SURFACE TEMPERATURE MEASUREMENT IN THIN PLASTIC FILMS

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Brian Laurence Akers

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IN THIN PLASTIC FILMS

by

Prian Laurence Akers

AN ABSTRACT

Submitted to
Michigan State University
in partial fulfillment of the requirements
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MASTER OF SCIENCE IN PACKAGING

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Present day packaging economics dictates short-dwell, high-speed heat sealing so it is becoming increasingly important to know the actual film surface temperatures at the interface. These temperatures have never been adequately measured.

This study develops an experimental procedure for measuring the temperature at the surface of thin plastic films. The procedure employs a vacuum metallized film thermistor as the temperature-sensing device.

In addition, the resulting experimental data is used to validate a computer model for determining thin-film surface temperatures that should provide experimental flexibility for future study of the heat sealing cycle.

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To

My Wife and Family

ACKNOWLEDGEMENTS

The writer wishes to express his sincere thanks to Mr. David Brouse, packaging research associate, whose film thermistor idea was the basis of this study and whose guidance and sound criticism were often relied upon in pursuit of this investigation.

Special thanks are extended to Dr. James Beck of the MSU Mechanical Engineering Department for his help in adapting the heat transfer computer program to the thin-film application in this study.

Finally, the writer is indebted to all of the faculty and staff of the Michigan State University School of Packaging for their comments and criticisms contributing to moral support during every phase of the work.

B. L. A.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION AND PURPOSE

The problems involved in effecting adequate package closures by heat sealing are well known. Certainly many packagers have experienced the frustration of being unable to seal a film when all of the conditions on the wrapping machine appeared just right. With present day packaging economics dictating short-dwell, high-speed heat sealing, it is becoming increasingly desirable to know the actual film temperatures as related to machine temperature, dwell time, and film thickness. The reduction of production time for package closure has become a prime goal.

With this goal in mind, one fundamental area deserves detailed attention: the heat transfer processes in thin plastic films during the heat sealing cycle. Satisfactory seals can not be obtained if the film temperature at the interface is not in the film's sealing range.

An article directly concerned with this goal was published by Mr. Sheldon Kavesh in the October, 1964 edition of PACKAGE ENGINEERING (4). Kavesh used a digital computer to make a series of calculations to determine the temperature profile of polypropylene film when it is contacted by the hot and cold platens of a heat sealing machine. Although the study advanced a considerable amount of theoretical information concerning the temperature profile of polypropylene, the experimental proof was very limited. This fact pointed up the need for an adequate surface-temperature measuring device for thin plastic films that might support Kavesh in his theoretical findings.

The purpose of this study is to develop an experimental procedure for measuring the temperature at the surface of thin plastic films. The resultant procedure hopefully will provide a means to better understanding the time-temperature relationship involved in the heat sealing cycle.

As a further aid to study of this cycle, two computer models of the experimental system are developed in the last section of this thesis. The first model is an adaptation of the computer program Kavesh used in the forementioned article. The second model was written by Dr. James Beck of Michigan State University and adapted for use in this thin-film surface temperature measurement application.

Both models are included because the computer can be used to great advantage once the analyst has achieved a parallelism between the practical situation and his model. It is normally much easier to manipulate the model to study the characteristics in which one is interested than it is to try to work with the practical system. A thorough understanding of the simulation procedures in describing the system modeled is not necessary if the forementioned parallelism can be shown to exist (7). The author will attempt to show this parallelism between the experimental data and the computer models. Hopefully, this may promote future systems analysis of similar systems through computer simulation.

This thesis project was partially sponsored under the multi-sponsor research program conducted by the School of Packaging at Michigan State University. The thesis goals directly parallel the

stated project goals and the results should represent a significant contribution to the goals of the multi-sponsor research program.

II. BACKGROUND ON TEMPERATURE MEASUREMENT

The measurement of surface temperature in thin plastic films has never been adequately accomplished. In any measurement situation, the measuring technique must first take into account what effects the measuring device will have on the system; that is, it must be determined if the measurement itself will disturb the system and to what extent the observed data will differ from that which would be obtained were the measuring device not in the system. It can be assumed that the more thermally massive the measuring device, the more probable it becomes that it will significantly affect the system. For this reason when using a temperature measuring device, two things must be kept in mind: (a) What are the possible effects the device will have on the system and (b) to what extent will they affect the measurement data derived from the device.

The most common methods of measuring temperature are based on one of four principles: fluid expansion, as in the familiar mercury in a glass tube; physical or chemical change as in certain heat-sensitive materials; the generation of a voltage, as in a thermocouple; and a resistance change with temperature, which is the basis for a resistance temperature transducer or thermistor. The following is a brief description of each.

Thermometer. The read-out in this type of sensor is direct and visual. The difficulties of using a sensor of this type in measuring surface temperatures in thin plastic film is apparent and will not be elaborated upon.

Heat Sensitive Materials. There is a variety of this kind of sensor on the market. The mechanism of this type of transducer is the ability of the material to undergo a physical or chemical change at a fixed temperature. The material is applied to the source either from a crayon or brushed on in solution or suspension form. The solvent is a volatile type which will evaporate leaving a deposit of the thermally sensitive material on the surface whose temperature is to be measured. A color or consistency change is a common indication when a particular temperature is sensed. These sensors appear accurate to within approximately one per cent of the indicated value in our brief laboratory checks.

The primary disadvantage of this type of device when trying to measure the surface temperature of thin plastic films is the response time of the material. Since heat transfer is a time dependent quantity, there will exist a temperature lag between the surface of the film and the thermally sensitive material. In order for the thermally sensitive material to respond, it first must be heated to its indicated temperature. Where time is not a factor, this sort of indicator is quite accurate. However, when trying to make short time duration measurements, it is simply not suitable due to the slow response time, determined experimentally to average approximately ten seconds.

Thermocouples. This is a temperature measuring device which might be used for thin film measurements. Depending on the thermocouple, response times in the millisecond range are possible. These would be adequate for the measurements proposed in thin plastic films which are of the order of one to five seconds duration corresponding to the typical heat sealing cycle. The read-out of a thermocouple is adequately displayed through the use of various read-out devices such as oscilloscopes.

The primary disadvantage in using a thermocouple lies in knowing what the couple is actually sensing. A temperature change generates a small difference in potential when two dissimilar metals are in intimate contact. When the point of contact is at some different temperature than the input leads to the read-out device, it is possible to detect the small amount of current which is generated in terms of temperature. The actual current generated is a function of the contact surface area whereas the change in voltage is a function of the temperature gradient that the entire contact area experiences (9). If this contact area is one mil thick as in a typical heat sealing situation, the voltage generated will be in proportion to the average temperature of the contact area. In a practical sense, a thermocouple one mil in diameter will measure the average temperature across a one mil film since the pressure generated by the sealing device will imbed the thermocouple into the film. If the heated bar temperatures are 300°F. and 100°F., and assuming the surface temperature that is of interest is 100°F., it is obvious that the recorded temperature will be in error since the thermocouple is no longer positioned on the surface of the film.

In attempting to establish a more accurate surface temperature measuring system, the requirements are that the sensor must be in contact only with the surface of interest and yet have a small enough thermal mass to not greatly affect the temperature of the system.

Thermistors. In an effort to comply with the above restrictions, the use of a vacuum metallized aluminum coated film to serve as a thermistor is proposed. Such films are readily available from many commercial packaging film sources.

The thickness of the aluminum coating is approximately 0.001 mil or 1/1000 the thickness of the film whose surface temperature is of interest. In regard to these conditions then: what is the temperature that the coating will see? Hopefully, there will be no thermal gradient across the aluminum coating, and the film must approach the surface temperature at both surfaces of the aluminum coating.

One indicative measure of this possibility is the thermal diffusivity of the film. This is the measure of how fast the temperature gradient will disappear through the material as opposed to the thermal conductivity which is a measure of how much heat a material will allow to pass through a given thickness and area under the influence of a temperature gradient or differential. Thermal diffusivity, in other words, is a measure of the speed of the thermal "wave" that is started when a hot surface is brought into sudden contact with a cold material (6). In the proposed situation, the thermal wave through the aluminum should be much greater than through the film whose surface temperature is to be measured. This value for aluminum is approximately 3.27 $ft.^2/hr.$ and for the film, polystyrene for example, it is $3.26 \times 10^{-3} ft.^2/hr.$ (Refer Calculation B, Appendix 1.) The relative velocity of the thermal waves in these two materials in identical situations show that of aluminum to be about 1000 times that of polystyrene. This rough comparison appears to support the notion that an aluminum coating of 0.001 mil thickness on a one mil thin plastic film would not significantly change the temperature distribution in the same film without the coating.

A factor which may alter the theoretical situation in an experimental temperature measuring system is contact resistance. In some theoretical heat transfer calculations, this factor can be ignored but its effects can seriously alter theoretical results in a practical situation.

Contact resistance is a term defining the nature of the bond formed between the heat source and the fluid or solid specimen which contacts it. If a solid receives heat by contacting a solid, it is almost impossible to exclude the presence of air from the interface. Contact resistance then defines the average thickness of this air layer at the interface of the two solids (6).

In a heat sealing situation, the heat transfer is independent of the pressure (5). A certain amount of pressure is required, however, to hold the films together and to approach the intimate contact necessary to minimize the imperfect heat transfer brought about by the contact resistance present.

Read-out of the proposed film thermistor necessitates the use of some device to measure the change in electrical resistance with a change in temperature. The most direct and accurate technique is comparison methods based upon an electrical resistance bridge circuit.

For some purposes, bridges are used strictly as comparison devices where, once the bridge is nulled, the value of the unknown area may be calculated by a simple ratio equation. In other cases, the bridges serve as a means to obtain a voltage roughly proportional to the deviation from the null condition. For design purposes, the condition for null must be known. To calculate deviation from the null, it is also necessary to know the bridge sensitivity either to the change in resistance or to the temperature that caused the resistance change (1). Where the application of the bridge is temperature measurement in thin plastic films, the latter use of the bridge circuit fits the situation.

III. THIN-FILM SURFACE TEMPERATURE MEASUREMENT EQUIPMENT

The following is a description of the experimental equipment used in the temperature measurement system for thin plastic films. Where necessary, the rationale behind the choice of equipment is explained.

Thermistor. As indicated previously, the choice of the aluminum coated film, in this case one mil polystyrene, was largely based upon its apparently favorable thermal qualities in the proposed temperature-measuring application.

The vacuum metallizing process by which the coating is applied is known to hold impurities caused by oxidation during the coating process to a minimum besides maintaining a fairly close control on the thickness of the coating. Both of these factors are highly desirable in resistance temperature transducers.

Additionally, it was hoped that the aluminum coating would provide a definite and linear relationship between electrical resistance and temperature over the potential heat sealing temperature range. Linearity is desirable in that it simplifies the relationship between resistance and temperature, easing calibration. The linearity of the resistance transducer is an inherent function of the material modified only by the impurities present and some mechanical factors (9).

Attempts were made to get coated polypropylene or polyethylene but the delivery time was prohibitive. The film used was available at the time of the study and was used primarily because of this availability.

It was a one mil metallized Dow Chemical Company polystyrene film, Q641.4, approximately ten years old. The film was felt to be satisfactory for thermistor use since polystyrene is relatively less susceptible to deterioration than some other types might be. The physical appearance of the film was excellent and the inherent physical properties of the film were assumed to be the same as known polystyrene, although no specific information on this particular film could be obtained.

The film samples used were eight inches by approximately one inch cut on a Model JDC 25 Precision Sample Cutter made by Thwing-Albert Instrument Company. The length and width of the individual samples was thus closely controlled. These dimensions showed approximately a 20-ohm resistance per thermistor sample.

Bridge Circuit. The bridge used was what might be termed a half symmetrical type. The two resistors in the upper half were equal requiring the two in the lower half to be equal at null. The effect of lead wires and variations in the lead wire resistance acted equally in both legs of the bridge so that the null was undisturbed.

A variable rheostat was placed in series with the thermistor to null the bridge. The thermistor was made one arm of the four-arm resistance bridge. The rheostat was then used to null the bridge by equalizing the resistance variations that might be present from one thermistor sample to the next.

A practical condition had to be placed on the bridge circuit. This was the self-heating limitation within the transducer, which had to be held to a minimum to avoid errors in the temperature measurements.

The high thermal sensitivity of the film made it susceptible to resistance changes due to heating by the bridge current during the balancing procedure. On the other hand, the sensitivity of the bridge circuit varied directly with the bridge current so a balance had to be found between the two in final bridge design (1).

The primary consideration appeared to be a maximizing of the circuit sensitivity so rough calculations of the heating effect were performed and are shown in Appendix 1, Calculation A (10). The final bridge circuit design was based upon these calculations. Some self heating was present within this final design according to the theoretical calculations but had negligible effect on the temperature measurement data. The final design of the bridge circuit is shown in Appendix 2, Figure C.

The bridge circuit power was supplied by a variable 30 volt - 225 milliamp DC power supply, Model 721A manufactured by Hewlett Packard. The 20 volts used for the bridge circuit provided a low enough voltage that no special precautionary measures on the experimental equipment were necessary. It was still high enough that the read-out noise caused by the antenna properties of the system lead wiring, thermistor, etc., were reduced to a workable level.

The final system sensitivity achieved was approximately a 2 millivolt change per one degree F. with 145 milliamps bridge current. The resistance change in a typical thermistor was about one ohm in 20 with a 100-degree rise in temperature. This sensitivity seemed satisfactory for following the environmental temperature changes experienced by the film thermistors throughout the experimentation.

Typical resistance changes are shown for some randomly chosen film thermistors in Table A, Appendix 3. Care was exercised in selecting the bridge components with sufficient thermal mass and reactances to insure resistive stability.

Heat Sealer. The laboratory heat sealer was constructed from a design by Olin Mathieson Chemical Corporation (8). It is specifically for laboratory use and provides control of the three variables of sealing: temperature, dwell time, and pressure.

The sealing unit is constructed in the form of a small table, 8½ inches by 4 inches, with an opening at the center large enough to admit the sealing bar. In its retracted position, the bar is one-half inch below the top of the table. An air piston actuates the upward travel of the bar. The sealing profile can be altered by replacing the demountable profile head with a head containing the desired profile. For this series of temperature measurements the profile head used was aluminum with a coating of approximately one mil thick Teflon. This profile head provides a flat sealing surface one inch wide by 6½ inches long. Heat is supplied to the profile head by a 150 watt heater mounted in the heating bar on which the profile head is mounted.

The sealing pressure is controlled by dead weight so it is possible to obtain a variety of sealing pressures. The weight used was 4 pounds seven ounces, mounted on a base 4 inches by 6½ inches. For the one inch wide sealing bar, the pressure was calculated to be 0.68 pounds per square inch.

Temperature and dwell time were regulated respectively by means of a temperature controller and an electric timer both mounted in a separate console. Although the timer was not used during the final recommended measurement procedure, it was used during the initial temperature measurement procedure. For an accurate estimate of the temperature of the surface of the sealing bar, a thermocouple is located as close to the sealing surface as possible. The electric timer is started by means of a microswitch adjusted so that the sealing cycle is timed from the instant the sealing bar first touches the test specimen or in this case, the thermistor. The timer, in turn, opens and closes a solenoid valve to the small air piston which moves the sealing bar into position and back down at the end of the sealing cycle.

The sealing table also contained the film thermistor clamps. These clamps were Acco Products paper clamps #125, to which banana plug electrical connections were added. The clamps were located in the heat sealer table in insulated positions at either end. These clamps proved to be somewhat troublesome during the experimentation as the electrical contact the clamps made with the thermistor aluminum coating was often imperfect. A Simpson Multimeter was used to check the initial resistance of the thermistor samples to insure good electrical contact.

<u>Oscilloscope</u>. The final major piece of equipment was a Tektronix Type 564 Storage Oscilloscope. The scope display was used as a read-out device for the voltage changes detected by the bridge circuit in the thermistor as the thermistor resistance changed with increasing temperatures in the heat sealer.

A photograph of the assembled temperature measuring system for thin plastic films is shown in Figure 1. The small black box in the foreground contains the resistance bridge excepting the film thermistor which is located on the heat sealer table suspended between the clamps. The rheostat control can be noted on this same black box. The large black console in the background is the Model JP temperature control unit by West Instrument Corporation. The temperature dial visible on this console is in Fahrenheit degrees at 5 degree increments with each major division equal to 25°F. All temperature readings throughout the experimental procedure are taken from this dial to interpret the voltage read-outs from the scope display. This console also contains a conventional heat sealer timer control. A powerstat control located in the lower left-hand corner is used to control the rate of bar heating in the heat sealer.

Notice the thermistor in position in the clamps on the heat sealer table.

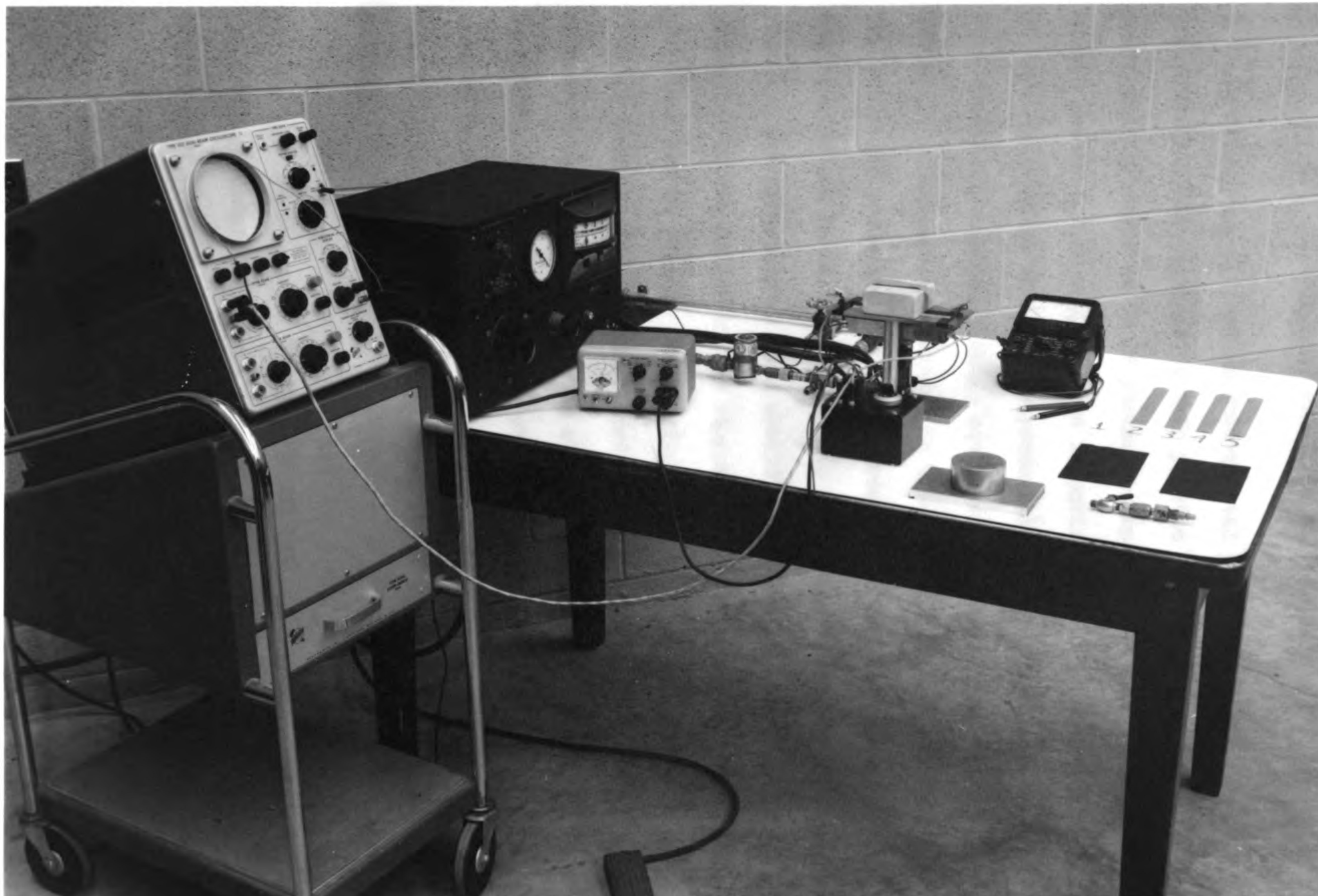


FIGURE 1 - Assembled [illegible] Temperature Measuring System for Thin-[illegible] Films

IV. EXPERIMENTAL PROCEDURE AND ANALYSIS

In attempting to find an experimental procedure to measure temperature at the surface of thin plastic films, the following conditions appeared to be of paramount importance. First, the system should detect only changes in environmental temperatures. Second, the results should be reproducible in a practical manner with relatively unsophisticated equipment and procedures. With a few basic conditions recommended in the experimental environment, the resultant procedure should be versatile in that duplication of the results can be easily attained in any similar laboratory situation. Finally, the experimental data should be related to a computer program suitable for simulation of the temperature measurement system in thin plastic films to promote future study.

To meet the forementioned conditions, two basic experimental procedures evolved, one from the other. The initial procedure will be briefly explained with the pertinent experimental data that dictated changes in procedure. The final temperature measurement procedure will then be outlined with the experimental results of the procedure summarized.

General Procedures

Both procedures involved the use of the aluminum coated polystyrene strip as a thermistor. Basically, the thermistor was made one arm of a four-arm resistance bridge. This involved clamping the film thermistor into the clamps on the heat sealer table. The remainder of the circuit including the rheostat was located in a circuit box. An initial scope display base line was used with bridge power off. This base line on the 10 millivolt per centimeter scale should be at the bottom scaleline on the scope face so that the uppermost temperature changes can be recorded without switching to the next higher scope scale. Using any lower scale made the signal noise (identified as 60 cycle interference) excessive. A precise balance position was achieved by adjusting the resistance of the variable rheostat in the adjacent arm of the bridge. This balance condition, observed on the oscilloscope display, was used as a base line for the subsequent readings. It will subsequently be referred to as "t_b" and represents the null condition of the initial environmental temperature or in this situation, the room temperature. All experimentation was conducted under non-controlled environmental conditions.

The procedure for balancing the bridge deserves further clarification. Throughout the experimentation, a ten-turn 50 ohm potentiometer wired as a variable rheostat was used. Even with the fine tuning capabilities of this rheostat, at the upper temperature ranges during the experimentation, setting t_b involved an averaging of the heated bar temperature cycle. If a certain bar temperature was desired, the setting was made on the temperature scale and the control unit then attempted to maintain that temperature with the thermostat. Nevertheless, enough cycling did occur that setting t_b often involved considerable judgment and a definite "feel" for the system. The rheostat control in the bridge circuit gave approximately a ten millivolt change in the scope display for each of the smallest divisions on the control knob. A ten-turn 25 ohm potentiometer with a 10 ohm resistor wired in series would provide somewhat more control. This problem with the initial setting of t_b, nulling the bridge, should be noted but it presented no real difficulty when the capabilities and limitations of the system in this regard were known. This setting determines all subsequent system accuracy so its importance cannot be overemphasized.

The entire bridge balancing procedure must take place with the thermistor in position in the clamps to complete the bridge circuit. Since the sealer bar was at some temperature over room temperature depending on the temperature control setting, some method of isolating the thermistor from the heated bar during the balancing process had to be found; the t_b base line at null should represent only the initial room temperature environment. This isolation was successfully accomplished using a wooden spacer cut from 2 inch by 4 inch wood stock. The spacer was checked on a sample film thermistor in bridge balance and there was no significant change in the t_b scope display after approximately 48 hours with bridge power on. Figure A, Appendix 2, illustrates the thermistor in the balancing position. In addition, it indicates that resistive heating in the thermistor was at a negligible level. Throughout the experimental procedure, a 1/16 inch commercial neoprene insulation was used to insulate the aluminum coating from the metal weight and prevent a short circuit during the timing procedure.

When t_b was set, the wooden isolation block was removed and the insulation and weight were placed on the thermistor sample. The heat sealing bar was then raised and a data record taken. This visual scope display represented the bridge unbalance signal due to thermistor heating and the voltage drop across the thermistor due to the increase in resistance as the temperature increases. In the experimental procedures used, the read-out from the scope display indicated an increase from the base line. This display appeared more conventional for the measurement purposes although it should be noted that the display actually represented a decreasing voltage as the resistance of the thermistor increased.

Calibration. During calibration, the primary objective was to sense the absolute changes in temperature of the heated jaw as voltage changes on the scope display for later interpretation into corresponding temperatures. With this in mind, all calibration of the thermistor was accomplished with the aluminum coating side of the thermistor in direct contact with the Teflon coated heated bar.

The timing solenoid was removed from the heat sealer control system and was replaced by a simple air valve. A relief valve to lower the heat sealer bar was provided and 15 PSIG air pressure was used throughout the procedures.

Timing. Although no actual heat sealing was to be accomplished during the experimentation, the temperature of interest throughout the measurement procedures was at the location on the surface of the thermistor that would represent the interface of two films in the normal heat sealing operation. This, then, was the desired location for the aluminum coating so throughout the timing measurements of temperature, the aluminum coating was reversed from the calibration procedures. In this way the temperature at any given time could be sensed at the surface of the film where the heat seal would normally occur.

Figure B, Appendix 2, illustrates the thermistor in position for either calibration or timing with the one difference that the position of the aluminum coating varied as previously noted.

Initial Procedure

In this procedure, the basic approach was that of determining an optimum sample size with the samples in this case being the film thermistors. An initial sample size of five was arbitrarily chosen.

Calibration. During calibration each sample was clamped in turn following the general procedures. A data record was made for each sample and data was recorded from the scope display for temperature settings ranging from 100°F. to 225°F. in 25 degree increments. The average of these results was plotted; temperature (from the temperature control setting) versus the scope display reading in millivolts corresponding to this temperature.

Timing. During timing, the same sample reclamping procedure was used as in calibration following the general procedures but in this case, the bar temperature was set first at a constant 200°F. and then at 175°F. The timer and solenoid were used to control the heat sealer bar action. The timer range used was 0.5 to 2.5 seconds in increments of 0.25 seconds. The average of these voltage readings was converted to temperatures from the plot of the average calibration data.

Analysis. The calibration curve indicated a linear relationship existed between the electrical resistance and thermal properties of the film thermistor in the temperature range checked. Many problems were apparent from this initial test procedure.

(a) Although the average plot of the samples appeared linear, the variation from this average value appeared significant. There also appeared to be positive correlation between initial resistance as checked by the Simpson voltmeter and the voltage readings. Higher initial resistance resulted in higher voltage readings and vice versa. This indicated that the vacuum metalizing process for coating the film did not maintain as tight control over coating thickness as originally thought. Variations of up to 8 ohms had been noticed in initial resistance with the voltmeter. With this apparent correlation, two thermistors with opposite extremes of initial resistance were calibrated and timed according to the initial procedure. The results are shown in Table B, Appendix 3. These results indicate that the average plots used in calibration of the five samples had not eliminated any errors in clamping or technique. In fact, the results seemed to indicate that even small differences in initial sample resistance might affect the data read-out significantly.

(b) The contact resistance in the system was another area that might possibly have affected the readings. Since this is representative of the thickness of the average air layer in the heat transfer system, it might be reduced by adding more pressure in the form of additional weights to the system. The results are shown in Table C, Appendix 3, and indicate that additional weight over the normal weight used with the heat sealer would not affect the system data.

(c) Another phenomenon was noted in this initial procedure. It appeared that a sample inadvertently stretched when in position with the weight in place for either calibration or timing experienced some stress that could affect the read-out scope display. To check this, samples were intentionally stressed by suspending the thermistor in the clamps while supporting the weight. Subsequent readings indicated that this was indeed a factor. The scope display for the typical sample in this condition indicated lower voltage than would be expected initially and as the sample heated, the display tends to rise back toward a normal non-stressed reading. The stress and resistance change appeared to act in opposite directions with temperature change. As the temperature went up, the stresses were relieved within the thermistor and the resistance increase then dominated the scope read-out. By exercising care in clamping the thermistor in the bridge circuit, no stress effect was noted.

(d) The thermistors used in the initial procedure showed drastic physical deformation at 200°F. after approximately 2.5 seconds. This in turn radically affected the scope display as the electrical conductivity of the thermistor broke down. The thermistors tested at 175°F. were satisfactory after relatively long lengths of time.

(e) The initial environmental conditions including temperature and convective air flow affected the bridge balance condition and the t_b setting. This had an obvious subsequent effect on the data read-out.

Final Procedure

This procedure is recommended for any duplication efforts of the surface temperature measurement apparatus for thin plastic films. It is based upon the changes dictated by the effects observed in the initial procedure. The most significant change is the use of one thermistor for both calibration and timing. The resultant curves and data will apply only to that particular thermistor, but it is believed that the errors apparently caused by variations in initial resistance probably due to variable aluminum coating thicknesses will be eliminated using this procedure.

Although not used in this final procedure, it should be recognized that any further experimentation should be conducted under closely controlled environmental conditions. Control of temperature and convective air movement should be given special attention.

Calibration.

1) The film thermistor should be positioned following the general procedures outlined on pages 17 through 21.

2) The calibration run should start with the heat sealing bar raised. The calibration cycle should begin with the bar at 175°F.

3) Allow the scope display to stabilize and record the scope voltage read-out in millivolts.

4) Turn the power OFF to the heat sealer.

5) Record the scope display readings at 5 degree increments read from the temperature control scale down through 125°F. as the heat sealer bar cools.

6) Turn the heat sealer control unit ON at just below a 125°F. indication and with the unit powerstat set at a slow rate of 50, reheat the heater bar.

7) Record the scope display during the heating cycle at the same 5 degree increments through 175°F. The two sets of readings will be the same if the cooling and heating rates are equal as desired. If not equal, the average readings can be used if the differences are minor.

8) Lower the heat sealer bar and remove the sample.

9) The calibration data is complete (total time should be less than 30 minutes).

Timing. NOTE: This should be done immediately following the calibration procedure to minimize changes in environmental conditions.

1) The same film thermistor should be positioned following the general procedures. The heat sealer timer unit is not used. The air valve assembly used in the calibration procedure is used with no changes necessary. The hot bar temperature remains at 175°F.

2) Using the storage features of the oscilloscope, trigger the pulse using the 0.5 second per cm sweep time on the scope.

3) Immediately raise the heat sealer bar.

4) The storage feature of the oscilloscope will store the data read-out through approximately 0.5 to 5.0 seconds which coincides with a typical range of heat sealing times.

5) Lower the sealer bar and remove the sample.

6) The scope voltage data should then be transcribed at 0.25 second intervals to be interpreted into temperatures from the plot of the calibration data.

7) The timed data is complete (total time should be less than one minute).

Analysis. This procedure satisfactorily accomplishes temperature measurement at the surface of thin plastic films. The calibration results for a typical thermistor are shown in Table 1 and plotted in Figure 2. The timing results from the oscilloscope picture of the timing read-out shown in Figure 3 are tabulated in Table 2. This data is then plotted in Figure 4 to show the temperature-time profile of the thermistor.

The temperatures in Table 2 were found by converting the timed scope voltages from Figure 3 to temperatures from the calibration curve in Figure 2. Calibration sensitivity appeared to be approximately 2 millivolts/degree in the final procedure.

The 31 millivolt indication in the timing read-out picture, Figure 3, before the bar was raised at the first vertical scale line should be noted. This 31 millivolt reading reflects the approximate 115 degree environmental temperature experienced by the thermistor before the heat sealer bar was raised. It was the temperature experienced by the thermistor when positioned as in Figure B, Appendix 2. The base line or t_b setting is shown on the first horizontal scale line of Figure 3.

The minor disturbance noted in Figure 3 after approximately 1.5 seconds is noise detected by the system when the heated bar temperature control thermostat cycled in attempting to maintain a constant hot bar temperature. It should be disregarded in interpreting the results of the timing procedure.

Note that the signal in Figure 3 appears approximately 1.5 millivolts wide. No further resolution of this signal was possible using the storage feature of the oscilloscope for read-out of the timing data due to the 60 cycle noise included in the signal. All data for interpretation from Figure 3 was taken from the center of this trace and no attempt was made to read the data to less than ½ millivolt because of this lack of resolution.

Some indication of the accuracy of the calibration results was obtained by totalling the differences between actual calibration readings from Table 1 and final calibration curve readings from Figure 2. The total was averaged and the results indicated that an accuracy of ± 1°F. can be expected during the final procedure calibration.

TABLE 1 - Experimental Calibration Data

Temperature (°F.)	Reading (mv) Cooling	Heating
175	51.0	51.0
170	49.5	49.0
165	48.0	48.0
160	47.0	47.0
155	45.0	45.0
150	43.0	43.0
145	42.0	42.0
140	40.5	40.0
135	38.0	38.5
130	37.0	37.0
125	35.0	35.0

NOTE: Initial Resistance - 19.5 ohms, 4.05 potentiometer reading

TABLE 2 - Experimental Timing Data

Time (seconds)	Reading (millivolts)	Temperature (°F.)
0.1	37.5	132.5
0.2	39.0	137.0
0.3	40.0	140.0
0.4	41.0	143.0
0.5	41.5	144.5
0.75	43.0	149.0
1.0	44.0	152.0
1.25	45.0	155.0
1.5	45.5	157.0
1.75	46.5	160.0
2.0	47.0	161.5
2.5	47.5	163.0
3.0	48.0	164.5
3.5	48.5	166.0
4.0	49.0	167.5

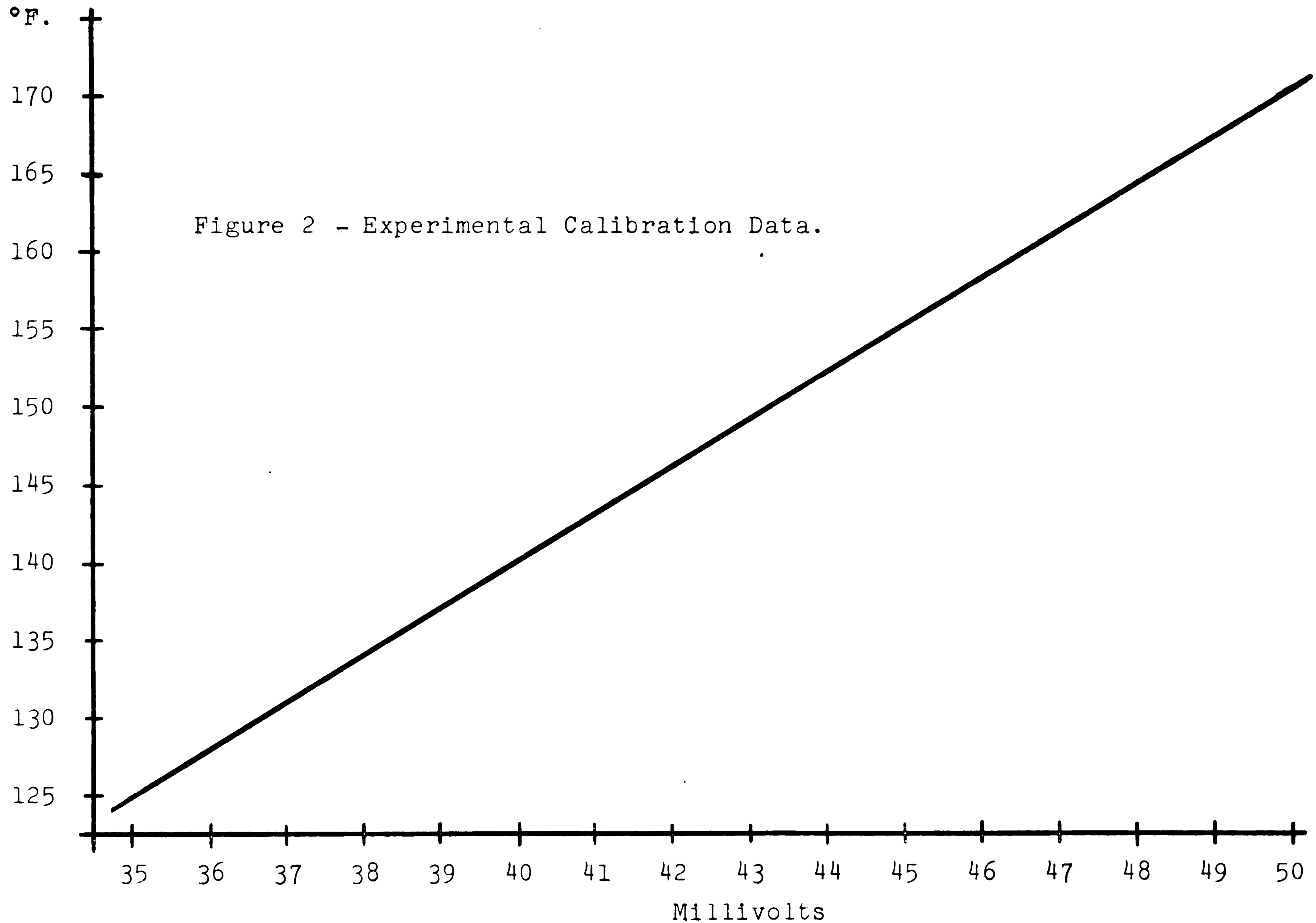


Figure 2 - Experimental Calibration Data.

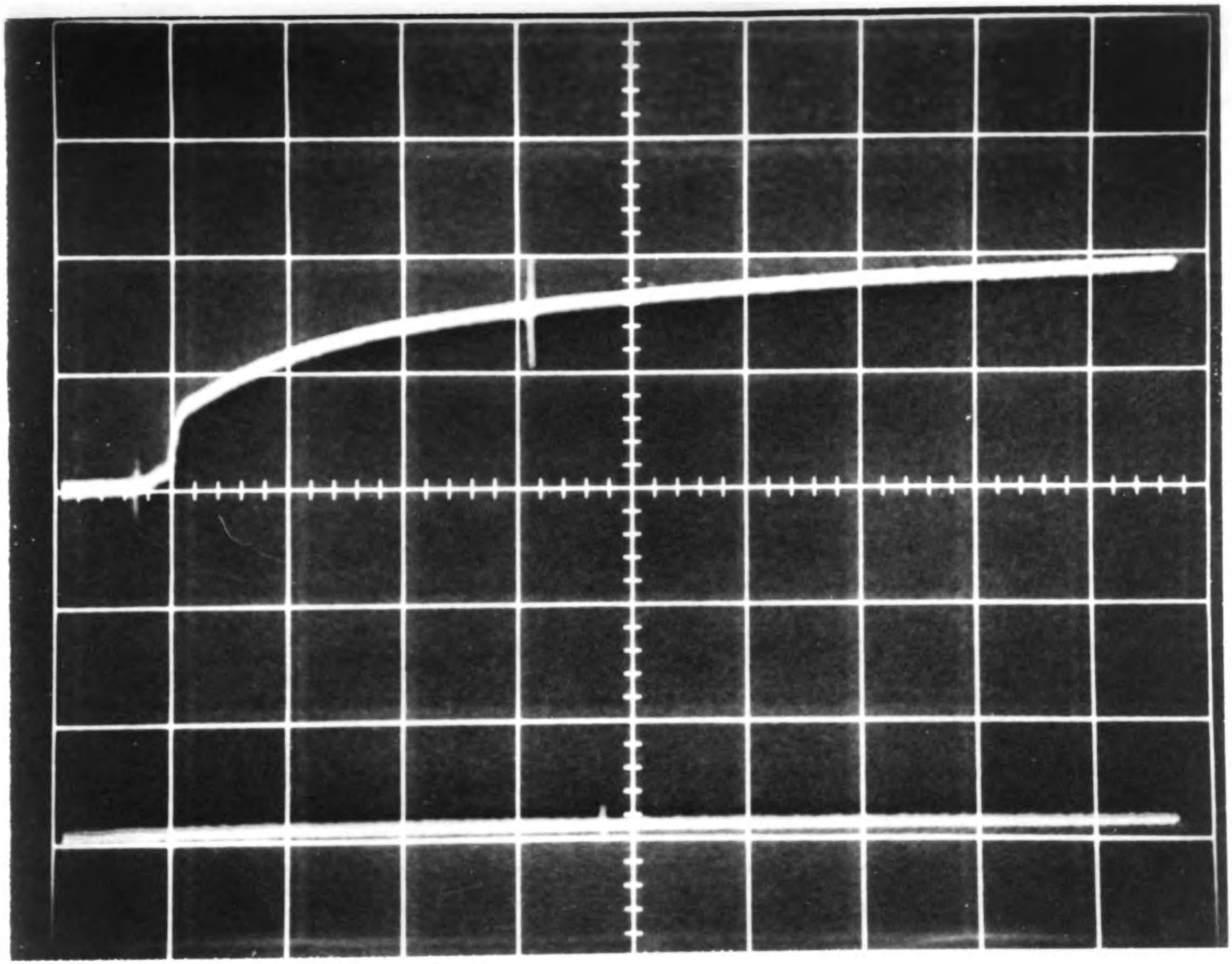


FIGURE 3 - Experimental Timing Data

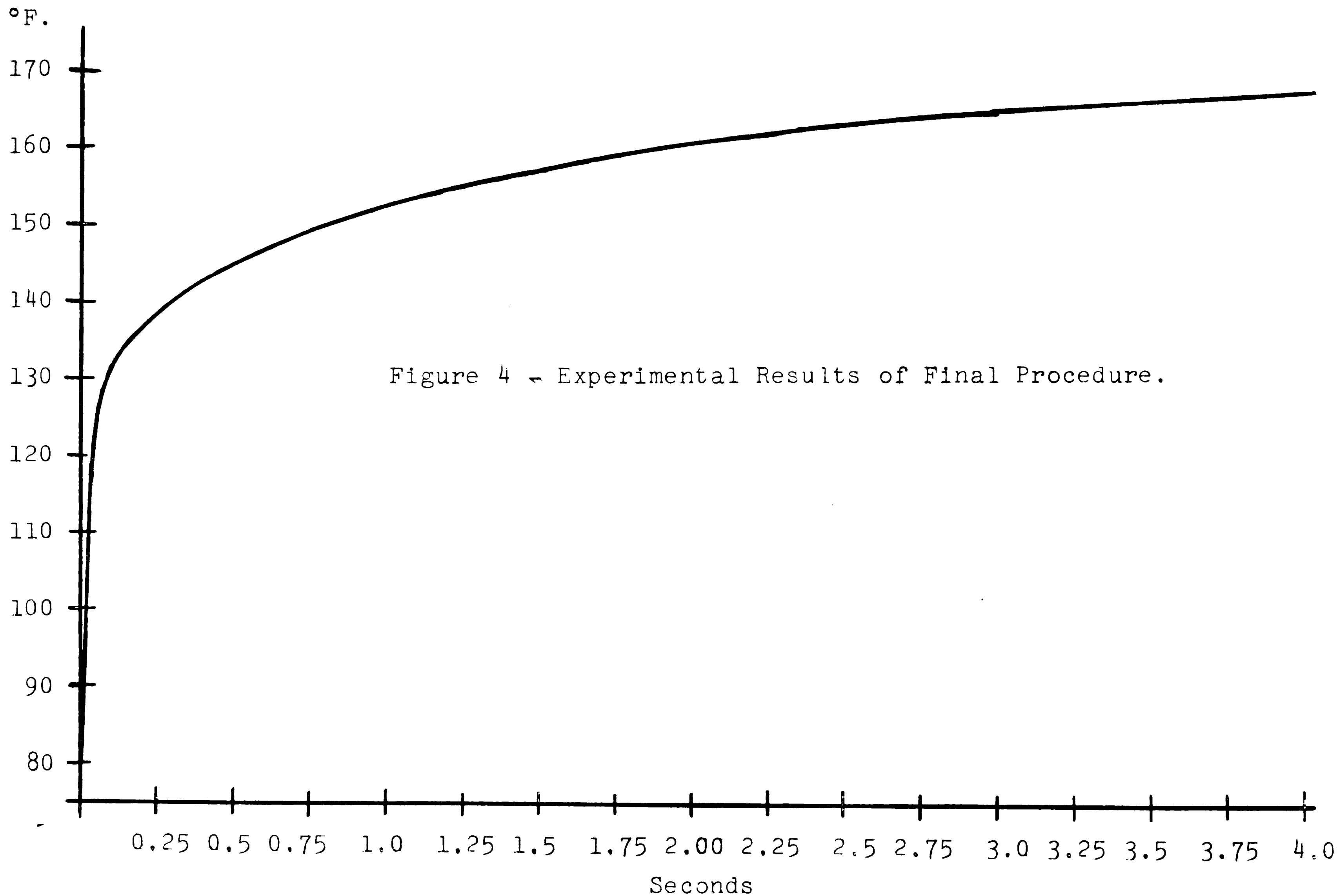


Figure 4 - Experimental Results of Final Procedure.

V. TEMPERATURE MEASUREMENT MODELS

The final procedure appears to fulfill the conditions of temperature measurement and reproducibility. In addition, two attempts were made to simulate the experimental system on the Michigan State University 3600 Control Data Corporation digital computer. FORTRAN 5/3600 is the language used in the simulations.

Computer models can provide a much more flexible method of experimentation than laboratory procedures. However, the model is useful in a practical sense only when it duplicates the behavior of the real world system. The testing or validation of a model can be done by making further observations and measurements of the system or by experimentation. It was this lack of experimental validity in Kavesh's article that initiated the development of the surface temperature measurement procedure for thin plastic films previously described (4). Using the results of the experimental procedure, an attempt was made to validate a computer model that would simulate the experimental system. This would meet the third of the conditions previously outlined and provide a valuable tool for future study of the heat transfer process in heat sealing.

Both programs are mathematical models of heat transfer systems which attempt to describe in two different ways with a set of mathematical expressions the experimental surface temperature measurement system. These mathematical expressions have been rewritten according to computer language rules. The mathematical equations pertinent to both models (with comparative data) are listed at the end of this section and will be referred to throughout the following discussion.

A complete program listing for both models is included in Appendix 4. The temperature range used for comparison is 80°F. to 175°F.

MODEL 1

This model was an adaptation of the program used by Kavesh (4). The theoretical data derived from its use prompted the experimental investigation reported previously.

Discussion. Assume a slab of infinite thickness comes into sudden contact with a hot surface at a temperature T_s. We want to know how far and how fast heat will penetrate this material. We can find the temperature (t) at any depth (x) and at any time (ϕ) by solving Equation 1.

It is possible to use this same equation going from a theoretical infinite thickness in a slab of film to a film of finite thickness (L), if the film is properly backed with insulation (6). The temperature-distance distribution for a short period after the heat has been applied will be nearly the same as for the infinite slab. This will occur if the same heat flow is removed from the remote face of the finite film thickness as would ordinarily flow through a plane in an infinite film at the same distance from the hot surface. The finite thickness of film must then be backed with a quantity of insulation that will remove this amount of heat flow.

The quantity of insulation required can be found by equating the heat flow at a distance x = L from the surface of an infinite body to the heat carried away through the insulation on a finite body of thickness (L). Heat flow at a distance x = L from the surface is given by Equation 2 (6).

Kavesh determined that by use of Equation 3, the number of inches of insulation required in a film of finite thickness could be found. This thickness of insulation should then duplicate the temperature profile of the infinite slab of film in films of finite thickness for short time periods (6).

Equation 4 (which was derived from equation 3, using the data generated by the computer program for heat in a slab of infinite thickness) was applied to determine the thickness of neoprene insulation required for the unheated platen in the experimental apparatus (4). The calculated thickness was less than the thicknesses commercially available so 1/16 inch was used. However, Kavesh recognized the fact that other factors such as the type film or the temperature differential might change so the factor of 0.213 used in Equation 4 is designed to approximate the maximum thickness of insulation that could possibly be needed to duplicate the infinite slab temperature profile. Kavesh calculated this factor based on Model 1 temperatures generated after 1 second.

Inputs. Model 1 inputs are the thermal conductivity, heat capacity and density of the film (polystyrene in this case). Equation 1 is an indefinite integral, so to be solved by the computer by numerical means, a numerical approximation using an error function was used just as Kavesh had done (2).

Print out. The computer print out of this model is in a tabulated form with temperatures for various times, film thicknesses and heated bar temperatures.

Analysis. The experimental surface temperature measurement system employed an excess of insulation over Equation 3 so the experimental temperature profile should be considerably lower than the infinite solid profile from Model 1. Kavesh's insulation thickness calculations were based on Model 1 film temperatures after one second (4). With increasing time, it is probable that a heat build-up would occur within a given insulation thickness so it would cease to perform like the infinite solid model. This could also explain the experimental variations from Model 1 data. In addition, no contact resistance is assumed in the infinite solid program calculations so this was another source of variation in comparative results. This factor should be programmed into the infinite solid model to make an equitable comparison of data possible.

MODEL 2

This model was adapted from a program written by Dr. James Beck of the Michigan State University Mechanical Engineering Department (11). Dr. Beck had used the program in many theoretical heat transfer situations but its use in the simulation of temperature profiles in thin-film systems had not been attempted previously.

Discussion. The model uses the Crank-Nicholson approximation for the solution of finite difference equations of heat conduction. This method uses the approximation constant, ETA, which equals 0.5. This approximation is an implicit method and requires that all the equations for the unknown temperatures at time (m + 1) be solved simultaneously using the known temperatures at time (m). The method has the advantage of being stable under most conditions (3).

The difference equations referred to above are developed using the "heat balance" approach where:

heat in - heat out = rate of increase of internal energy

Equations 5, 6 and 7 follow this general format.

Equation 5 is the equation for the temperature calculations at the general interior nodes (11). This equation solves for the temperature coefficients at node (n) in Figure 5, where the initial conditions at time (m - 1) are known. The temperature at point (n) at time (m + 1) is the average of the temperatures at either side of point (n) at the previous time.

Equation 6 is the special interface equation, in this case solving for the temperature coefficients at Node 2 in Figure 6 (11). The special interface node calculations include a contact resistance (h) at the interface. The equation is written in the same heat balance form but in this case the Crank-Nicholson approximation constant (ETA) could not be used for the "heat out" term in the balance equation but had to be replaced by $h(T_2^m - T_3^m)$. This was due to oscillations noted in initial model runs using ETA when the contact resistance (h) approached infinity (no air layer). The additional approximation constant, LAMBDA, appearing in this equation and equal to 0.75, is used for the interface boundary calculations.

To solve for the other interface Node 3 the equation subscripts can be reversed, switching subscripts: 2 and 3, 1 and 4, 3 and 2. The result is Equation 7, identical to Equation 6 except for the above subscript changes (11).

The choice of the number of space nodes and the size of the time steps is decided on the basis of experience with the type of problem at hand. Nodes can be reduced in a material that is of little interest or where no temperature-time gradient appears to exist. As the time steps and node spacing are simultaneously reduced, greater accuracy is obtained.

Equations 5, 6 and 7 compute the coefficients necessary to complete the finite-difference equations of heat conduction. This is accomplished in SUBROUTINE COETS and the finite-difference equations resulting are solved for the various temperature-time-node locations throughout the system in SUBROUTINE TRIDI (11).

Inputs. The input data required is the thermal conductivity, the product of heat capacity and density of each material, and the time steps and nodes desired in each material. The thickness of each material or region in the system is also necessary. The interface location must be specified and this acts as the location for the contact resistance specified and also as the temperature division point of the system.

Printout. The Model 2 printout consists of the complete temperature profile of the system for various times according to the nodes selected for all system materials. This requires a previous knowledge of node spacing so the temperature at the desired location in the system can be located.

Analysis. Using Model 2 data, attempts were made to determine a contact resistance that would provide close agreement with the experimental surface temperature data. The results can be seen from Table 3 and Figure 7. The data agrees very closely assuming a contact resistance of 700 BTU/hr. - ft.^{2} -°F./ft. equal to an air layer of approximately 0.2 mils calculated from Equation 8. The initial portion of the Model 2 temperature profile proved most sensitive to contact resistance changes during the comparison trials so more effort was made to make the Model 2 data and experimental data closely agree in this area. Contact resistance to the nearest 50 units was considered satisfactory for comparison and proof of agreement. The resultant 0.2 mil air layer value seemed "reasonable" for the experimental system. Any physical measurement of this contact resistance value in the experimental system was considered unnecessary if not impossible. Figure 7 then indicates that Model 2 can be used for future experimentation based upon its validation by the experimental results. It should be noted that the validation is restricted to the experimental time-temperature range, although there is no reason to believe it would not also be applicable to higher temperatures.

The minor differences between Model 2 and the experimental data in this figure could be for several reasons. One possible reason is that the average values of the thermal properties for the various materials in the experimental system used for Model 2 inputs may be in error. Furthermore, variations of these properties with increasing temperatures might have some effect. Probably the main reason is that the difference depends upon the value of contact resistance used in the Model 2 program. Further agreement might have been shown if values to less than the previously indicated 50 units had been checked but this was considered unnecessary for comparative purposes. The maximum difference of 3°F. is considered negligible for a practical heat sealing application and for future surface temperature measurement experimentation involving Model 2. However, the differences emphasize the necessity of accurately describing the practical system in the computer simulation to minimize possible errors when using Model 2. The experimental validation of this Model for use in thin-film surface temperature measurements is clearly evident in Figure 7 despite these differences.

Model 1 Equations

EQUATION 1

$$t_x\emptyset = T_s + (t_o - T_s)\ \frac{2}{\sqrt{\pi}} \int_0^{z = \frac{x}{2\sqrt{\alpha\emptyset}}} e^{-z^2}\,dz$$

where:

t_o is initial body temperature
T_s is hot surface temperature
α is thermal diffusivity of the film ($\alpha = K/C_p\rho$)
$\emptyset$ is time after contact
$t_x\emptyset$ is temperature at distance x, time $\emptyset$
K is thermal conductivity
C_p is heat capacity
ρ is density

EQUATION 2

$$\frac{Q}{A} = K(T_s - t_o)\ \frac{e^{-L^2/4\alpha\emptyset}}{\sqrt{\pi\alpha\emptyset}}$$

where:

$\frac{Q}{A}$ is heat flow per area per unit time

EQUATION 3

$$L_i = \frac{K\Delta T}{Q/A}$$

where:

L_i is insulation thickness in inches
K is the insulation thermal conductivity (BTU/hr-ft.^{2} - °F./ft.)
ΔT is the temperature change (°F.)

EQUATION 4

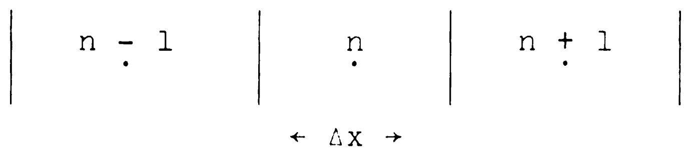
$$L_i = 0.213K$$

Model 2 Figures and Equations

NOTE: All equations follow the "heat balance" approach format where:

heat in - heat out = rate of increase in internal energy

FIGURE 5 - General Interior Nodes



EQUATION 5

$$\eta\left(\frac{K}{\Delta x}\right)\left(T_{n-1}^{m} - T_{n}^{m}\right) + \left(1-\eta\right)\frac{K}{\Delta x}\left(T_{n-1}^{m-1} - T_{n}^{m-1}\right)$$
$$-(\eta)\frac{K}{\Delta x}\left(T_{n}^{m} - T_{n+1}^{m}\right) - (1-\eta)\frac{K}{\Delta x}\left(T_{n}^{m-1} - T_{n+1}^{m-1}\right)$$
$$= \rho\,\frac{c\Delta x}{2}\,\frac{T_{n}^{m} - T_{n}^{m-1}}{\Delta t}$$

where:

Δt is time

m is time that temperature is evaluated

T is temperature

Δx is equal node spacing

n is node point

η is Crank-Nicholson approximation constant (ETA)

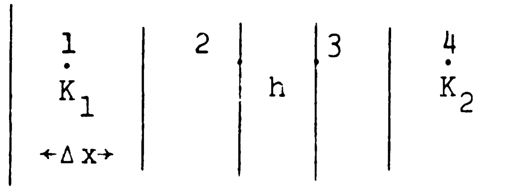
ρ is density of material

C is heat capacity of material

K is thermal conductivity of material

Model 2 Figures and Equations continued

FIGURE 6 - Special Interface Nodes



EQUATION 6

$$\eta \frac{K_1}{\Delta x_1} (T_1^m - T_2^m) + (1 - \eta) \frac{K_1}{\Delta x_1} (T_1^{m-1} - T_2^{m-1})$$

$$-h\ (T_2^m - T_3^m)$$

$$= \lambda_1 (\rho c) \frac{\Delta x_1}{2} \frac{T_2^m - T_2^{m-1}}{\Delta t} + (1-\lambda_1)\ (\rho c) \frac{\Delta x_1}{2} \frac{T_1^m - T_1^{m-1}}{\Delta t}$$

collecting terms:

$$T_1^m \left[2\eta K_1 - \lambda_2 \frac{C_1(\Delta x_1)^2}{\Delta t}\right] - T_2^m \left[2\eta K_1 + 2h\Delta x_1 + \lambda_1 \frac{C_1(\Delta x_1)^2}{\Delta t}\right]$$

$$+ T_3^m\ [2h\Delta x_1]$$

$$= T_1^{m-1} \left[2\beta K_1 - \lambda_2 \frac{C_1(\Delta x_1)^2}{\Delta t}\right] - T_2^{m-1} \left[2\beta K_1 = \lambda_1 \frac{C_1(\Delta x_1)^2}{\Delta t}\right]$$

where:

C is ρc

β is η - 1.0

λ_1 is boundary approximation constant

h is contact resistance

λ_2 is 1.0 - λ_1

K is thermal conductivity of the material

EQUATION 7

NOTE: Let $2 \longrightarrow 3$, $3 \longrightarrow 2$, $1 \longrightarrow 4$.

$$T_2^m[2h\Delta x_2] - T_3^m[2\eta K_2 + 2h\Delta x_2 + \frac{\lambda_1 C_2(\Delta x_1)^2}{\Delta t}]$$

$$+ T_4^m[2\eta K_2 - \frac{\lambda_2 C_2(\Delta x_2)^2}{\Delta t}]$$

$$= T_4^{m-1}[2\beta K_2 - \lambda_2 \frac{C_2(\Delta x_2)^2}{\Delta t}] - T_3^{m-1}[2\beta K_2 + \frac{\lambda_1 C_2(\Delta x_2)^2}{\Delta t}]$$

EQUATION 8

$$h = k/x$$

where: h is contact resistance air
k is thermal conductivity air
x is thickness of air layer

TABLE 3 - Comparative Data: Experimental, Model 1, Model 2

Time (seconds)	Temperature (°F.) Experimental	Model 1	Model 2
0.1	132.5	160.29	124.60
0.2	137.0	164.57	135.45
0.3	140.5		140.80
0.4	143.5		144.25
0.5	145.0	168.96 (0.6)	146.75
0.75	149.5		150.75
1.0	152.5	170.32	153.47
1.25	155.5		155.32
1.5	157.0	171.05 (1.4)	156.71
1.75	159.5	171.51 (1.8)	157.84
2.0	161.0		158.69
2.5	163.5	171.84 (2.2)	160.06
3.0	165.0		161.07
3.5	166.5		161.84
4.0	168.0		162.46

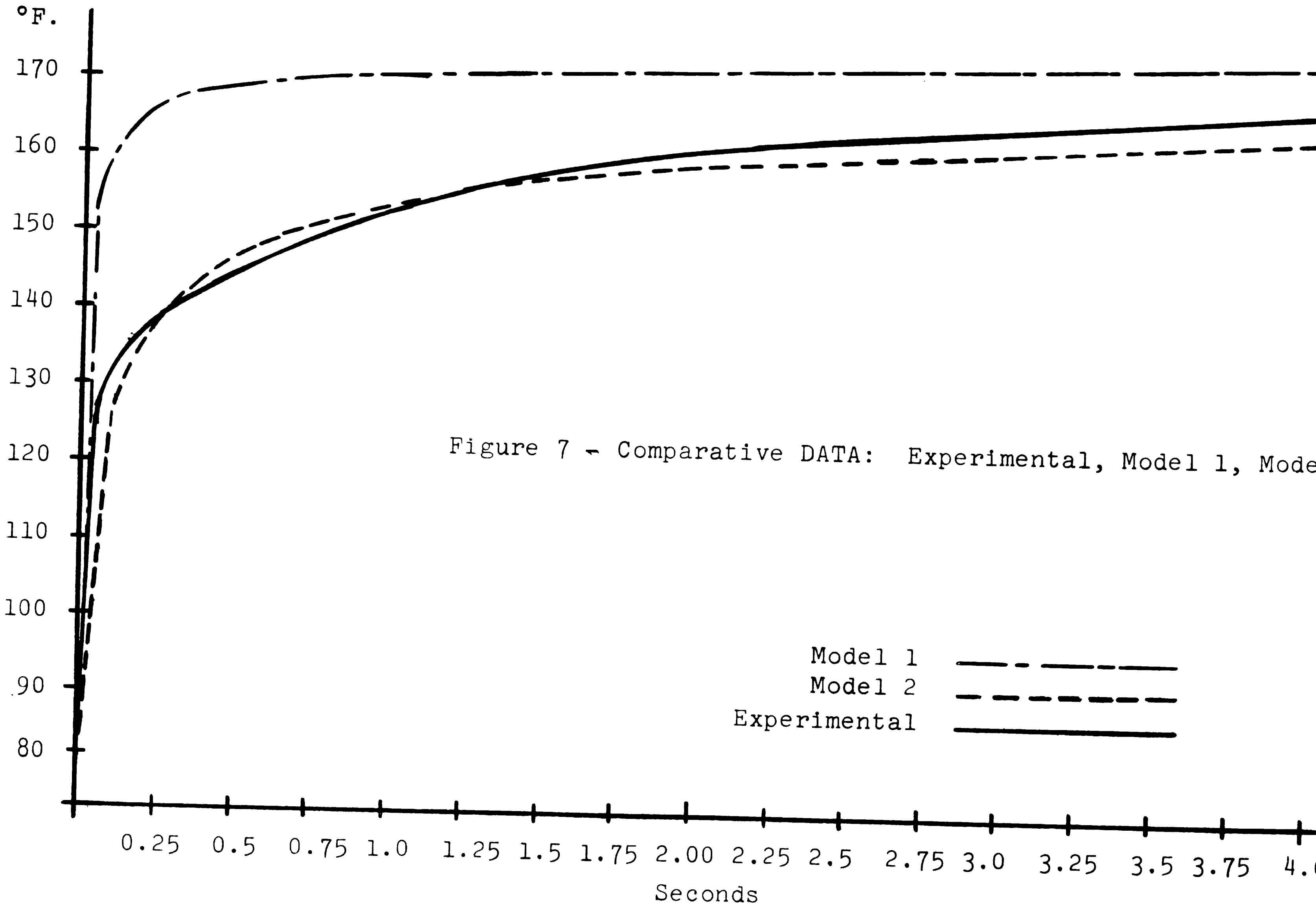


Figure 7 - Comparative DATA: Experimental, Model 1, Model 2.

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

The linear relationship between the electrical and thermal properties of the aluminum coated film thermistor as the environmental temperature is increased has been shown. The sensitivity of the experimental system is satisfactory to detect changes in this environmental temperature. It can be concluded that temperature measurement at the surface of thin plastic films can be accomplished experimentally by the use of the final procedure described in this study.

The experimental procedure can be easily duplicated using relatively unsophisticated experimental equipment. However, some limitations on the procedure are apparent when attempting to duplicate experimentally a particular set of heat sealing conditions. The film involved in the heat sealing process and the aluminum coated film used as the thermistor must be identical for accurate comparative data. Each film thermistor must be calibrated individually and any subsequent surface time-temperature measurements must be performed using this same temperature calibrated thermistor. If extensive data is sought, deterioration of the film thermistor midway through the experimentation is possible so that recalibration of a new thermistor might be necessary with a possible loss of valuable information.

These limitations to the experimental flexibility of the final temperature measurement procedure can be eliminated using a computer model of the surface temperature measurement system.

A comparison of Model 2 data and the experimental data showed a clear agreement that indicates Model 2 can be used to simulate any heat sealing process with none of the limitations of the experimental procedure. Satisfactory surface temperature data for thin plastic films can be obtained using Model 2 if care is exercised in describing the practical heat sealing conditions to be simulated by the computer. The experimental flexibility offered by Model 2 should provide the packaging engineer with an additional tool to investigate the heat sealing cycle.

Contact resistance in a practical or experimental system is an uncertain area in surface temperature measurement. The 0.2 mil air layer in the experimental system determined using Model 2 data could perhaps be considered representative in a similar system. However, it should be noted that definition of a contact resistance in a specific heat transfer system in terms of air layer thickness is extremely difficult.

Additional work using the final temperature measurement procedure should be accomplished on a plastic film of known thermal properties and a higher melting point. In this way, a wider temperature range to fully encompass the actual heat sealing range normally encountered can be investigated. This will extend the known applicability of the temperature measurement procedure for thin plastic films. Accordingly, Model 2 should be extended in its application. Model 1 may still have valid application in surface temperature measurement experimentation if reprograming is accomplished to make an equitable comparison of data possible for experimental validation.

Only through a complete understanding of the elements of the heat sealing cycle can satisfactory production control of package closure be assured. Hopefully, the results of this study will aid in developing this understanding.

LIST OF REFERENCES

1. "Bridge Techniques in Temperature Measurement," Application Bulletin #1, NOVA-NETICS corporation, 1963, p. 3.

2. Carslaw, H. S. and J. C. Jaeger, Conduction of Heat in Solids, Oxford University Press, 2nd Edition 1959, p. 100.

3. Forsythe, G. E. and W. R. Wasow, Finite-Difference Methods for Partial Differential Equations, John Wiley and Sons, New York, 1960, p. 103.

4. Kavesh, Sheldon, "Heat Sealers Need Insulation-Polypropylene Study Shows," PACKAGE Engineering, 9: 125-44, October, 1964.

5. Kavesh, Sheldon and Robert J. Ridgway, "Heat Sealing-The Film's Opinion vs. The Machine's Position," The Packet, Packaging Professional Edition, 3:10-15, Winter, 1965.

6. Kern, Donald Q., Process Heat Transfer, New York, McGraw-Hill Book Company, 1950, pp. 9, 11, 641-5.

7. McMillan, Claude and Richard F. Gonzalez, Systems Analysis-A Computer Approach to Decision Models, Homewood, Illinois, Richard D. Irwin, Inc., 1965, pp. 7-8.

8. Ninnemann, K. W., "An Improved Laboratory Heat Sealer," Modern Packaging, 31:171-5, November, 1957.

9. "Resistance Temperature Transducers," Application Bulletin #2, NOVA-NETICS Corporation, 1963, p. 2.

10. White, Harvey E., Modern College Physics, New Jersey, D. VanNostrand Company, Inc., Third Edition, 1956, p. 524.

11. Personal Conferences with Dr. James Beck, Mechanical Engineering Department, Michigan State University, East Lansing, Michigan.

APPENDIX 1 - Calculations

CALCULATION A - Bridge Circuit Thermistor Theoretical Self-Heating Effect

Data:

0.225 cal./gram @ 100°C	specific heat of aluminum on thermistor
3.55×10^{-4}	(grams)

Solution:

1. $0.225 \times (3.55 \times 10^{-4}) = 8.0 \times 10^{-5}$ calories

   (Necessary to Raise Thermistor 1°C)

2. $$H = \frac{RI^2t}{4.18} = \frac{20 \times I^2 \times 20}{4.18} = 8.0 \times 10^{-5}$$

   $\therefore$ I = 2.9 milliamps

   (Bridge Current to Raise the Thermistor Temperature 1°C in 20 seconds)

where:

H is calories
R is ohms electrical resistance
I is amperes of current
t is time in seconds

CALCULATION B - Thermal Diffusivity of Polystyrene

Solution:

$$\alpha = \frac{K}{C_p\rho} = \frac{0.068}{20.45}$$

$$= 3.26 \times 10^{-3} \text{ft.}^2/\text{hr.}$$

where:

α is thermal diffusivity of polystyrene

K is thermal conductivity of polystyrene

C_p is heat capacity of polystyrene

ρ is density of polystyrene

APPENDIX 2 - Figures

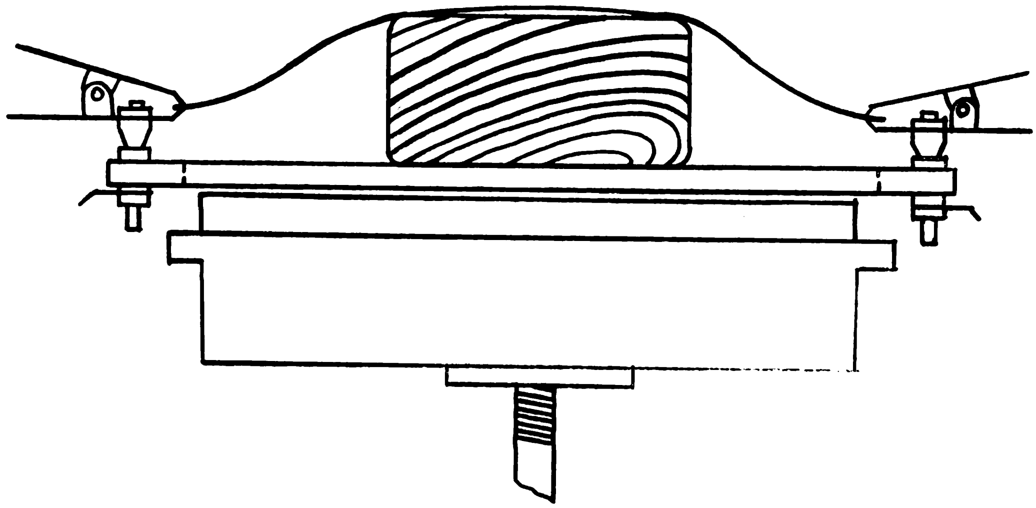


FIGURE A - Thermistor in Clamps with Wood Spacer in Place to Null Bridge (set t_b).

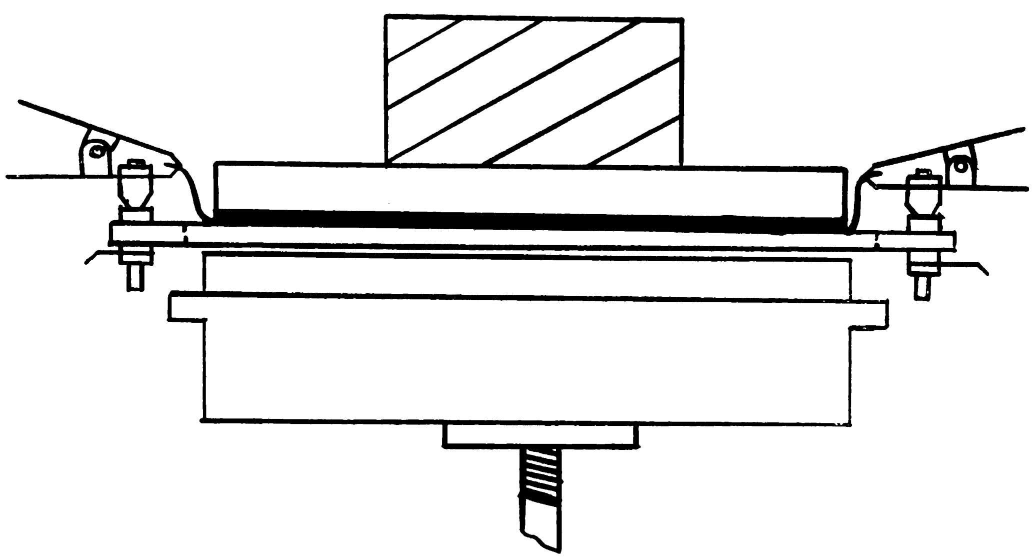
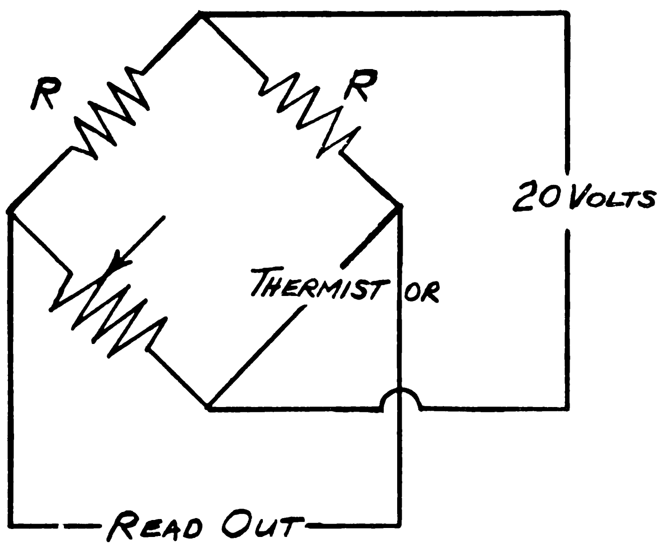


FIGURE B - Thermistor in Clamps with Unheated Platen in Place for Experimental Timing or Calibration (heated bar in retracted position).

FIGURE C - Bridge Circuit Design for Surface Temperature Measurement in Thin Plastic Films.



where:

R = 250 ohms (5 watts)

APPENDIX 3 - Tables

TABLE A - Thermistor Electrical Resistance Change with Increase in Temperature

Sample #	Initial Resistance (75°F.)	Final Resistance (200°F.)
1	23.5 ohms	25.0 ohms
2	14.2	14.9
3	14.6	15.4
4	14.0	14.8
5	18.3	19.2

TABLE B - Thermistor Calibration Results with Initial Resistance at Sample Extremes

	Reading (millivolts)	
Temperature (°F.)	Sample 1 - 22 ohms	Sample 2 - 14.0 ohms
170	79	64
165	76	60
160	73	58
155	70	56
150	67	55
145	64	53
140	61	48
135	59	44
130	57	41
125	53	38

TABLE C - Results of Added Weight During Calibration at 175°F.
(Sample removed and reclamped each time)

Sample #	Reading (millivolts) Normal (4 lb. 7 oz.)	6 lb. 5 oz.	8 lb. 5 oz.	18 lb. 5 oz.
1	45	45	48	48
2	41	40	41	41
3	49	46	43	43

NOTE: The minor variations in the readings were caused by the reclamping procedures.

TABLE D - Thermal Influence of the Aluminum Coating on the Normal Polystyrene Film Temperature Profile from Model 2 Data

Time (seconds)	Temperature (°F.) With Coating	Without Coating
1.0	153.48	153.48
1.5	156.70	156.71
2.0	158.69	158.69
2.5	160.05	160.06
3.0	161.07	161.07
3.5	161.84	161.85
4.0	162.46	162.46

APPENDIX 4 - Models

```
'JOB,440079,TEMP,3,AKERS,BRIAN,L,GROUP A
'FTN,L,X,*
      PROGRAM FILM
C MODEL 1 OF EXPERIMENTAL TEMPERATURE MEASUREMENT SYSTEM
C PROGRAM TO CALCULATE FILM SURFACE TEMP FOR NO CONTACT RESISTANCE, WELL
C INSULATED, UNHEATED PLATEN
C  POLYPROPYLENE PROGRAM HAS ALPHA = .0001573
C  POLYSTYRENE PROGRAM HAS ALPHA = TO .0001311
      DIMENSION X(10), THETA(11), T(10), TEMP(10)
      PRINT 300
  300 FORMAT (1H1*OTEMP = 80*5X*ALPHA = .0001311*//)
      PRINT 1
    1 FORMAT (/3HHOT,40X,27HFILM TEMP AT GIVEN DISTANCE,/,7HSURFACE,4X,7
     1HCONTACT,25X,41HFROM HOT SURFACE (COLD SURFACE INSULATED),/,4HTEMP
     2,7X,4HTIME,40X,6H(TEMP),/,3H(T),8X,7H(THETA),/,9HDEGREES F,3X,3HSE
     3C,6X,5H.0005,3X,5H.0010,3X,5H.0015,3X,5H.0020,3X,5H.0025,3X,5H.003
     40,3X,5H.0035,3X,5H.0040,3X,5H.0045,3X,5H.0050)
      READ 2, OTEMP
    2 FORMAT (1F10.0)
      READ 3, ALPHA
C   ALPHA = K/C TIMES RHO
    3 FORMAT (1F10.7)
      READ 4, (X(I), I=1,10)
    4 FORMAT (8F10.4/2F10.4)
      READ 5, (THETA(J), J=1,11)
    5 FORMAT (8F10.2/3F10.2)
      READ 6, (T(K), K=1,10)
    6 FORMAT (7F10.0/3F10.0)
      DO 205 K=1,10
      DO 204 J=1,11
      DO 25 I=1,10
C BEGIN PROGRAM CALCULATIONS
C CALCULATE UPPER LIMIT OF ERFZ
      Z=X(I)/(2.0*SQRTF(ALPHA*THETA(J)))
C CALCULATE ERFZ
   21 ZZZZ1=((((((.430638E-4*Z + .2765672E-3)*Z + .1520143E-3)*Z + .9270
     152721E-2)*Z + .422820123E-1)*Z + .705230784E-1)*Z + 1.0)**16
   23 ERFC = 1.0/ZZZZ1
   24 ERFZ = 1.0-ERFC
C CALCULATE SURFACE TEMP OF FILM
   25 TEMP(I) = T(K) - ERFZ*(T(K) - OTEMP)
      IF (J-1) 200,200,202
  200 PRINT 201, T(K),THETA(J),(TEMP(I), I=1,10)
  201 FORMAT (/1F9.0,1F10.2,10F8.2)
      GO TO 204
  202 PRINT 203, THETA(J),(TEMP(I), I=1,10)
  203 FORMAT (9X,1F10.2,10F8.2)
  204 CONTINUE
  205 CONTINUE


  206 END
          SCOPE
'LOAD
'RUN,3,2000,,M
        80
  .0001311
     .0005     .0010     .0015     .0020     .0025     .0030     .0035     .0040
     .0045     .0050
       .02       .04       .06       .08       .10       .20       .60      1.00
      1.40      1.80      2.20
        80       100       125       150       175       200       225
       250       275       300
```

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'JOB,440079,FILM,3,AKERS,BRIAN,L,GROUP A
'FTN,L,X,*
      PROGRAM FILM
C  MODEL 2 OF EXPERIMENTAL TEMPERATURE MEASUREMENT SYSTEM
C  THE PROGRAM IS SET UP WITH ONE MIL POLYSTYRENE TO MODEL EXPERIMENTAL
C  PROGRAM ACCURACY INCREASES AS THE TIME STEPS AND NODES ARE INCREASED
C  THE MAXIMUM NUMBER OF NODES AVAILABLE IN THE PROGRAM ARE 50/SYSTEM
C  IMPORTANT NOTE - T(K) OF DESIRED FILM INTERFACE IS T(15) AND T(16)
C CASE 3.1 AND 4.1 ARE THE MODEL CASES WITHOUT AND WITH THE COATING
C THE AIR LAYER IMPLIES SOME FINITE CONTACT RESISTANCE (H)
C  0.2 MIL AIR LAYER IN MODEL 2 WITH H = 700
C  THE TEMP RANGE IS 80 TO 175 DEGREES F
      DIMENSION A(50),B(50),C(50),D(50),       TL(10),MN(10),MAT(10),
     1PC(10),PK(10),DB(10),PB(10),SBB(10),SBB1(10),T(200)
      COMMON A,B,C,D,T,             DT,ETA,ALAM1,TT,GAM1,TL,MN,MAT,NMN,
     1INTF,ET,J,NN,PC,PK
  100 FORMAT (F9.4, 15F7.2)
   99 READ 107,NEL,(PC(I),I=1,NEL)
C NEL = NUMBER OF MATERIALS = 5
C  PC = HEAT CAPACITY TIMES DENSITY = RHO*C
 107  FORMAT (I5/8F8.2)
      READ 113,(PK(I),I=1,NEL)
C  PK = THERMAL CONDUCTIVITY OF THE MATERIAL = K
 113  FORMAT (8F8.3)
      READ                 110,NMN,(MAT(IA),IA=1,NMN)
C  NMN = NUMBER OF REGIONS = 6 WITH ALUMINUM HEATER IN 2 REGIONS
C NMN = SEVEN WITH THE ALUMINUM COATING
C  MAT(IA) = NUMBER DESIGNATING A PARTICULAR TYPE OF MATERIAL
  110 FORMAT (I5/(10I4))
      READ                 111,(TL(IB),IB=1,NMN)
C  TL(IB) = THICKNESS OF REGIONS
 111  FORMAT (8F10.8)
      READ                 112,(MN(IC),IC=1,NMN)
C  MN = THE NUMBER OF NODES IN EACH REGION
  112 FORMAT(10I4)
 103  READ 104,CASE,DT,YYY,INTF,BT
C  CASE = ARBITRARY CASE NUMBER TO DESIGNATE VARIABLES CHANGED EACH RUN
C  DT = TIME CHANGE OF EACH STEP IN PROGRAM
C  YYY = THE TIME LIMIT ON THE CHANGES IN THE TIME STEPS = 4.3 SECONDS
C  INTF = THE SYSTEM TEMPERATURE DIFFERENCE DIVISION POINT
C BT=ESTIMATED CONTACT RESISTANCE(H) AT FILM INTERFACE
 104  FORMAT (1F5.1, 2F15.10, 1I5, 1F15.2)
      IF(DT)6,6,5
    5 PRINT 106, CASE, INTF, BT
 106  FORMAT (1H1*CASE = *F5.1, 5X*INTF = * I5,5X*BT = *F15.2//)
C  TT IS TIME
C  T(K) IS THE TEMPERATURE AT NODE K
C     N=SUM OF MN,S
C ETA, ALAM1 AND GAM1 ARE PROGRAM CONSTANTS
```

```
      ETA = 0.5
      ALAM1 = 0.75
      GAM1 = 1.0
      JSIM=3
      DO 121 I2=1,4
  121 SBB1(I2)=0.0
      TT=0.0
C  THE UNITS OF K = BTU/HR-FT-F DEGREES
      NSMN1=0
      NSMN2=0
      DO 130 KK1=1,INTF
  130 NSMN1=MN(KK1)+NSMN1
      INTP=INTF+1
      DO 131 KK2=INTP,NMN
  131 NSMN2=MN(KK2)+NSMN2
      NN=NSMN1+NSMN2+2
      NS1P=NSMN1+1
      NS1PP=NSMN1+2
      DO 199 KK3=1,NS1P
      T(KK3) =  80.
      KKP=KK3+50
 199  T(KKP) =  80.
      DO 200 KK4=NS1PP,50
      KKP1=KK4+50
      T(KK4) = 175.
 200  T(KKP1) = 175.
C     BEGINNING OF PROGRAM CALCULATIONS
      IBLA = 0
  210 TT=TT+DT
      IBLA = IBLA+1
      J=1
C  COETS-GENERATES THE NECESSARY COEFFICIENTS
C TRIDI-CALCULATES THE TEMPERATURES USING THE FINITE DIFFERENCE METHOD
      CALL COETS
      CALL TRIDI
C  T(K) IS THE TEMPERATURE AT NODE K
C  TS = THE TIME IN SECONDS
 760  TS = TT*3600.
      IF (IBLA-10)901,761,761
 761  IBLA = 0
      PRINT 100, TS, (T(K), K=10,40)
  901 IF(TT-YYY)210,210,1000
C     YYY IS MAX TIME FOR CALCULATIONS
 1000 CONTINUE
 1001 GO TO 103
    6 CONTINUE
      END
      SUBROUTINE COETS
      DIMENSION A(50),B(50),C(50),D(50),T(200),        TL(10),MN(10),
```

```
      1MAT(10),DX(10),PK(10),PC(10)
       COMMON A,B,C,D,T,              DT,ETA,ALAM1,TT,GAM1,TL,MN,MAT,NMN,
      1INTF,BT,J,NN,PC,PK
  120  FORMAT (F10.3,11F9.5)
  100  FORMAT (8F15.5)
       BETA=ETA-1.0
       ALAM2=1.0-ALAM1
       GAM2=0.5*(1.0-GAM1)
C      THE FIRST ENTRY IN Q IS FOR TIME = 0.0
       DO 10 IT=1,NMN
       AMN=MN(IT)
   10  DX(IT)=TL(IT)/AMN
       I=1
       NMNN=1
       AJ=J-1
       AJJ=AJ*50.0+1.0
       JJ=AJJ
       K5=0
       KK=TT/DT
       M=MAT(1)
       AN=MN(1)
C      FIRST NODE
       BA=PC(M)*DX(1)*DX(1)/DT
       B1=ALAM1*BA
       C1=ALAM2*BA
       B(1)=-(2.0*ETA*PK(M)+B1)
       C(1)=2.0*ETA*PK(M)-C1
       D11=-(2.0*BETA*PK(M)+B1)
       D12=2.0*BETA*PK(M)-C1
       D(1)=D11*T(JJ)+D12*T(JJ+1)
C      END FIRST NODE
C      BEGIN INTERIOR NODES FOR A REGION
  200  AN=MN(I)
       M=MAT(I)
       BA=PC(M)*DX(I)*DX(I)/DT
       A1=GAM2*BA
       B1=GAM1*BA
       C1=GAM2*BA
       AA=ETA*PK(M)-A1
       BB=-(2.0*ETA*PK(M)+B1)
       CC=ETA*PK(M)-C1
       K1=NMNN+1+K5
       K2=NMNN+MN(I)-1+K5
       DO 2 K=K1,K2
       A(K)=AA
       B(K)=BB
    2  C(K)=CC
       DKA=BETA*PK(M)-A1
       DKB=-(2.0*BETA*PK(M)+B1)
```

```
      DO 3 KD=K1,K2
      KT=JJ+KD-1
    3 D(KD)=DKA*T(KT-1)+DKB*T(KT)+DKA*T(KT+1)
C     END INTERIOR NODES
      IF(I-INTF)400,450,300
  300 IF(I-NMN)400,500,500
C     BEGIN GENERAL INTERFACE NODE
  400 MM=MAT(I+1)
      PA=DX(I)/DT
      A1=GAM2*DX(I)*PC(M)*PA
      B1=GAM1*(DX(I)*PC(M)+DX(I+1)*PC(MM))*PA/2.0
      C1=GAM2*DX(I+1)*PC(MM)*PA
      FX=DX(I)/DX(I+1)
      K3=K2+1
      A(K3)=ETA*PK(M)-A1
      B(K3)=-(ETA*(PK(M)+FX*PK(MM))+B1)
      C(K3)=ETA*PK(MM)*FX-C1
      DIAA=BETA*PK(M)-A1
      DIBB=-(BETA*(PK(M)+FX*PK(MM))+B1)
      DICC=BETA*PK(MM)*FX-C1
      K4=JJ+K2
      D(K3)=DIAA*T(K4-1)+DIBB*T(K4)+DICC*T(K4+1)
C     END   GENERAL INTERFACE NODE
      GO TO 460
C     BEGIN INTERFACE NODE
  450 PA=DX(I)/DT
      A1=      DX(I)*PC(M)*PA*ALAM2
      B1=      DX(I)*PC(M)*PA*ALAM1
      K3=K2+1
      BJ = BT/PK(M)
      B2 = 2.0*BJ*DX(I)*PK(M)
      A(K3)=2.0*ETA*PK(M)-A1
      B(K3)=-(2.0*ETA*PK(M)+     B2+B1)
      C(K3)=B2
      DIAA=2.0*BETA*PK(M)-A1
      DIBB=-(2.0*BETA*PK(M)+          B1)
      DICC=0.0
      K4=JJ+K2
      D(K3)=DIAA*T(K4-1)+DIBB*T(K4)+DICC*T(K4+1)
C     END FIRST INTERFACE NODE
C     BEGIN SECOND INTERFACE NODE
      K3=K3+1
      L=I+1
      PA=DX(L)/DT
      MM=MAT(L)
      BJ = BT/PK(MM)
      B2 = 2.0*BJ*DX(L)*PK(MM)
      B1=      DX(L)*PC(MM)*PA*ALAM1
      C1=      DX(L)*PC(MM)*PA*ALAM2
```

```
      A(K3)=B2
      B(K3)=-(2.0*ETA*PK(MM)+     B2+B1)
      C(K3)=2.0*ETA*PK(MM)-C1
      DIAA=0.0
      DIBB=-(2.0*BETA*PK(MM)+          B1)
      DICC=2.0*BETA*PK(MM)-C1
      K4=JJ+<2+1
      D(K3)=DIAA*T(K4-1)+DIBB*T(K4)+DICC*T(K4+1)
      K5=1
  460 NMNN=NMNN+MN(I)
      I=I+1
      GO TO 200
C     LAST NODE,NN
  500 NN=NMNN+MN(I)+K5
      A1N=ALAM2*BA
      B1N=ALAM1*BA
      A(NN)=2.0*ETA*PK(M)-A1N
      B(NN)=-(2.0*ETA*PK(M) +B1N)
      C(NN)=0.0
      DNAA=2.0*BETA*PK(M)-A1N
      DNBB=-(2.0*BETA*PK(M)+B1N)
      NT=JJ+K2-1
      NNT=NT+1
      D(NN)=DNAA*T(NT)+DNBB*T(NNT)
      RETURN
      END
      SUBROUTINE TRIDI
      DIMENSION A(50),B(50),C(50),D(50),T(200),CC(50),DD(50),PC(10)
     1,TL(10),MN(10),MAT(10),PK(10)
      COMMON A,B,C,D,T,              DT,ETA,ALAM1,TT,GAM1,TL,MN,MAT,NMN,
     1INTF,BT,J,NN,PC,PK
C     THIS SUBROUTINE SOLVES A TRIDIAGONAL SET OF EQUATIONS
  100 FORMAT (8F10.6)
C     CC IS C*, DD IS D*
      CC(1)=C(1)/B(1)
      DD(1)=D(1)/B(1)
      DO 1 K=2,NN
      M=K-1
      CC(K)=C(K)/(B(K)-A(K)*CC(M))
    1 DD(K)=(D(K)-A(K)*DD(M))/(B(K)-A(K)*CC(M))
      AJ=J-1
      AJJ=AJ*50.0+1.0
      JJ=AJJ
      NB=JJ+NN-1
      T(NB)=DD(NN)
      DO 2 K<=2,NN
      KKK=NN-KK+1
      KKKK=NN-KK+1+JJ
      KKB=NN-KK+JJ
```

```
    2 T(KKB)=DD(KKK)-CC(KKK)*T(KKKK)
      RETURN
      END
          SCOPE
'LOAD
'RUN,3,3000,,M.
    5
   38.78     24.06     20.75     35.00     41.75
  117.00      0.17     0.068      0.14     121.0
    6
   1    2    3    4    5    5
    0.0425    0.00617 0.0000834 0.0000834     0.0310     0.0834
   2   12   12   12    5    2
  3.1      0.000000556          0.00120     3              700.
```