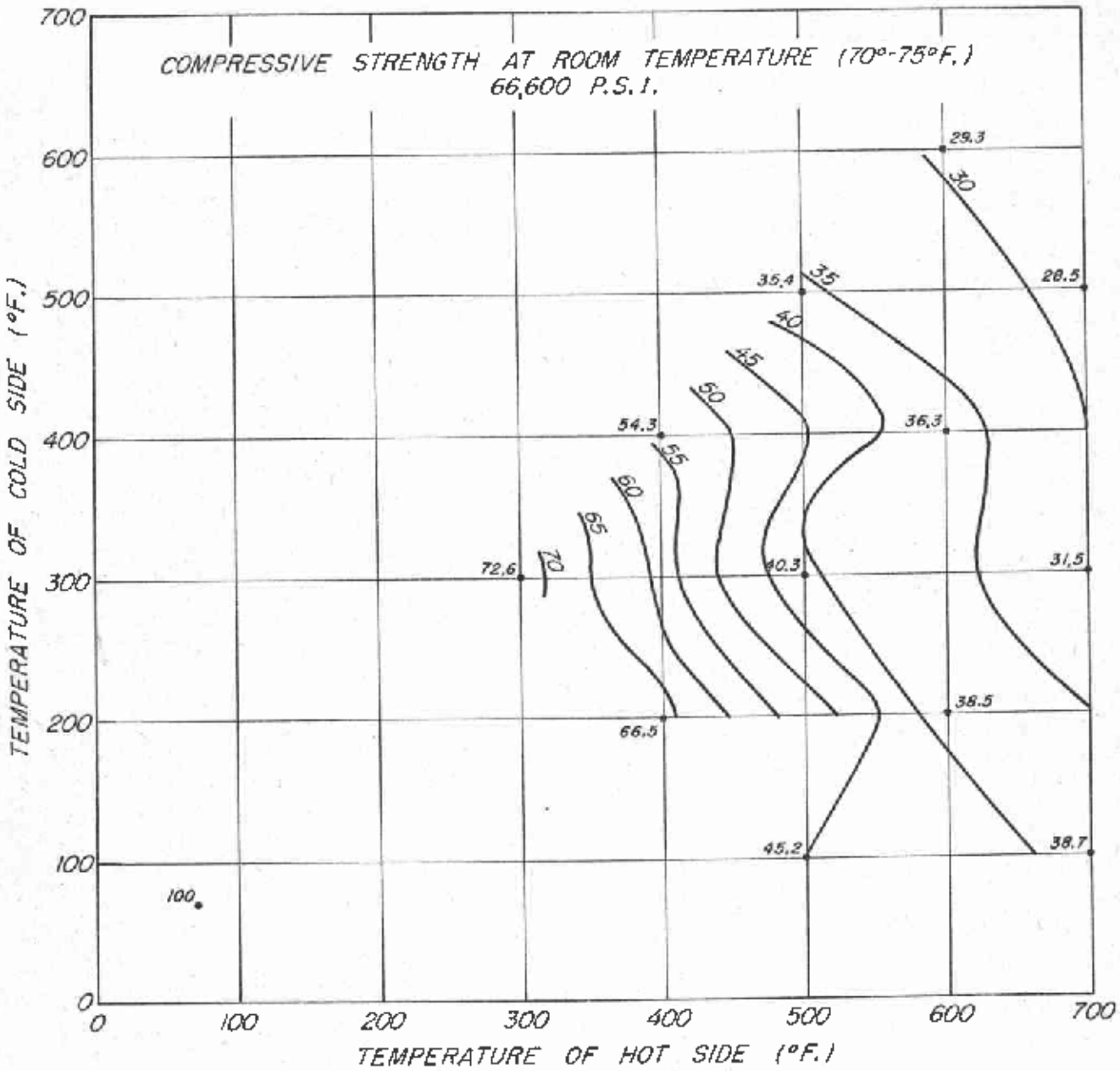


Figure 9.--Contour lines showing percent of compressive strength at room temperature that might be expected from a phenolic resin reinforced with 14 plies of parallel laminated, 181-A1100 glass fabric at different temperature gradient levels. (Percentages at solid points are average test values of 5 specimens.)

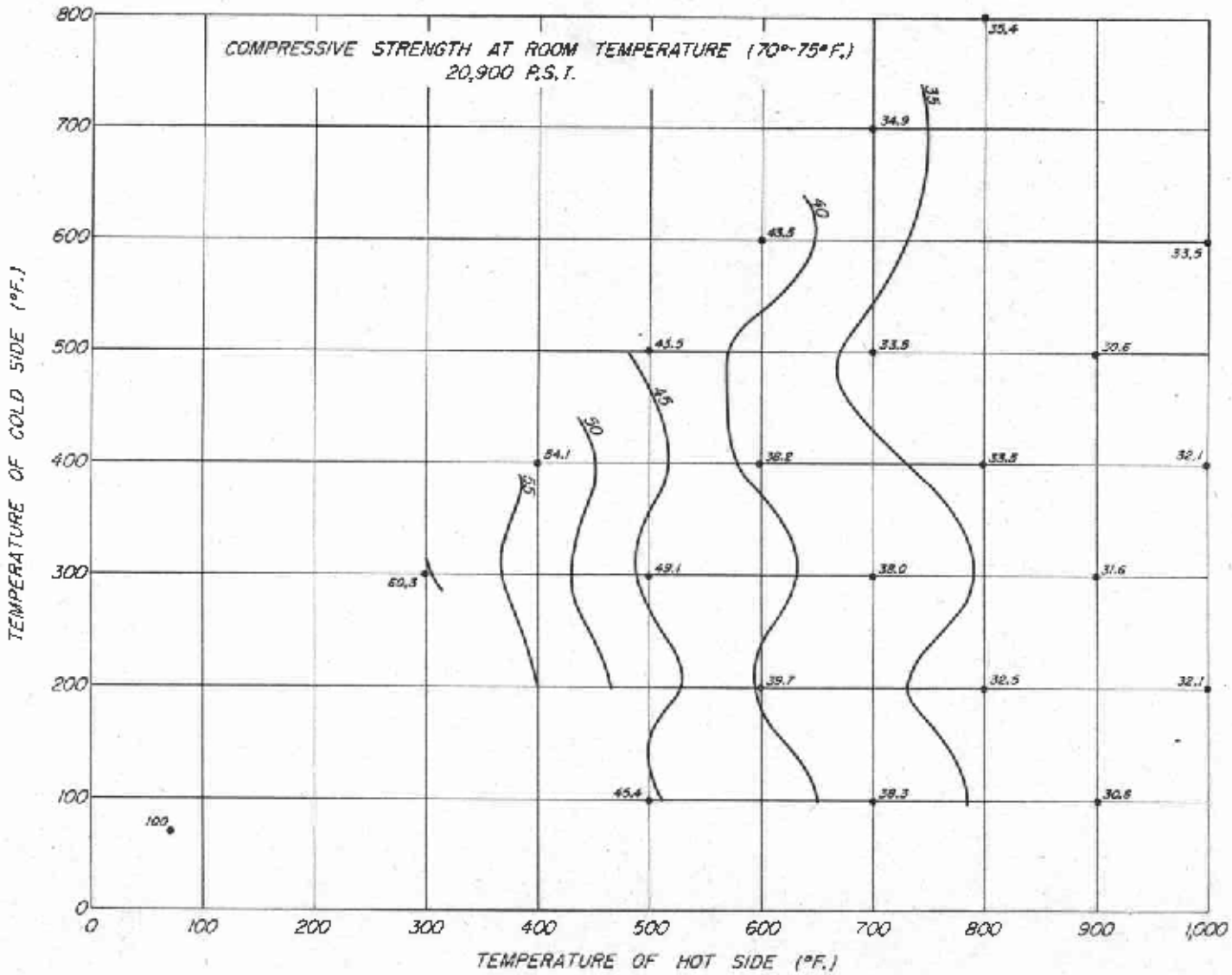


Figure 10.--Contour lines showing percent of compressive strength at room temperature that might be expected from a silicone resin reinforced with 14 plies of parallel laminated 181-heat cleaned glass fabric at different temperature gradient levels. (Percentages at solid points are average test values of 5 specimens.)

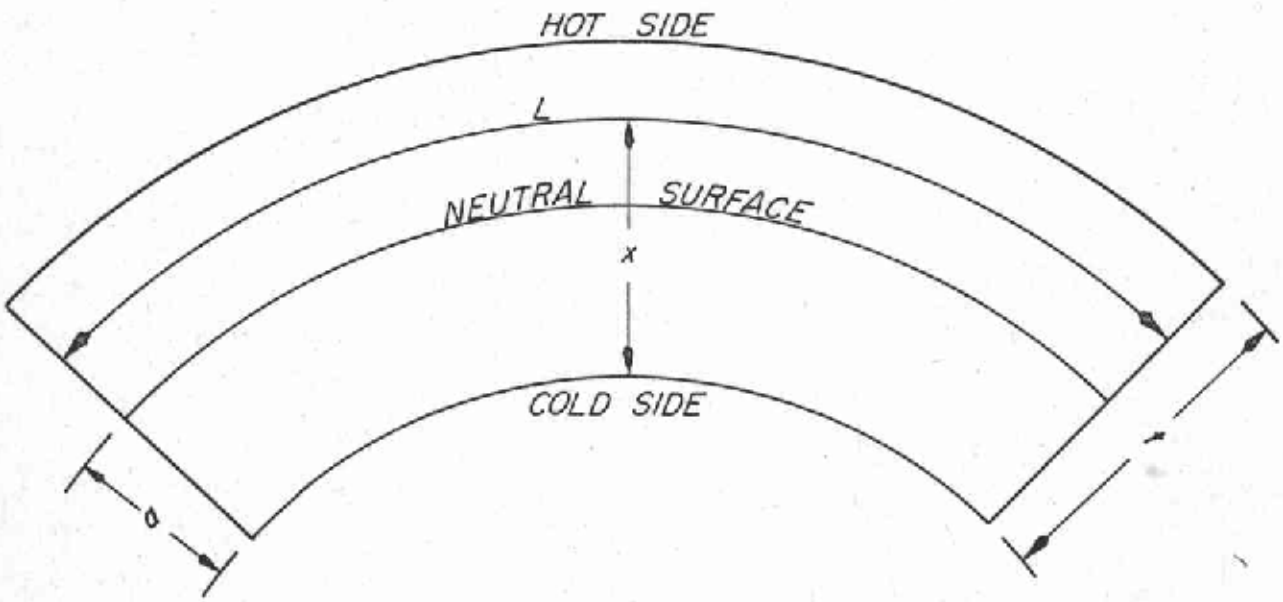


Figure 11.--An initially straight specimen after a constant temperature gradient is established across its thickness.