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A THERMAL COMPARATOR FOR NONDESTRUCTIVELY EXAMINING FIBER COMPONENTS

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September 1971

EUSTIS DIRECTORATE

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A series of test results for metallic and nonmetallic inclusion detection is presented. The applicability to thickness determinations is examined, and several promising users of the device are suggested.

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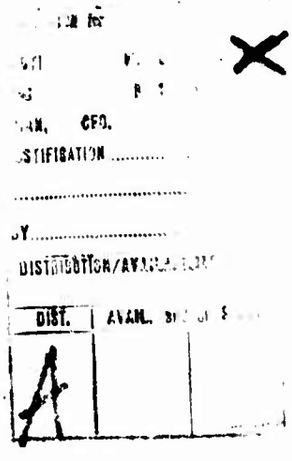

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The data contained in this report are the result of research conducted to develop a thermal comparator for nondestructively examining fiber components. Applications for the device are presented.

The report has been reviewed by this Directorate and is considered to be technically sound. It is published for the exchange of information and the stimulation of future research.

This program was conducted under the technical management of Mr. James P. Waller, Structures Division.

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SUMMARY

A novel device for the nondestructive testing of fiber composites is discussed. It is basically a comparator designed to detect nonconformities in the thermal properties of the material studied. Principal advantages of the instrument are its simplicity of design and operation and its very modest cost.

A series of test results for metallic and nonmetallic inclusion detection is presented. The applicability to thickness determinations is examined, and several promising uses of tne device are suggested.

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Q_1	heat flow into the specimen
Q_2	heat flow out of the specimen
q_1	rate of heat flow into the specimen
q_2	rate of heat flow out of the specimen
$\bar{x}$	arithmetic mean
σ	standard deviation

INTRODUCTION

Increased elegance of design and construction demands more efficient use of engineering materials. It requires a thorough knowledge of behavior in the appropriate environment. However, statistical methods of evaluation cannot ensure an acceptable level of reliability and integrity of many engineering systems. Thus, nondestructive test procedures which can be applied at all steps of construction or operation are of paramount importance. In this respect, there is no more vital area than that of thin sheet or composite panel structures fabricated from fiber reinforced plastics. Such materials are observed under laboratory conditions to have the attractive properties of high strength and low weight. Unfortunately, under the relatively severe conditions of practical construction and application, a drastic reduction in these properties along with a marked decrease in the reliability is observed to occur for as yet largely unidentified and, thus, uncontrollable reasons. It is an objective of nondestructive testing in this application to present at least a qualitative measure of the reliability of such structures.

Several established testing techniques have found satisfactory application in determining the quality of thin sheet and honeycomb core composites. Ultrasonic equipment, for instance, has proven to yield very precise and accurate information on the quality of adhesive bonds and on the extent of internal voids in these structures. Usually, instruments using either pulse-echo or through-transmission techniques are employed. Devices utilizing electromagnetic radiation with wavelengths from microwave through infrared to X-ray have also been variously and successfully employed with glass and plastic composite structures.

Unfortunately, for many applications, these relatively refined, sophisticated methods prove to be both costly and cumbersome. Normally, ultrasonic devices require high frequency (up to 5 mhz) and high excitation power. Furthermore, these transducers often need a messy couplant medium which, in many applications, consists of immersion baths or directed water jets. Although radiation does not generally necessitate contact with the specimen, precision transmitters and receivers are fundamental.

The device reported here has been designed principally to determine nonconformities, including inclusions and construction variations, in multilayer glass fiber reinforced plastic sheets. It is not quite as precise or as accurate as either of the aforementioned instruments for this application. Its strong advantages are, however, its relative simplicity of design and operation and its modest cost. In the present configuration, such an instrument could, at the least, supply go/no-go information. It is, essentially, a thermal comparator designed to indicate variations in certain thermal properties of the specimen; these are properties which have knowingly been used for years to differentiate between such materials as fused silica and soda glass or mild and high-alloy steel. Simple handling tests reveal that the first material in each case always feels colder to the touch when both of the materials are handled at the same temperature. The instrument described adds a quantitative measure to these simple observations by indicating variations in specific heat, thermal conductivity, and thermal volume of the specimen as compared to a standard reference. In other applications, it is

possible to detect changes in specimen conductivity due to variations in the gap between the specimen and the measuring device.

The ability to detect changes in these thermal properties makes it possible for the instrument to indicate related variations in surface finish, thickness, resin content, inclusions, and construction technique. The comparator should also find application with materials other than those described here, where it would indicate variations in material characteristics related to detectable changes in the previously mentioned thermal properties.

THE THERMAL COMPARATOR PRINCIPLE

The thermal comparator principle is not new. In the 1950's, Powell[1] (in England) constructed a simple, "one-sided" device whose main objective was the determination of the conductivity of various specimens. This particular instrument recorded the temperature change of a small preheated ball after it contacted the surface of the specimen. He achieved excellent correlation of output with conductivity, surface finish, and thickness; however, the thickness determinations on thin glass plates showed poor resolution over 0.050 inch. This limitation indicated that a "two-sided" thermal comparator: the "hot-hot" and the "hot-cold". The "hot-hot" device, utilizing two identical sinks, either above or below the initial specimen temperature, would cause the specimen to undergo a change in average temperature. The heat flow from the sinks would be an indication of the average change in internal energy of the plate, which depends on density, specific heat, thickness, and lateral conduction effects. The temperature profiles and resulting heat flows for this type of device are sketched in Figure 1a. The second basic possibility, the "hot-cold" device, is shown in Figure 1b. With this device, through-conduction is measured which depends primarily on the specimen conductivity and thickness.

The scheme utilized in the device described is a combination of the two basic types. If the sink temperatures are above and below the initial specimen temperature but their average is not equal to it, then the heat flows to and from the sinks will indicate both conduction and thermal volume effects. The thermal system for the configuration used is shown in Figure 2.

The usual thermodynamic convention is to consider heat flow rate into a volume as having the opposite sign to heat flow rate out of the volume. For these tests, however, q_1 has been used to denote heat flow rate into the specimen from the source, and q_2 has been used to denote heat flow rate out of the specimen and into the sink. With this convention, then, all measured heat flow rates will have a positive sign. For these tests,

$$Q_1 = \int^{15\ \text{sec}} q_1 dt \quad \text{and} \quad Q_2 = \int^{15\ \text{sec}} q_2 dt$$

were recorded. Utilizing these total conduction integrals increased the sensitivity of the device and simplified the data collection and reduction procedure. It was found that the differences and sum of these quantities, $Q_1 - Q_2$ and $Q_1 + Q_2$, were most sensitive to the thickness and inclusion properties of the specimens. The quantities represent approximately the stored heat and twice the through-conduction, respectively. They are denoted "difference" and "sum" in the remainder of this report.

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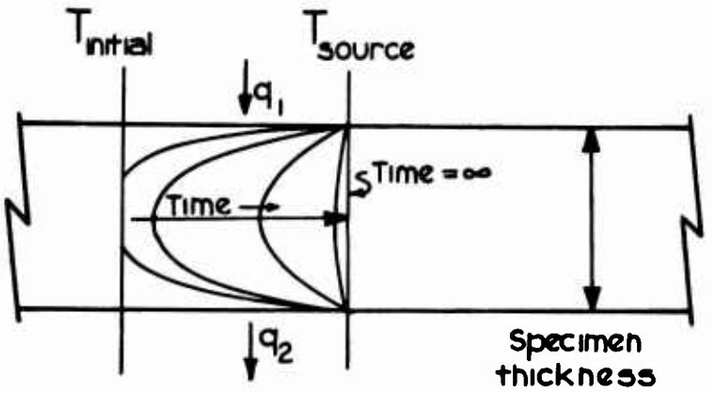
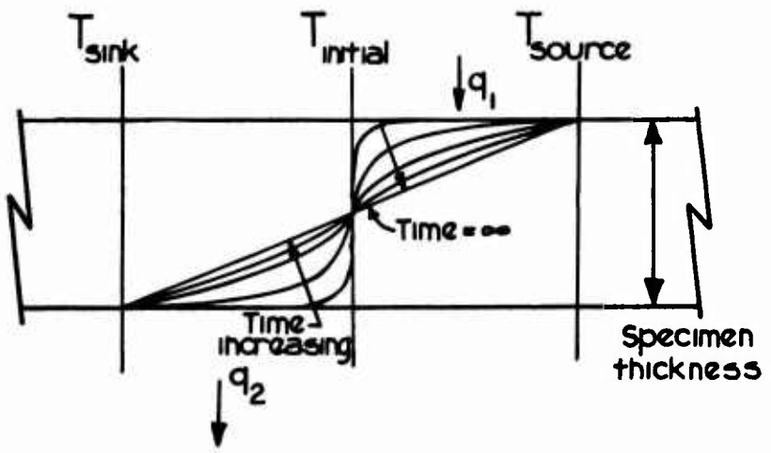
[1] R. W. Powell, "The Thermal Comparator in Nondestructive Testing," Techniques of Nondestructive Testing, ed. C.A. Hogarth and J. Blitz, Butterworth's, London, 1960, p. 175.



a. "Hot-Hot" System With Two Sources.



b. "Hot-Cold" System With Source and Sink.

Figure 1. The Two Basic Thermal Systems Considered for the "Thermal Comparator".

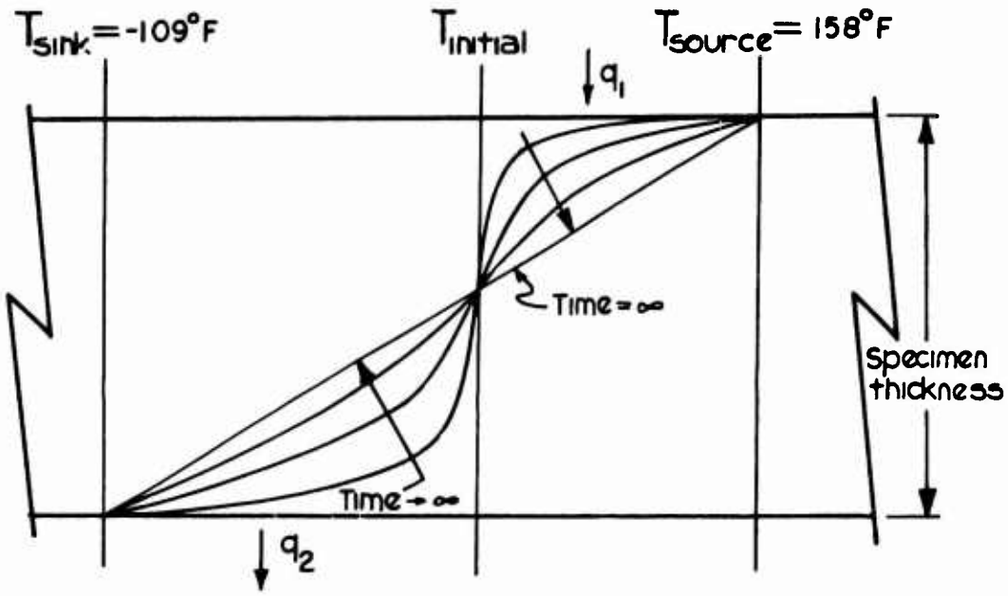


Figure 2. The Thermal System of the Present "Thermal Comparator".

There are a number of complicated effects that are not accounted for in the preceding simplified discussion. Most important are the surface contact conductance and lateral conduction effects. Surface roughness and contact pressure will affect surface conductance, and this will, in turn, affect the heat flows, particularly in the early transients. Correlation with surface finish may be possible by reading the early transients.

Lateral conduction will have a large effect on the indication of the heat stored in the specimen and allows the easy determination of inserts of different conductivity from the base material.

In the series of tests described in this paper, full utilization was not made of the potential of the device. Tests on all specimens were run for a fixed time (15 seconds), and the outputs at that time were recorded. In most cases, this does not allow a separation of effects (i.e., surface conductance effects cannot be differentiated from internal conduction changes). To separate these effects, a complete heat flow vs. time record must be taken, and the evaluation of this would be quite laborious. In the spirit of developing an inexpensive and fast test for comparison to a standard, such effects as these were not taken into account in this study.

THE DESIGN OF THE APPARATUS

On the basis of the preceding discussion, a two-sided device was constructed using a hot source (above room temperature) and a cold sink (below room temperature). As shown schematically in Figure 3, the source and sink were arranged so that they nominally contacted opposite sides of the specimen simultaneously. They were mounted in a small arbor press to provide suitable alignment. The cold sink was manually raised and lowered against the hot source, and contact pressure was adjusted in a direct manner by adding weights to the press shaft.

The hot source was designed with a large Cerro-Bend eutectic alloy core. By operating at the alloy melting point and utilizing the heat of fusion, temperature stabilization to within 2°F of the eutectic temperature, 158°F, was obtained. The thermal energy was supplied by a common "immersion"-type water heater potted around the core and controlled from the power mains by rheostats.

The cold sink was constructed around a bath of "dry ice" and acetone. The warming "dry ice" served effectively to maintain the sink within 1°F of its sublimation point, -109°F. Thermal insulation of the sink was provided by 1 inch of urethane foam. With this design, temperature difference between the source and sink could be maintained within 3°F.

The heat flow into and out of the specimen was measured with two 1/16-inch-thick-by-1/2-inch-diameter N. L. L. "heat flow discs" bonded between the sinks and the contactors as shown in Figure 3. The discs are made from solid tellurium with thin copper mesh layers bonded to each face, forming a differential thermocouple. The output is read between the copper facings, thus providing a signal directly proportional to temperature differences across the thickness of the disc. This difference is, in turn, proportional to the thermal gradient and, hence, the normal heat flow through the disc. The use of a tellurium-copper thermocouple junction utilizes the unusually high thermoelectric potential of these metals and results in outputs of up to 2.5μv.

The contactors employed in these tests were 1/8-inch-thick, soft copper discs with a thermocouple embedded near the contact surface. The entire arrangement was bonded together with special highly conductive silver-filled epoxy. A close-up view of the comparator showing the source and the sink, and the contactors is presented in Figure 4.

The concept and physical configuration of the components are simple and straightforward, but as other researchers (Powell[3]) have pointed out, the extraction of usable information from the instrument presents a more involved problem. As outlined earlier in this report, analysis indicates that a

[3] Powell, loc. cit.

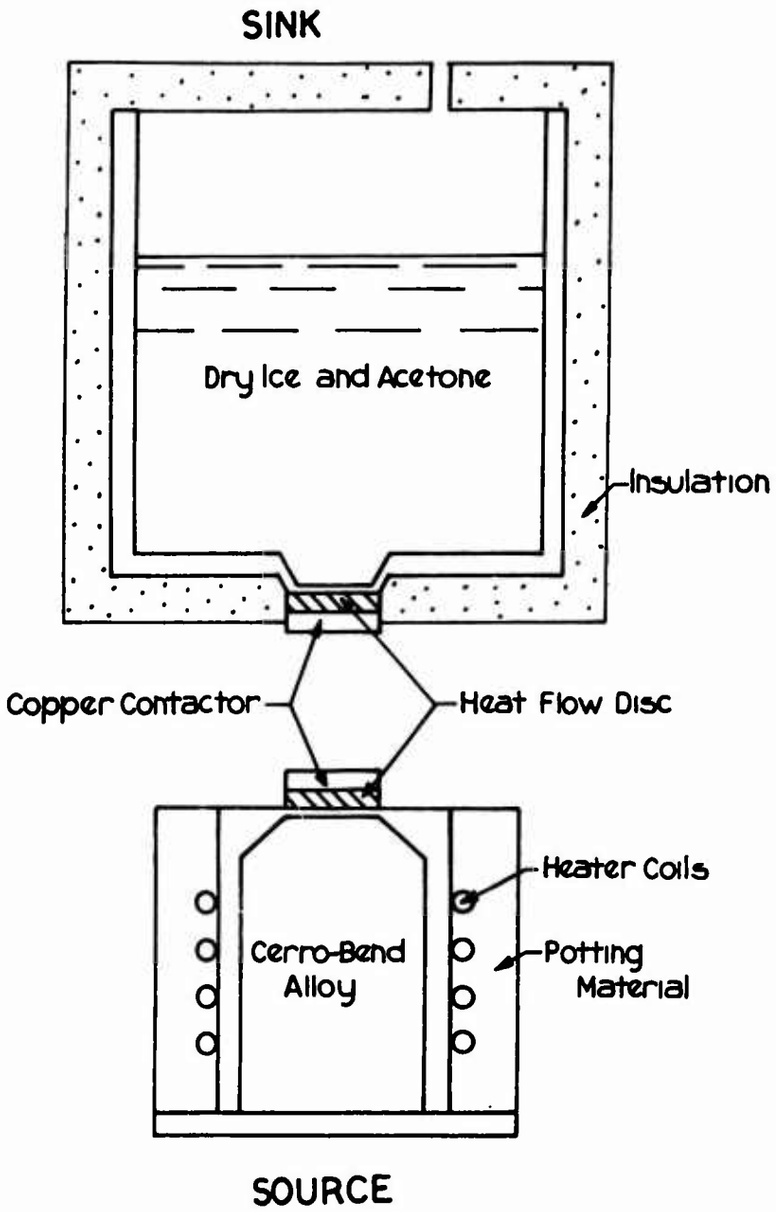


Figure 3. Cutaway View of Comparator Source and Sink.

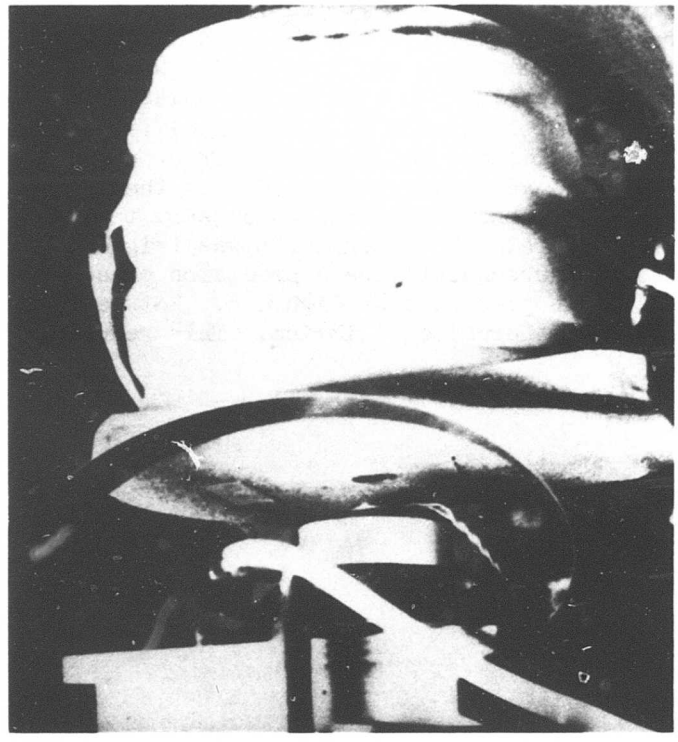


Figure 4. Detail of Comparator Showing Sink (white insulated body at top) and Source (small banded cylinder immediately below) Along With Alignment and Contacting Equipment.

modified exponential-type output is to be expected, and this was the observed case. This, combined with the presence of large transient effects, prevented the recording of reliable information before 10 seconds after initial contacts with the specimen. These considerations indicated that an integration of the outputs over a preset time would display the desired information most efficiently.

In operation, the signal from the heat flow discs was amplified and monitored in a Sanborn amplifier - strip-chart recorder system, as shown in Figure 5. The output from these amplifiers was then fed into a small Donner analog computer where signal conditioning and integration were completed. The signal conditioning was required to eliminate a quiescent output from the heat flow discs and was accomplished by a signal differentiation followed by an integration. In this manner, any constant effect of drift or error arising from too-rapid recycle was eliminated from the integration process. With this configuration, then, it was only necessary to insert the specimen and to lower the contactors. The integration was triggered automatically at contact and was stopped subsequently by a precision preset timer. A view of the complete system is presented in Figure 6. Between runs, the system was allowed to return to thermal equilibrium. This required from 45 to 60 seconds.

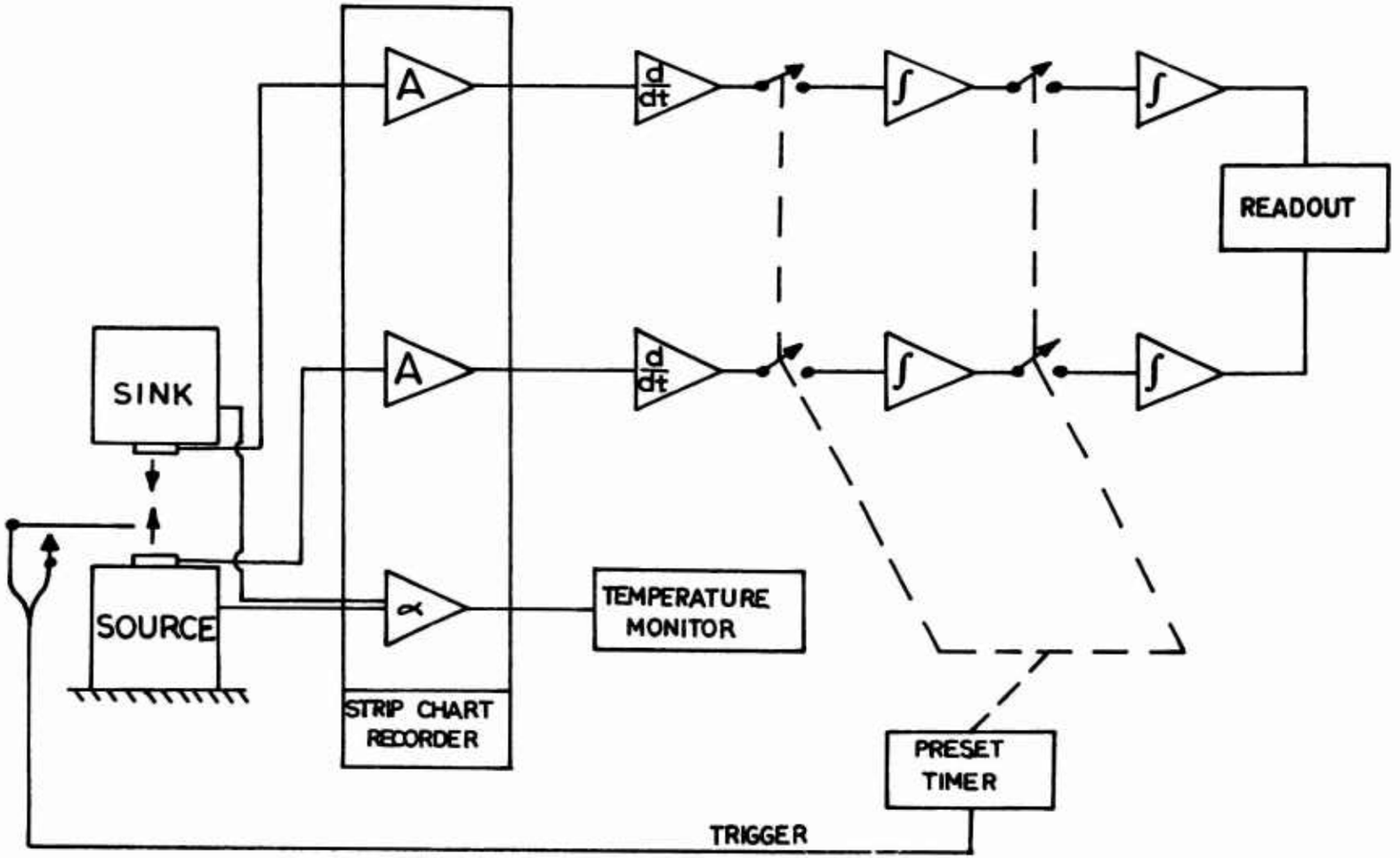


Figure 5. Schematic of Instrumentation System.

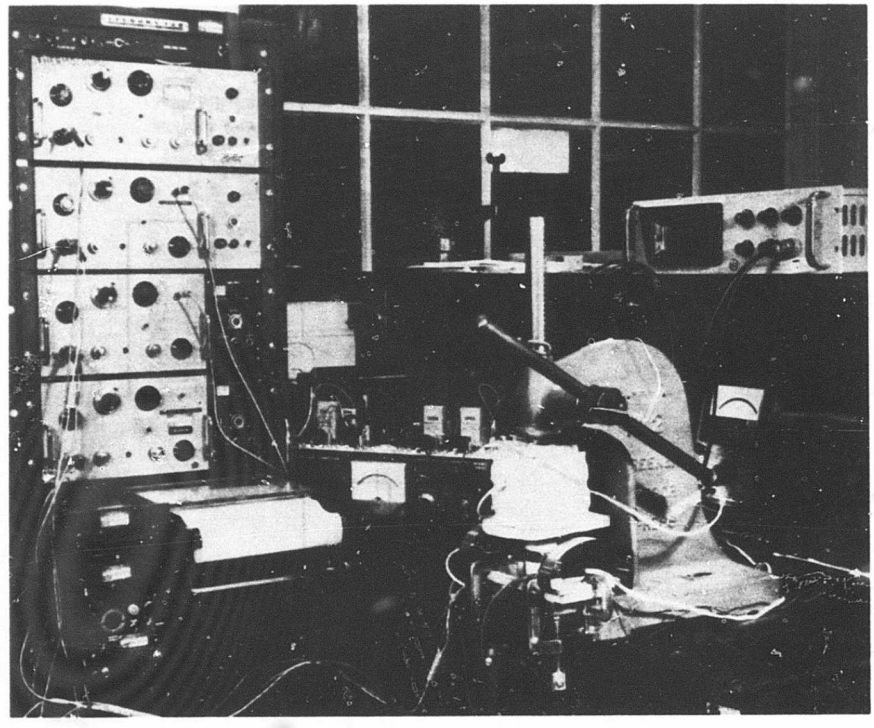


Figure 6. Complete Apparatus Showing Comparator (at the lower right) With the Analog Computer and Strip-Chart Recorder (in the rear).

THE DESIGN OF THE SPECIMENS

All specimens used in the series of tests described in this report were fabricated from "Epon 826" resin with methane-diamene hardener reinforced with "Volan-A" finished 181 glass cloth. Cure was accomplished at elevated temperatures and pressure. The specimens are shown in Figure 7.

The specimens used in the thickness calibration tests were multilayered layups constructed with uncontrolled direction of the cloth weave. These samples were nominally 4 inches square.

The specimens used in the inclusion detection tests were specially fabricated to minimize the thickness variation across each inclusion. With the exceptions noted below, these samples were composed of three layers of cloth with cutouts in the middle layer to accept the inclusions. These inclusions were 2 inches square and approximately .009 inch thick - the cloth nominal thickness. Due to the physical form of these materials, the "lamp black" and "release agent" inclusions were constructed without cutouts by introducing the materials between two of the cloth layers. Thickness variations in the finished specimens over any 6-inch traverse were nominally within 2-percent of the average thickness. A detailed description of each inclusion is found in Table I.

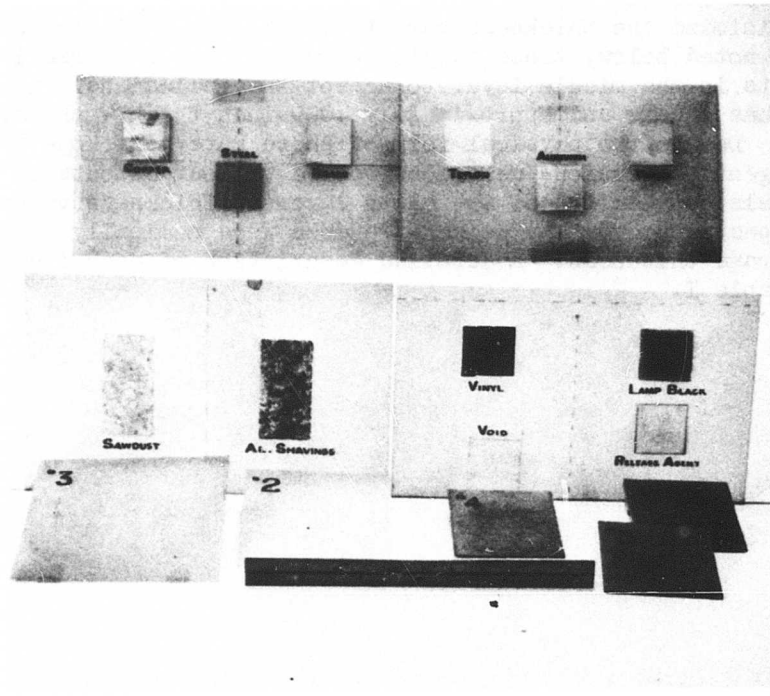
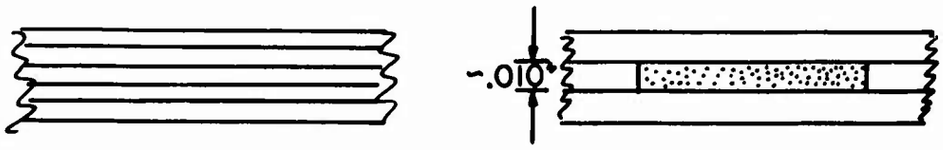


Figure 7. Test Specimens.

TABLE I. DESCRIPTION OF SPECIMENS

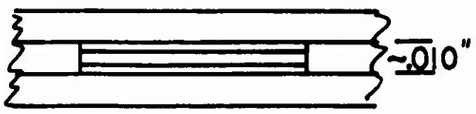
No.	Type	Sketch	Description
2	2-layer, .016-in.	A	Multilayer panels used in the thickness calibration investigation. All were fabricated with no control of weave direction for each layer. The specimens were constructed individually.
3	4-layer, .036-in.	A	
4	9-layer, .073-in.	A	
5	15-layer, .131-in.	A	
6	25-layer, .210-in.	A	
	The following specimens were used for the inclusion detection tests only and were fabricated in one 18" x 36" panel. This panel was cut into four smaller segments for testing.		
A	Sawdust	B	Sawdust-filled epoxy was included in the middle layer cutout, 2-in.-by-4-in. cutout.
B	Aluminum Filings	B	Fine, soft aluminum filings with epoxy binder were included in the middle layer cutout, 2-in.-by-4-in. cutout.
C	Paper	C	Four layers of common paper were used in a 2-in.-by-2-in. cutout.
D	Aluminum Foil Stack	C	Five layers of Alzac foil were used in a 2-in.-by-2-in. cutout.
E	Teflon	C	A single.010-in-by-2-in. sheet of Teflon was placed in the cutout.
F	Release Agent	D	A thin 2-in.-by-2-in. layer of "Dow 20" release agent was deposited between two of the layers.
G	Lamp Black	D	"Decolorizing" carbon powder was deposited between two of the layers.
H	Vinyl Tape	C	"Scotch No. 33" black electrical tape (two layers) was placed in a 2-in.-by-2-in. cutout.
I	Copper	C	One .010-in. sheet of copper was placed in a 2-in.-by-2-in. cutout.
J	Brass	C	Two sheets of yellow brass shim were placed in a 2-in.-by-2-in. cutout.
K	Steel	C	Two sheets of steel shim were placed in a 2-in.-by-2-in. cutout.

TABLE I. (Continued)

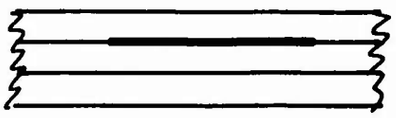


Sketch A

Sketch B



Sketch C



Sketch D

Cross Sections of Test Specimens

DISCUSSION OF RESULTS

The raw data and reduction are found in the Appendix. A summary in graphic form is presented in Figures 8 through 11. All results are shown in error band form, representing the average reading for each specimen ± 2 standard deviations. The data for each specimen represent a minimum of eight determinations for each thickness and, at least five readings for each inclusion test. A ± 2 standard deviation band was considered sufficient and conservative, because only 7 or 266 result points fell outside this bound.

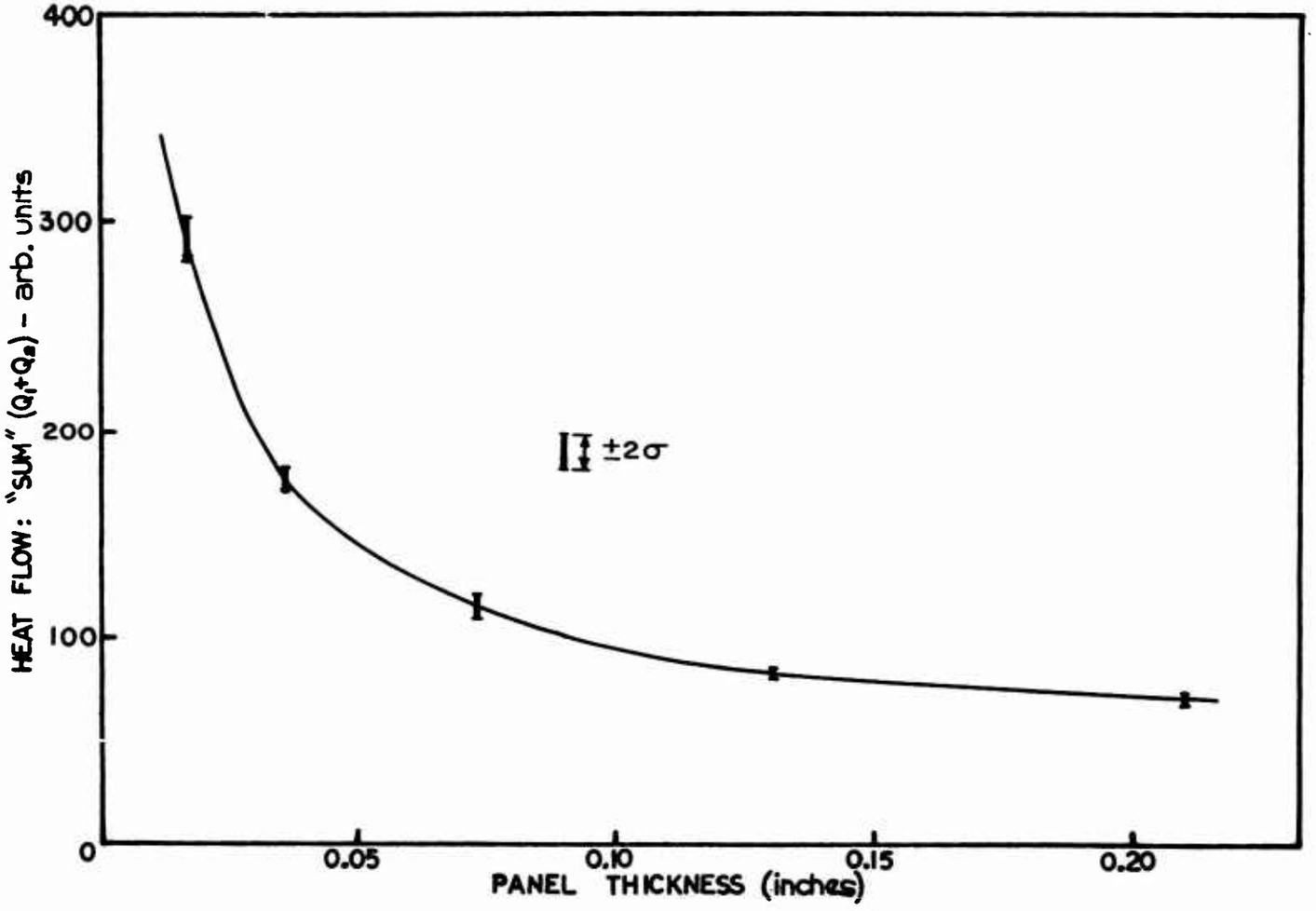


Figure 8. Thickness Determination by "Sum" of Heat Flow Readings From Source and Sink.

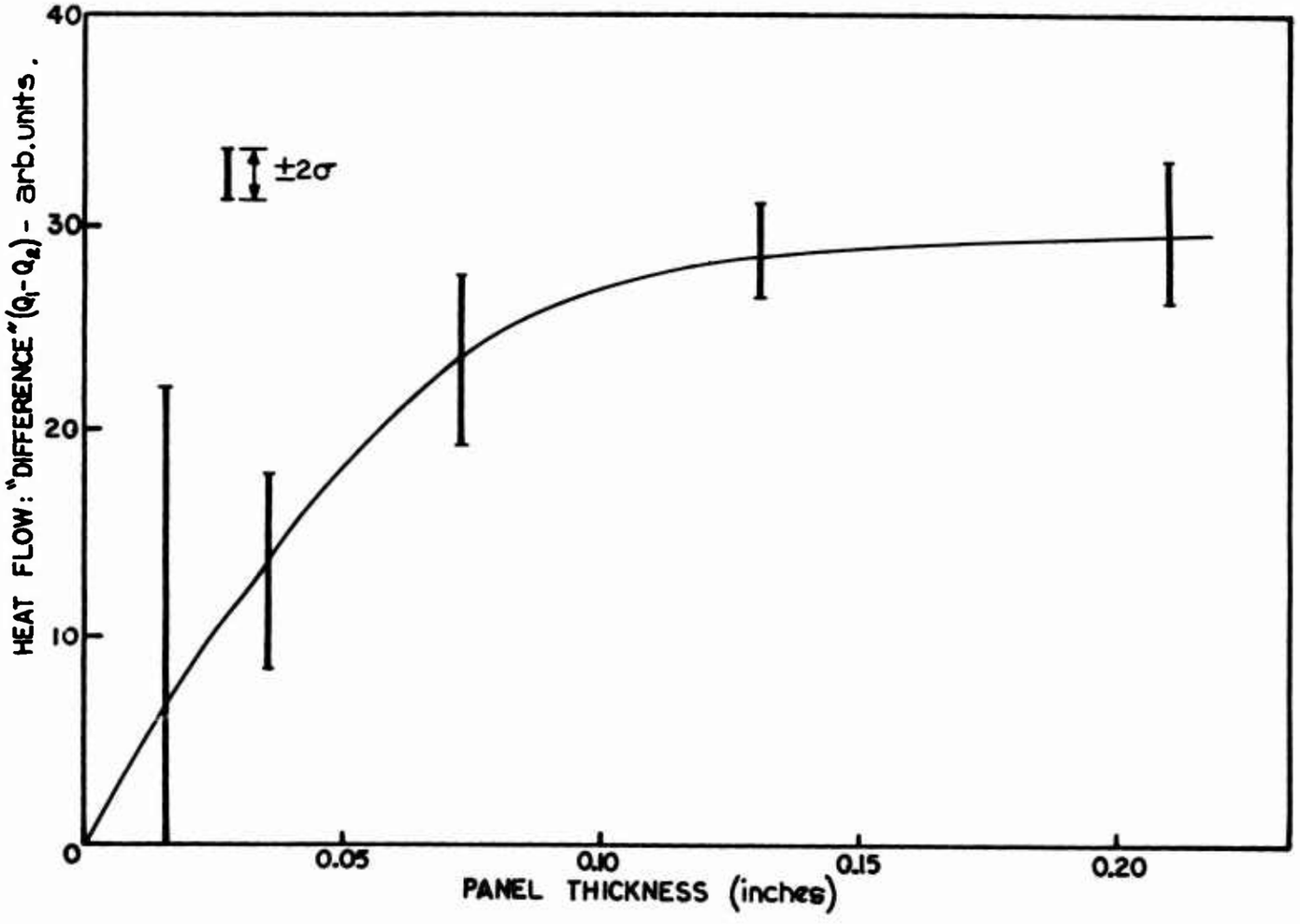


Figure 9. Thickness Determination by "Difference" of Heat Flow Readings From Source and Sink.

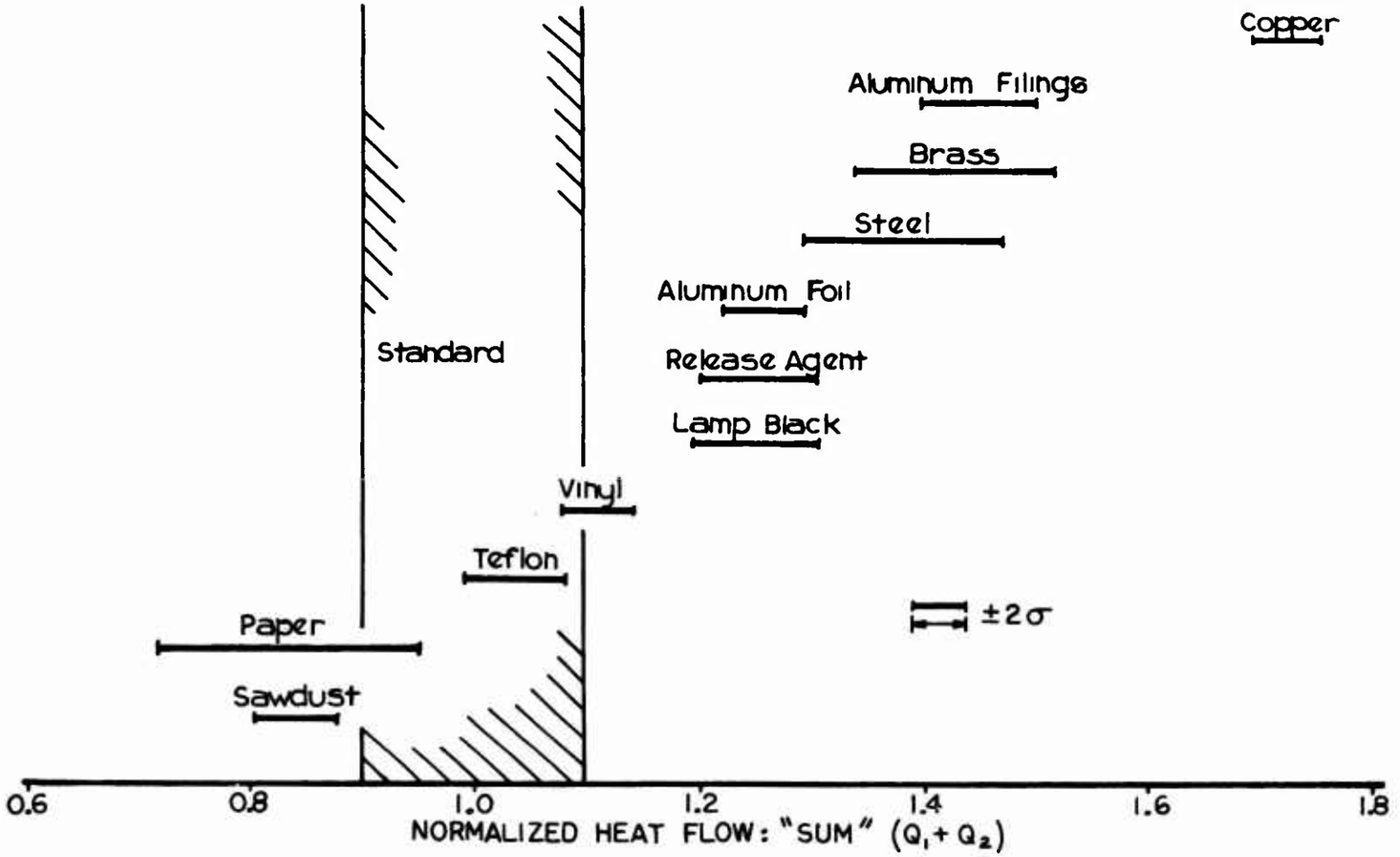


Figure 10. Inclusion Detection by "Sum" of Heat Flow Readings From Source and Sink.

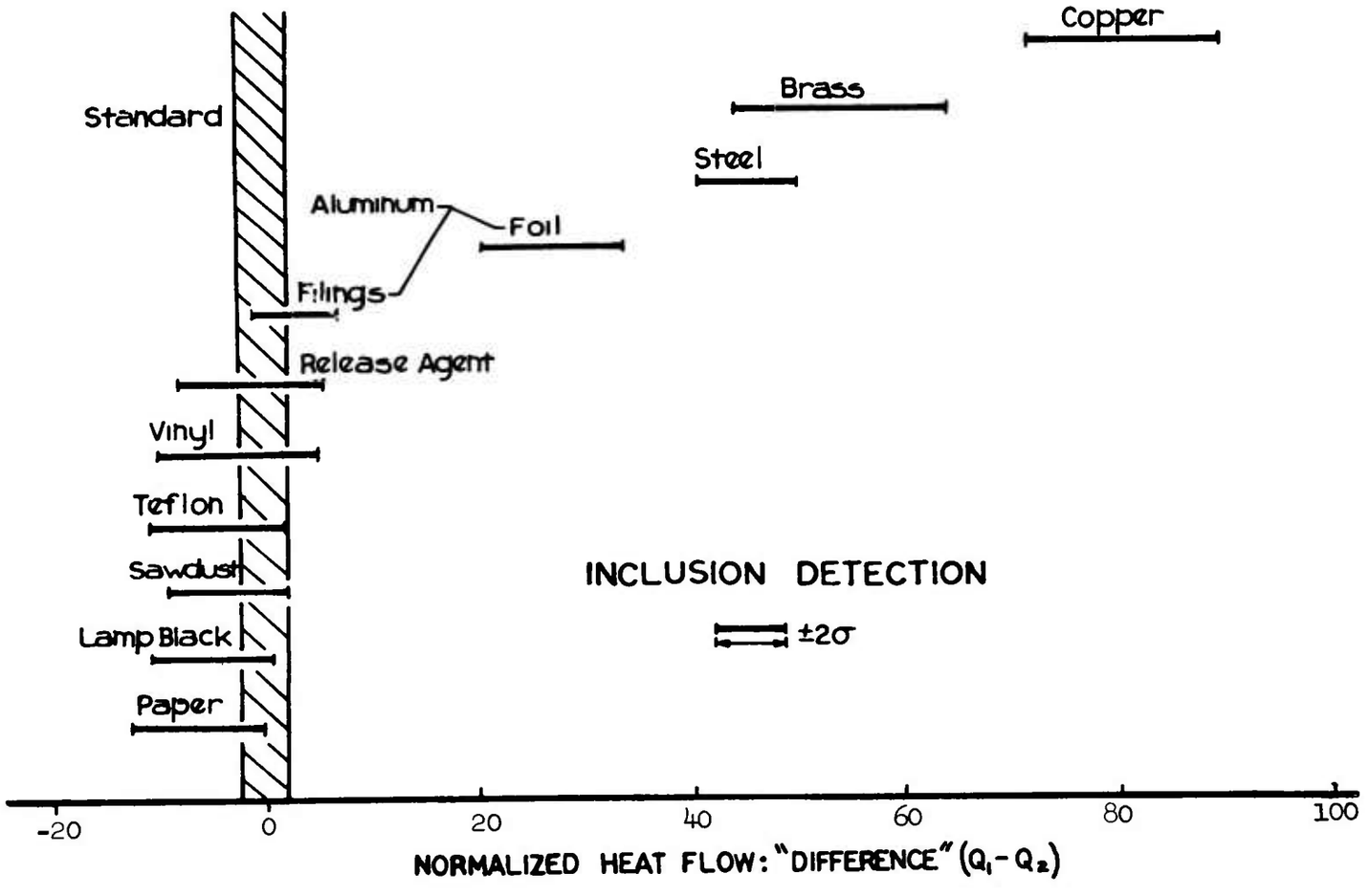


Figure 11. Inclusion Detection by "Difference" of Heat Flow Readings From Source and Sink.

THICKNESS DETERMINATION

The results of the thickness determination using the sum and difference of the outputs are shown in Figures 8 and 9. The curve of the sums of outputs, which would be most sensitive to conductivity divided by thickness, shows a sharp decrease in output with increasing thickness from zero to about 0.150 inch, after which it levels off to nearly horizontal at about 0.025-inch thickness.

As an indication of the resolution of this device for thickness measurements, the outputs are given in Table II with the error range of the thickness reflected by the ±2-standard deviation error band device output.

As may be seen, this conservative rating indicates good resolution to over 0.100 inch. Above 0.130 inch, the resolution, when compared to the error band, is poor.

Results from the difference of outputs on thickness determination (Figure 9) show a very wide error band compared to change in average output.

TABLE II. LIST OF SPECIMENS

No. of Layers	Thickness (inches)	±2 Error Band (inches)	% Error From Actual Thickness
2	.016	± .0006	± 3.75
4	.036	± .0017	± 4.72
9	.073	± .0065	± 8.90
15	.131	± .0210	± 16.0
25	.210	± .0570	± 27.1

DETECTION OF INCLUSIONS

The "sum of readouts" inclusion test results are shown in Figure 10. Again, the data are presented in the conservative ±2-standard deviation error band form. The "standard" specimen result is made up of readings from points of maximum and minimum thickness on the inclusion specimen sheets, and all are considered as one population. This results in a very wide (conservative) error band.

As may be seen, the resolution of most of the inclusions is excellent. The presence of metal inclusions is most easily determined, as would be expected, and all others, with the exception of Teflon, are easily differentiated from the standard specimens. Notice should be drawn to the easy recognition of release agent in the layup. This is an inclusion that could easily occur in a production layup, and the detection of its presence is very important. It is a disappointment that Teflon cannot be detected, but its thermal properties are very similar to those of the layup materials.

The difference of output criteria (Figure 11) shows better resolution of metallic inclusions than the "sum" tests, and the type of metal involved is more easily defined. It is apparent from these tests that changes in the difference of outputs are most dependent on transverse conduction and that they are rather insensitive to specific heat changes. This conclusion is reached because the inserts with good conductivity show a large amount of stored heat, while the poorer conductor inserts show little or no difference from the standard despite differences in specific heat.

Comparison of the "sum" and "difference" results shows that, in some cases, the nature of the inclusion may be deduced as well as that of the material. From a comparison of the results for the aluminum foil stack and the aluminum filings, it is seen that the filings show a higher result from the "sum" determinations and that the foil stack is higher on the "difference" results. This is as expected because the chips aid through-conduction and the foil aids transverse conduction, the two variables to which the two result types are most sensitive. A solid aluminum inclusion would give a high result for both data handling techniques.

As a test of resolution of the system, Thickness Specimens 4 and 5 were tested in a stack to see if the composite could be differentiated from the standard thickness curve. An average of two tests was taken, and the combination of specimens was marginally detectable on the "sum" determination.

GENERAL DISCUSSION

The investigators believe that the error bands, found in this series of tests, are not as good as might be expected from such tests. Errors arose from several uncontrolled specimen variables and changes in technique.

First, and probably most important, there was some variation in surface finish both among specimens and across each individual specimen. Errors in each data point are due, in part, to changes in surface finish resulting from small changes in test point location. Tests with known surface finish must be made, and this variation should be included as a calibration variable.

A second major source of scatter is in the contacting technique. If the test specimen contacts either or both of the sinks much before the electronic readout timing switch is triggered, some of the important initial transients will not be recorded, thus creating an error. Switch contact before thermal contact, on the other hand, would obviously create timing errors. Other contacting errors creating a constant offset in the signal are largely removed in the analog computer system.

An obvious source of error is indicated by a shift in data by the two operators. This was very small for all specimens except the two-layered layup, where the volume conductivity was very high and the surface resistance was very important. Small differences in the nominally identical technique of specimen contact and contact pressure resulted in a considerable shift in data for this panel. To correct this, a controlled contacting device must be made. Variations of this form indicate that a study of the interaction of surface finish and contact pressure would be worthwhile.

A source of overall error in the thickness determinations is the possibility of variation of resin content and state of cure from specimen to specimen. For this reason, the thickness curves are not to be considered as calibration curves except to indicate trends. There will certainly be a variation with resin content, and the state of cure may be detectable.

It is assumed that electrical and computing errors are consistent and are accounted for by calibration to a standard.

CONCLUSIONS

It has been shown that a thermal testing device such as that described can be useful for finding inclusions and for determining thickness in fiber glass reinforced plastic panels.

Inclusions of many materials are easily detected and, in some cases, it is possible to deduce the material and physical form of the insert.

It appears possible to determine the thickness of a panel with good resolution up to about 0.130 inch.

Although it has not been studied specifically in this series of tests, there is a strong indication that correlation may be made of output and surface finish, resin-glass ratio, and extent of cure.

At the present state of development, the device can be considered to give only qualitative data which will show differences from a standard. The machine does give, in many cases, a reliable and fast criterion for acceptance or rejection of the hypothesis that a sample is similar to a standard. It does, therefore, satisfy the original intentions of the study.

To develop the machine into a quantitative device, further work is required to determine the effect of the following variables: (1) Surface Finish, (2) Contact Pressure, (3) Resin-Glass Ratio, (4) Extent of Cure, and (5) Raw Material Variation. In addition, some mechanical refinement is required to reduce the scatter in readings.

It is hoped that extensive testing will allow the separation of effects of the important variables. The probability of separating surface phenomena from interior variations is good, but internal errors in construction may have to be separated by other techniques after their presence is detected by the thermal comparator.

APPENDIX
RAW DATA AND DATA REDUCTION

Specimen #2 2-Layer (0.016 in.)

Reading #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	153.0	146.5	299.5	6.5
2	151.5	143.5	295.0	8.0
3	145.5	148.0	293.5	-2.5
4	150.5	146.5	297.0	4.0
5	152.0	148.0	300.0	4.0
6	151.0	147.0	300.0	2.0
7	148.5	145.0	293.5	3.5
8	150.5	141.5	292.0	9.0
9	154.0	139.5	293.5	14.5
10	154.0	139.0	293.0	15.0
11	155.0	139.0	294.0	16.0
12	154.0	139.5	293.5	14.5
13	154.0	139.0	293.0	15.0
14	155.0	135.0	290.0	20.0

$\bar{x} = 294.8$ $\bar{x} = 9.25$

$\sigma = 4.65$ $\sigma = 6.32$

$\bar{x} + 2\sigma = 304.1$ $\bar{x} + 2\sigma = 21.9$

$\bar{x} - 2\sigma = 285.5$ $\bar{x} - 2\sigma = -3.4$

Specimen #3 4-Layer (0.036 in.)

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	90.4	80.6	171.0	9.8
2	96.4	84.8	181.2	11.6
3	97.6	85.0	182.6	12.6
4	93.8	80.4	174.2	13.4
5	94.4	80.2	174.6	14.2
6	93.0	82.4	175.4	10.6
7	95.0	82.5	177.5	12.5
8	94.0	82.0	176.0	12.0
9	94.0	80.5	174.5	13.5
10	94.4	84.8	179.2	9.6
11	98.0	80.4	178.4	17.6
12	97.0	80.4	177.4	16.6
13	95.0	80.0	175.0	15.0

$\bar{x} = 176.7$ $\bar{x} = 13.0$

$\sigma = 2.52$ $\sigma = 2.34$

$\bar{x} + 2\sigma = 181.7$ $\bar{x} + 2\sigma = 17.7$

$\bar{x} - 2\sigma = 171.7$ $\bar{x} - 2\sigma = 8.3$

Specimen #4 9-Layer (0.073 in.)

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	73.6	44.2	117.8	29.4
2	66.8	43.2	110.0	23.6
3	69.0	46.8	115.8	22.2
4	70.0	48.2	118.2	21.8
5	69.4	46.8	116.2	22.6
6	64.0	42.4	106.4	21.6
7	68.4	46.8	115.2	21.6
8	68.6	46.6	115.2	22.0
9	69.6	45.2	114.8	24.4
10	68.6	45.0	113.6	23.6
11	70.4	45.2	115.6	25.2
12	67.6	44.8	112.4	22.8
13	69.8	46.2	116.0	23.6
14	70.0	47.2	117.2	22.8

$\bar{x} = 114.6$ $\bar{x} = 23.4$

$\sigma = 3.08$ $\sigma = 1.98$

$\bar{x} + 2\sigma = 120.8$ $\bar{x} + 2\sigma = 27.4$

$\bar{x} - 2\sigma = 108.4$ $\bar{x} - 2\sigma = 19.4$

Specimen #5 15-Layer (0.131 in.)

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	55.8	25.4	81.2	30.4
2	56.0	28.0	84.0	28.0
3	56.4	27.8	84.2	28.6
4	54.2	26.6	80.8	27.6
5	55.8	27.4	83.2	28.4
6	54.0	25.4	79.4	28.6
7	56.0	27.0	83.0	29.0
8	55.8	27.0	82.8	28.8
9	56.2	27.8	84.0	28.4
10	56.0	26.2	82.2	29.8
11	57.0	25.8	82.8	31.2
12	56.0	26.8	82.8	29.2
13	55.4	28.6	84.0	26.8

$\bar{x}_{,} = 82.6$ $\bar{x} = 28.8$

$\sigma = 1.12$ $\sigma = 1.13$

$\bar{x} + 2\sigma = 84.8$ $\bar{x} + 2\sigma = 31.1$

$\bar{x} - 2\sigma = 80.4$ $\bar{x} - 2\sigma = 26.5$

Specimen #6 25-Layer(0.210 in.)

Run #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	53.0	20.2	73.2	32.8
2	52.0	21.4	73.4	30.6
3	51.4	22.4	73.8	29.0
4	50.4	21.4	71.8	29.0
5	50.6	22.4	73.0	28.2
6	50.6	23.2	73.8	27.4
7	52.0	22.0	74.0	30.0
8	52.0	23.2	75.2	28.8

$\bar{x} = 73.5$ $\bar{x} = 29.5$

$\sigma = 1.25$ $\sigma = 1.68$

$2\sigma = 2.5$ $2\sigma = 3.4$

$\bar{x} + 2\sigma = 76.0$ $\bar{x} + 2\sigma = 32.9$

$\bar{x} - 2\sigma = 71.0$ $\bar{x} - 2\sigma = 26.1$

Inclusion Tests

Specimen A Sawdust

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	71.0	66.4	137.4	4.6
2	70.0	64.5	134.5	3.5
3	74.0	65.5	139.5	8.5
4	67.5	62.5	130.0	5.0
5	70.0	63.0	133.0	7.0
6	73.0	61.4	134.4	11.6
7	74.2	63.6	137.8	10.6

$\bar{x} = 135.2$
$\sigma = 2.94$
$2\sigma = 5.9$

$\bar{x} = 7.54$
$\sigma = 2.58$
$2\sigma = 5.2$

$\bar{x} + 2\sigma = 141.1$
$\bar{x} - 2\sigma = 129.3$

$\bar{x} + 2\sigma = 12.7$
$\bar{x} - 2\sigma = 2.3$

Specimen B Aluminum Filings

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	120.5	107.5	228.0	13.0
2	124.5	111.0	235.5	13.5
3	123.0	111.5	234.5	11.5
4	126.0	110.0	236.0	16.0
5	121.5	105.0	226.5	16.5

$\bar{x} = 232.1$ $\bar{x} = 14.1$

$\sigma = 4.02$ $\sigma = 1.88$

$2\sigma = 8.0$ $2\sigma = 3.8$

$\bar{x} + 2\sigma = 240.1$ $\bar{x} + 2\sigma = 17.9$

$\bar{x} - 2\sigma = 224.1$ $\bar{x} - 2\sigma = 10.3$

Specimen C Paper

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	63.0	62.8	125.8	0.2
2	67.5	67.0	134.5	0.5
3	69.5	67.0	136.5	2.5
4	62.5	56.0	118.5	6.5
5	69.5	62.0	131.5	7.5
6	76.0	68.4	144.4	7.6
7	77.2	69.8	147.0	7.4

$\bar{x} = 134.0$
$\sigma = 9.21$
$2\sigma = 18.4$

$\bar{x} + 2\sigma = 152.4$
$\bar{x} - 2\sigma = 115.6$

$\bar{x} = 4.6$
$\sigma = 3.15$
$2\sigma = 6.3$

$\bar{x} + 2\sigma = 10.9$
$\bar{x} - 2\sigma = -1.7$

Specimen D Aluminum Foil Stack

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	120.0	84.0	204.0	36.0
2	120.0	86.5	206.5	33.5
3	119.5	79.0	198.5	40.5
4	120.0	80.0	200.0	40.0
5	122.0	79.5	201.5	42.5

$\bar{x} = 202.1$
$\sigma = 2.85$
$2\sigma = 5.7$

$\bar{x} + 2\sigma = 207.8$
$\bar{x} - 2\sigma = 196.4$

$\bar{x} = 38.5$
$\sigma = 3.27$
$2\sigma = 6.5$

$\bar{x} + 2\sigma = 45.0$
$\bar{x} - 2\sigma = 32.0$

Specimen E Teflon

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	87.2	80.8	168.0	6.4
2	82.0	78.5	160.5	3.5
3	85.0	82.5	167.5	2.5
4	86.0	75.5	161.5	10.5
5	87.5	83.5	171.0	4.0
6	89.2	79.0	168.2	10.2
7	88.4	79.0	167.4	9.4

$\bar{x} = 166.3$ $\bar{x} = 6.64$

$\sigma = 3.54$ $\sigma = 3.15$

$2\sigma = 7.1$ $2\sigma = 6.3$

$\bar{x} + 2\sigma = 173.4$ $\bar{x} + 2\sigma = 12.9$

$\bar{x} - 2\sigma = 159.2$ $\bar{x} - 2\sigma = 0.3$

Specimen F Release Agent

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	108	98.6	206.6	9.4
2	105.5	97.5	203.0	8.0
3	105.0	99.5	204.5	5.5
4	104.5	89.5	194.0	15.0
5	104.5	97.0	201.5	7.5
6	106.0	92.5	198.5	13.5

$\bar{x}$ = 201.4 $\bar{x}$ = 9.8

σ = 4.14 σ = 3.36

2σ = 8.3 2σ = 6.7

$\bar{x} + 2\sigma$ = 209.7 $\bar{x} + 2\sigma$ = 16.5

$\bar{x} - 2\sigma$ = 193.1 $\bar{x} - 2\sigma$ = 3.1

Specimen G Lamp Black

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	106.0	102.0	208.0	4.0
2	105.0	97.5	202.5	7.5
3	102.5	98.5	201.0	4.0
4	102.5	92.0	194.5	10.5
5	101.0	97.5	198.5	3.5

$\bar{x} = 200.9$
$\sigma = 4.46$
$2\sigma = 8.9$

$\bar{x} + 2\sigma = 209.8$
$\bar{x} - 2\sigma = 192.0$

$\bar{x} = 5.9$
$\sigma = 2.71$
$2\sigma = 5.4$

$\bar{x} + 2\sigma = 11.3$
$\bar{x} - 2\sigma = 0.5$

Specimen H Vinyl Tape

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	95.0	87.0	182.0	8.0
2	91.0	87.0	178.0	4.0
3	91.5	86.0	177.5	5.5
4	93.5	88.0	181.5	5.5
5	94.0	81.4	176.0	12.6
6	95.0	81.0	176.0	14.0

$\bar{x} = 178.4$
$\sigma = 2.52$
$2\sigma = 5.0$

$\bar{x} + 2\sigma = 183.4$
$\bar{x} - 2\sigma = 173.4$

$\bar{x} = 8.3$
$\sigma = 3.78$
$2\sigma = 7.6$

$\bar{x} + 2\sigma = 15.9$
$\bar{x} - 2\sigma = 0.7$

Specimen I Copper

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	186.5	95.0	281.5	91.5
2	186.5	89.0	275.5	97.5
3	182.5	95.5	278.0	87.0
4	180.5	93.0	273.5	87.5
5	185.0	89.0	274.0	96.0
6	185.5	89.0	274.5	96.5

$\bar{x} = 276.2$ $\bar{x} = 92.7$

$\sigma = 2.44$ $\sigma = 4.41$

$2\sigma = 4.9$ $2\sigma = 8.8$

$\bar{x} + 2\sigma = 281.1$ $\bar{x} + 2\sigma = 101.5$

$\bar{x} - 2\sigma = 271.3$ $\bar{x} + 2\sigma = 83.9$

Specimen J Brass

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	150.0	85.0	235.0	65.0
2	156.0	84.5	240.5	71.5
3	145.5	83.0	228.5	62.5
4	141.5	83.0	224.5	58.5
5	141.0	77.0	218.0	64.0
6	150.5	78.0	228.5	72.5

$\bar{x} = 229.2$ $\bar{x} = 65.7$

$\sigma = 7.1$ $\sigma = 5.02$

$2\sigma = 14.2$ $2\sigma = 10.0$

$\bar{x} + 2\sigma = 243.4$ $\bar{x} + 2\sigma = 75.7$

$\bar{x} - 2\sigma = 215.0$ $\bar{x} - 2\sigma = 55.7$

Specimen K Steel

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	140.5	84.5	225.0	56.0
2	144.5	86.5	231.0	58.0
3	137.0	82.5	219.5	54.5
4	141.0	87.0	228.0	54.0
5	139.0	82.0	221.0	57.0
6	137.0	77.0	214.0	60.0
7	136.0	75.5	211.5	60.5

$\bar{x} = 221.4$
$\sigma = 6.9$
$2\sigma = 13.8$

$\bar{x} + 2\sigma = 235.5$
$\bar{x} - 2\sigma = 207.6$

$\bar{x} = 57.14$
$\sigma = 2.4$
$2\sigma = 4.8$

$\bar{x} + 2\sigma = 61.9$
$\bar{x} - 2\sigma = 52.3$

3-Layer Glass at Maximum and Minimum Thickness

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	90.0	77.5	167.5	12.5
2	81.0	71.5	152.5	9.5
3	90.0	79.0	169.0	11.0
4	81.5	71.5	153.0	10.0

$\bar{x} = 160.5$ $\qquad$ $\bar{x} = 10.8$

$\sigma = 7.8$ $\qquad$ $\sigma = 1.1$

$2\sigma = 15.6$ $\qquad$ $2\sigma = 2.2$

$\bar{x} + 2\sigma = 176.1$ $\qquad$ $\bar{x} + 2\sigma = 13$

$\bar{x} - 2\sigma = 144.9$ $\qquad$ $\bar{x} - 2\sigma = 8.6$

Specimen 4 + 5 Total Layers = 24

Total Thickness = .204 in.

Test #	$\int_0^{15} qdt_{Cold}$	$\int_0^{15} qdt_{Hot}$	Sum	Difference
1	54.2	24.4	78.4	30.0
2	52.4	24.2	76.6	28.2

Avg. of sum = 77.5

Avg. of diff. = 29.1