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EFFECT OF THERMOCOUPLE WIRE SIZE AND CONFIGURATION ON INTERNAL TEMPERATURE MEASUREMENTS IN A CHARRING ABLATOR

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EFFECT OF THERMOCOUPLE WIRE SIZE AND CONFIGURATION ON INTERNAL TEMPERATURE MEASUREMENTS IN A CHARRING ABLATOR

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SUMMARY

Results are presented from an experimental investigation to determine the effect of thermocouple wire size and configuration on internal temperature measurements in a charring ablator subjected to a severe heating environment. The responses of thermocouples of various wire sizes with the lead wires parallel to the direction of heat flow and the responses of thermocouples with some length of the lead wires perpendicular to the direction of heat flow are compared with the responses of a reference thermocouple. The results show that, if the lead wires are parallel to the direction of heat flow, considerable heat is conducted away from the thermocouple junction and thus large errors occur in the temperature measurement. Heat losses due to conduction along the lead wires can be minimized by using thermocouples with lead wires perpendicular to the direction of heat flow. However, large errors in temperature measurements may also result from the uncertainties in the location of the thermocouple junction. For a given configuration, thermocouples made from the smallest wire produce the best results.

INTRODUCTION

The evaluation of the performance of thermal protection systems subjected to a severe heating environment often depends upon the temperature histories at various points within the thermal protection material during exposure to the heating environment. In most applications internal temperatures are measured by the use of thermocouples embedded in the material. The purpose of a temperature measuring device is to measure the temperature which would exist at some known location if the device were not present. It is therefore necessary that a thermocouple produce a minimum disturbance in the material. Previous studies (e.g., refs. 1 and 2) have shown that significant errors in temperature measurements can result if considerable heat is conducted away from the point of measurement by the sensor itself. This so-called conduction error is of particular significance if the thermocouple lead wires are oriented parallel to the direction of heat flow and if there is a large difference between the thermal conductivity of the thermocouple material and the conductivity of the material in which the thermocouple is embedded. Also the possibility of differences in temperature measurements for thermocouples of various wire sizes should not be overlooked inasmuch as thermocouples made from wires of different sizes would be expected to cause different disturbances within the material and hence give different results.

This paper presents the results from an experimental investigation to determine the effect of thermocouple wire size and configuration on internal temperature measurements in a low-conductivity charring ablator subjected to a severe heating environment. Thermocouples made from lead wires of various sizes were used. For some thermocouples the lead wires were parallel to the direction of heat flow, and for others some length of the lead wires was perpendicular to the direction of heat flow. The responses of the thermocouples were determined for various heating rates.

Factors which may affect the absolute error in temperature measurements, such as the length of lead wire and good thermal contact between the thermocouple junction and ablation material, are considered to be the same for all thermocouples in the present investigation. Therefore, since only relative performances are considered, these factors should not affect the results.

For the physical quantities defined in this paper the International System of Units (SI) is used. Factors relating this system to the U.S. Customary System are given in reference 3.

TEST SPECIMENS

The ablation material used in this investigation is a phenolic nylon composite (50 percent nylon powder and 50 percent phenolic bonding material) with a nominal density of 1200 kg/m^3. The thermal conductivity of this material is about 0.35 $W/m\text{-}^{o}K$. The test specimens were machined from a large block of the phenolic nylon and were in the form of 7.6-centimeter-diameter flat-faced cylinders 3.1 centimeters thick. The instrumented portion of each specimen was a 2.5-centimeter-diameter plug cut from the center of the cylinder (fig. 1). A brass mounting ring was bonded to the back surface of each specimen for positioning on the test apparatus. Eight specimens were tested. Two specimens (1A and 2A) contained nine thermocouples each, and six specimens (1B, 2B, 3B, 4B, 5B, and 6B) contained seven thermocouples each.

INSTRUMENTATION

Thermocouples

All thermocouples were platinum—platinum 13-percent rhodium. Five wire sizes and three thermocouple configurations were used in this investigation. The sizes of thermocouple wire used were 24, 30, 36, 40, and 49 gage. (See table I for the relationship between gage number and wire diameter.) The three thermocouple configurations are referred to as R (reference), A, and B. (See fig. 2.) Specific thermocouples are designated by wire size and configuration. For example, a 24-A thermocouple refers to a thermocouple with 24-gage wires and configuration A. The three thermocouple configurations considered are described in this section.

Configuration R.- Each instrumented plug contained five 49-R thermocouples located at various depths within the material. These reference thermocouples were designed to produce a minimum disturbance in the area of the temperature measurement and to minimize the conduction of heat along the lead wires. The responses of these thermocouples are used as standards with which to compare the responses of all other thermocouples. A typical reference thermocouple is shown schematically in figure 2. The thermocouple junctions were formed by capacitance welding and the diameter of each junction bead was less than two wire diameters. For installation of these thermocouples, five grooves of appropriate sizes were machined in each instrumentation plug. The grooves extended along the side of the plug from the back surface to the required depths and were equally spaced around the circumference of the plug. At the end of each groove a radial hole 0.013 centimeter in diameter was drilled to a depth of 0.51 centimeter. The thermocouple junctions were positioned in the holes and potted into place with a phenolic cement. This particular cement was used since it is made from the same basic material as the ablation material and therefore should have the same ablation characteristics. The lead wires extended outward to the side of the plug and back through the grooves to the back surface of the plug. Each 49-R thermocouple was electrically insulated by placing the wires in double-bore quartz sheathing 76 micrometers in diameter. The sheathing extended from the back surface of the plug to within 51 micrometers of the thermocouple junction.

Platinum—platinum 13-percent rhodium step-up lead wires were used to make the transition from the 49-gage wires to larger copper-alloy duplex compensating lead wires. The lead wire junctions were located as close as possible to the back surface of the specimen and were adequately protected against movement by epoxy resin. The junctions were enclosed in a water-cooled sting so that they were all at the same constant temperature. The depth of each thermocouple in each plug is given in table II.

Configuration A.- In addition to five reference thermocouples, two specimens (1A and 2A) contained thermocouples of various wire sizes with the lead wires parallel to the direction of heat flow. For these thermocouples (referred to as configuration A thermocouples), holes were drilled to the required depths directly through the back surface of the plug. The diameter of each hole was no more than 51 micrometers greater than the diameter of the particular thermocouple assembly (wires plus insulation) placed in the hole. The thermocouples were positioned in the holes and potted into place with phenolic cement. The entire length of the lead wires in the ablation material lay parallel to the direction of heat flow. The 40-gage wires were placed separately, inside single-bore quartz sheathing 0.013 centimeter in diameter. All wires larger than 40 gage were coated with a ceramic cement to provide insulation. A typical configuration A thermocouple is shown schematically in figure 2. The wire sizes and the junction locations for the thermocouples in specimens 1A and 2A are given in table II.

The diameter of each junction bead of the 40-A thermocouples was less than 2 wire diameters. The diameter of each of the beads of the larger configuration A thermocouples was less than $1\frac{1}{2}$ wire diameters. The configuration A installation was used to determine the effect of wire size on the errors in temperature measurements caused by conduction of heat along the lead wires.

Configuration B.- The other six specimens (1B, 2B, 3B, 4B, 5B, and 6B) contained, in addition to the five reference thermocouples, thermocouples of various wire sizes with as much of the lead wire as possible lying perpendicular to the direction of heat flow (referred to as configuration B thermocouples). For each configuration B thermocouple a diametric hole was drilled through the instrumentation plug at the required depth. The diameter of each hole was no more than 51 micrometers greater than that of the particular thermocouple wire placed in the hole. Grooves were machined along the side of the plug from the back surface to each end of the diametric hole. Two single wires were butt-welded to form the thermocouple junction. The wires were positioned in the hole, with the junction located in the center of the plug, and were cemented in place such that 2.5 centimeters of lead wire lay in a plane perpendicular to the direction of heat flow. From the junction the lead wires extended radially outward in opposite directions and back through the grooves along the side of the plug. The insulation extended from the back surface of the specimen to the diametric hole in the plug. Only the bare thermocouple wire was placed in the hole. A configuration B thermocouple is illustrated in figure 2. The wire sizes and the locations of the junctions for the thermocouples in specimens 1B, 2B, 3B, 4B, 5B, and 6B are given in table II. Configuration B thermocouples were used to determine whether or not the conduction error could be eliminated by placing a significant portion of the lead wires perpendicular to the direction of the flow and to find if the size of the wire affected the thermocouple response. Configuration A and configuration B thermocouples are referred to as test thermocouples.

Data Recording Instrumentation

The outputs of all thermocouples were recorded directly on magnetic tape by the Langley central digital data recording facility. The data were reduced to time-temperature tabulations by means of a computer program and plotted as temperature-time histories by a computer-controlled plotting machine.

TEST APPARATUS AND PROCEDURES

All specimens were tested in the 2.5-megawatt arc jet at the Langley Research Center. For the present investigation, this facility produces a subsonic airstream at atmospheric pressure with a static temperature range from about 3100° K to 4200° K and enthalpy range from 4.6 MJ/kg to 8.3 MJ/kg. The facility is described in detail in reference 4. Figure 3 shows the arc jet with a specimen in the test position. The cold-wall heating rates to the surface of the specimens were measured by a 7.6-centimeter-diameter flat-faced inconel calorimeter 0.08 centimeter thick. The calorimeter is also shown in figure 3.

The investigation was performed by subjecting each specimen to a hot airstream produced by the 2.5-megawatt arc jet. The arc jet was placed into operation and was run for a few seconds to allow the stream conditions to stabilize. The calorimeter was inserted into the stream and the cold-wall heating rate was determined from the responses of thermocouples attached to the back surface of the calorimeter. The specimens were then positioned in the test stream by the water-cooled sting (fig. 3). Each specimen was tested until all thermocouples had responded.

The two specimens which contained the configuration A thermocouples were tested at a cold-wall heating rate of 1.03 MW/m^2. Specimens containing 24-B and 40-B thermocouples were tested at cold-wall heating rates of 0.75, 1.27, and 1.36 MW/m^2, and those containing 30-B and 36-B thermocouples were tested at cold-wall heating rates of 0.76, 1.29, and 1.66 MW/m^2.

DATA ANALYSIS

Data from the reference thermocouples were used to obtain the movement of various isothermal planes through the material. That is, plots were made of depth from the initial front surface as a function of the time at which a given temperature was reached. These plots were made for eight different temperatures ranging from 395° K to 1370° K. The data indicated that, over the time span considered, straight lines could be fitted very well to the data points. Straight lines were then fitted by the method of least squares. A typical plot for a temperature of 810° K is presented in figure 4. The reference data points as well as the least-squares fit to the data are shown in this figure. From the equations of the least-squares curves, the time at which the test thermocouples should indicate any particular temperature could be calculated. In this manner, temperature histories at the location of each test thermocouple could be predicted from reference thermocouple data. These predicted temperatures could then be compared with the temperatures actually indicated by the test thermocouples.

The major problem associated with the procedure described is the uncertainty in the location of the point at which the temperature is being measured. This uncertainty arises from two major sources. First, the positions of all thermocouples were determined from measurements made on X-ray photographs of the instrumented plugs and are accurate only within certain limits (± 0.013 cm). Second, the location of the effective junction within the thermocouple wire itself is uncertain. The effective junction is defined as that point within the material at which the material temperature corresponds to the measured electromotive force output of the thermocouple. It can be seen from figure 5 that, even for a wire as small as 36 gage, the temperature difference across a distance equal to one wire diameter may be as much as 200° K. Thus significant errors in temperature measurements are possible if the effective thermocouple junction is assumed to be at one location when it may actually be at some other location (for example, in the center of the wire when it is actually at the front surface of the wire).

For configuration A thermocouples a junction bead, instead of a single wire, must be considered. The diameter of this bead may be as much as twice that of a single wire. Therefore, a configuration A thermocouple may allow for even more error in determining the location of the effective junction than does a configuration B thermocouple with the same wire size.

Because of the uncertainty in the location of the thermocouple junctions, the predicted temperature histories at the locations of the test thermocouples, as determined from the reference thermocouple data, are shown as bands rather than as single curves (e.g., see fig. 6). These bands indicate the magnitude of the errors in the temperature measurements which can result from the inability to determine the exact location of the effective thermocouple junction. In the specimens containing configuration A thermocouples, there was more than one thermocouple at a given depth in the material and, for clearness of presentation, the band is shown only for the largest thermocouple at a given depth. Bars within or at the top of these bands indicate the size of the bands for the smaller thermocouples.

In order to obtain the boundaries of the temperature bands, the location of the center of each test thermocouple junction was determined from the X-ray photographs of the instrumented plugs. Temperature histories were then determined from reference thermocouple data at points within the material, the locations of which were given by the expression $x = x_0 \pm (r + \delta)$ where x is the point at which the temperature history is determined, x_0 is the measured location of the center of the thermocouple wire, r is the radius of the test thermocouple wire, and δ is the tolerance within which the location of the center of the wire was determined (±0.013 cm). The temperature histories at these points are the boundaries of the bands, and the temperatures indicated by the test thermocouples are compared with these bands.

The particular method of data analysis used required that the location of the reference thermocouple junctions be known exactly. There is, of course, some uncertainty in the locations of these junctions. However, the uncertainty in the location for the reference thermocouple is much less than that for any of the test thermocouples, since the wire is much smaller. Therefore, when calculating each least-squares fit to the reference thermocouple data, the measured locations of the centers of the thermocouple beads were assumed to be the correct junction locations.

RESULTS AND DISCUSSION

Table II gives a complete summary of the thermocouple configurations and wire sizes used in this investigation as well as the location of each thermocouple junction within the material. The cold-wall heating rates are also given in this table.

Configuration A Thermocouples

The results for specimens containing configuration A thermocouples are given in figures 6 to 8. Figure 6 shows the results for specimen 1A. The shaded areas are the temperature bands obtained from the reference-thermocouple data, as discussed previously. The solid curves are the temperatures actually indicated by the test thermocouples. The results from only three test thermocouples (24-A, 30-A, and 40-A) are given in figure 6 since in this particular instance no data were received from the 36-A thermocouple.

It can readily be seen from figure 6 that the time required for a particular test thermocouple to reach any given temperature is significantly greater than that predicted from the reference thermocouple data, even when the possible errors due to the uncertainties in the location of the test thermocouple junctions are considered. As would be expected, the responses of thermocouples made from the larger wires deviate more from the predicted response than do those of thermocouples made from the smaller wires. At a temperature of 1200° K the 24-A, 30-A, and 40-A thermocouple responses lag the predicted responses (when measured from the center of the band) by about 20, 16, and 7 seconds, respectively. This lagging of the responses indicates that a considerable amount of heat is being conducted away from the junction by the lead wires.

The temperatures shown in figure 6 do not go beyond about 1250° K. The investigation showed that, even though 1250° K is well below the limit of the capabilities of platinum thermocouples, several of the thermocouples responded somewhat erratically at temperatures higher than 1250° K and little confidence could be placed in the readings. The behavior of the thermocouples at high temperatures is discussed subsequently.

Figure 7 shows the results for specimen 2A. The 40-A thermocouple failed to respond and no data were received from it. In this specimen all test thermocouples were located at the same depth within the material. It can again be seen that all test thermocouple responses lag the predicted responses considerably. Also, the larger the thermocouple, the larger the difference between the test thermocouple data and reference thermocouple data. For example, at 70 seconds the 24-A thermocouple indicated a temperature about 440° K too low and the 30-A and 36-A thermocouples indicated temperatures about 390° K and 380° K too low, respectively (again measurements were made from the center of the band). These temperature differences get larger as the time and temperature increase. Errors of as much as 800° K were obtained from the 24-A thermocouples and errors as large as 600° K from the 36-A thermocouples.

Although the data from the smaller thermocouples are closer to the reference data, the reference curves could not be expected to be matched exactly even with data from a very small configuration A thermocouple. The data indicate that large errors result even when a 40-A thermocouple is used. The insulation has a thermal conductivity which is much greater than that of the ablation material and hence heat is conducted away from the junction not only by the lead wires but also by the insulation. Also, after a certain point is reached, using smaller thermocouple wire would probably not reduce the size of the total assembly (wire plus insulation) significantly. Therefore, there is most likely a limit to how nearly the reference data can be approached by using a thermocouple with lead wires parallel to the direction of heat flow. Configuration A thermocouples appear to be undesirable for measuring temperatures within charring ablators or in any material which has a very low thermal conductivity and in which large temperature gradients exist.

Figure 8 shows the effect of heat conduction along thermocouple lead wires in specimen 2A after testing and sectioning. The thermocouples in view are 24-A and 30-A. The very evident thermal degradation of the ablation material along the lead wires indicates that a large amount of heat was conducted along the lead wires of both thermocouples. The degradation of the material along the length of the wires indicates that the wires conducted heat away from the area of the junction. Thus, temperatures at the junction are significantly lower than the temperatures which would exist at that point if the thermocouple were not present. At points close to the lead wires, at some distance behind the thermocouple junction, the temperature is obviously higher than that at corresponding depths some distance away from the lead wires. However, the temperatures measured at the junction are always too low. Without question, the situation illustrated in figure 8 would lead to serious errors in temperature measurements.

Configuration B Thermocouples

Conduction error can be minimized by using thermocouples with lead wires perpendicular to the direction of heat flow. Figure 9 shows the results for specimens containing 24-B and 40-B thermocouples. Specimen 1B was tested at a cold-wall heating rate of 0.75 MW/m^2, and the results are given in figure 9(a). The solid lines are the actual responses of the test thermocouples. The shaded areas are the temperature bands obtained from reference thermocouple data, as discussed previously. These bands indicate the possible errors in temperature measurements which can result from the uncertainty in the exact location of the effective thermocouple junctions. In figure 9(a), both the 24-B and 40-B thermocouple responses are within the bands at all times. However, as the temperature increases, both test thermocouple curves appear to move slowly to the right with respect to the reference bands. This shifting of the curves indicates that the thermocouples may be responding slightly more slowly than the reference thermocouples. Also the two test thermocouple curves have essentially the same shape; thus, at this low heating rate (0.75 MW/m^2) there is evidently little difference between the response of a 24-B thermocouple and that of a 40-B thermocouple. However, the 40-B thermocouple data are expected to be more reliable since the location of the effective junction can be determined more accurately.

Figure 9(b) shows the results for specimen 2B at a cold-wall heating rate of 1.27 MW/m^2. The response of the 40-B thermocouple is similar to that of the 40-B thermocouple in specimen 1B at a cold-wall heating rate of 0.75 MW/m^2 (fig. 9(a)). At temperatures below 500° K the curve lies along the upper limit of the reference band. For temperatures above 500° K the curve shifts to the right with respect to the band; thus, the 40-B thermocouple must be indicating temperatures slightly lower than would be expected. The 24-B thermocouple curve lies along the lower limit of the reference band at temperatures below 700° K but falls completely outside the band at higher temperatures. However, the difference in response of the 24-B and 40-B thermocouples is not as great as might be expected from briefly examining figure 9(b). In fact, there is little difference between the responses of these two thermocouples.

It should be noted that the relative position of a test thermocouple curve with respect to the corresponding reference band is probably an indication of the location of the effective junction of the thermocouple. For example, as previously mentioned, in figure 9(b) the 24-B thermocouple curve lies along the lower limit of the band for temperatures below about 700° K, and thus the effective junction is probably located near the back side of the wire (i.e., the side of the wire farthest from the heated surface of the specimen).

The deviation of the curve from the reference band at higher temperatures indicates that the 24-B thermocouple responded more slowly than the reference thermocouples. The results for the 40-B thermocouple are similar except that the 40-B curve lies along the upper limit of the reference band at low temperatures, the indication being that the effective junction is most likely at the front side of the wire. If the 40-B curve were shifted to the lower limit of the band (corresponding to a shift in effective junction from front to back of the wires), it would also lie outside the band at high temperatures.

The results for specimen 3B at a cold-wall heating rate of 1.36 MW/m^2 are shown in figure 9(c). The responses of both test thermocouples deviate from the reference data more than for the two lower heating rates. Also, the 24-B thermocouple responded somewhat more slowly than the 40-B thermocouple. This trend would be expected since, at the higher heating rates, the temperature gradients through the material are greater than at the lower heating rates and the larger wires create greater disturbances within the material.

Since some length of lead wire lies along an isotherm for each configuration B thermocouple, it is unlikely that the differences in the responses of these thermocouples and the reference thermocouples are caused by the conduction of heat along the lead wires. However, the thermocouple wires have large heat capacities compared with the ablation material and may act as heat sinks by absorbing a significant amount of heat. Therefore the test thermocouples would tend to respond more slowly than predicted from the reference thermocouple data.

Figure 10 shows the results for specimens containing 30-B and 36-B test thermocouples. The three heating rates used were 0.76, 1.29, and 1.66 MW/m^2. The results for the 30-B and 36-B thermocouples were similar. At the lowest heating rate (fig. 10(a)) both thermocouples responded very nearly as would be expected. At the higher heating rates (figs. 10(b) and 10(c)), however, both thermocouples appeared to respond more slowly than the reference thermocouples at the higher temperatures (above about 800° K).

As indicated in the preceding discussion, the junction locations must be determined very accurately if reliable temperature measurements are to be made. Thus, very small thermocouples are desirable even for installation perpendicular to the direction of heat flow.

High-Temperature Data

The temperature data presented in figures 6, 7, 9, and 10 do not go beyond 1250° K. As mentioned previously, most thermocouples responded somewhat erratically at temperatures higher than 1250° K and little confidence could be placed in the temperature readings. Figure 11 shows the temperature-time histories for all thermocouples in specimen 2B as plotted by the computer-controlled plotting machine. It can be seen that temperature readings above the range from 1200° K to 1350° K (with the exception of those from the 24-B thermocouple) are most likely not reliable. A sudden drop in temperature in the range from 1200° K to 1350° K was indicated by all reference thermocouples as well as by the 40-B thermocouple. Only the 24-B thermocouple continued to behave normally at higher temperatures. This type of thermocouple behavior was typical for all specimens. It should be noted that only the 24-gage thermocouples functioned normally at temperatures above 1300° K in all specimens. All other thermocouples showed erratic behavior above this temperature in at least one specimen. Also, the configuration B thermocouples showed a greater tendency toward erratic behavior than did the configuration A thermocouples, and the reference thermocouples showed erratic behavior in almost every instance.

The fact that all the thermocouples which experienced some unusual behavior did so at approximately the same temperature indicates that some unexpected phenomena may occur at that particular temperature. However, as far as can be determined, 1300° K has no particular significance regarding the thermocouples themselves or the insulation. The melting point of both platinum and quartz is approximately 2000° K. Therefore, the thermocouples used should be capable of measuring temperatures well above 1300° K. Also, 1300° K is above the thermal degradation temperature of the ablation material and the thermocouple junction should be some distance into the char when this temperature is recorded. Thus any connection between the break in the thermocouple responses and the process of pyrolysis is unlikely.

The unusual thermocouple behavior is believed to be caused by the breaking of the thermocouple lead wires due to the thermal expansion of the ablative material. Since the charred material is electrically conducting at the temperature at which the break occurs, the thermocouple could "remake" through the char and continue to give a continuous response. Several factors tend to support this hypothesis. As mentioned previously, the configuration A thermocouples did not show as much tendency toward erratic behavior as the configuration B thermocouples. The configuration B and configuration R thermocouples have one characteristic in common (not present in configuration A thermocouples) which may make them vulnerable to breaking – that is, a 90° bend in the lead wires at the side of the instrumented plug. Expansion of the test material in the direction of heat flow could cause the wires to break and the most likely point for this break to occur is at the bend.

The experimental data are consistent with the theory that the lead wires are breaking near the bend with a resulting shift of the thermocouple junction to the side of the plug. Examination of figure 11 reveals that the slopes of the temperature curves after the break in response are somewhat less than before the break. This difference in slopes would seem to indicate that after the break the configuration R and configuration B thermocouples responded as if they were configuration A thermocouples. Therefore heat was conducted away from the area of the junction (now located at the side of the plug) and the temperatures measured are lower than those that would have been measured if the break had not occurred.

X-ray photographs were made of specimen 2B after testing. These X-rays showed that some of the thermocouple wires had indeed broken near the bend. It was not possible to tell whether the wires had broken in all the thermocouples which showed erratic behavior. It was apparent, however, that the 24-B thermocouple had not broken. Although the time or the temperature at which the breaks occurred could not be determined from the X-rays, it is reasonable to conclude that the erratic behavior of the thermocouples at about 1300° K was caused by the breaking of the wires. The very small thermocouple wires (e.g., 40 gage and 49 gage) are especially susceptible to breaking, particularly if there is considerable difference between the thermal expansion characteristics of the thermocouple material and the specimen material.

CONCLUDING REMARKS

Results are presented from an experimental investigation to determine the effect of thermocouple wire size and configuration on internal temperature measurements in a charring ablator. Thermocouples of four different wire sizes with lead wires parallel to the direction of heat flow (referred to as configuration A thermocouples) and with wires perpendicular to the direction of heat flow (referred to as configuration B thermocouples) were investigated at various heating rates. The responses of these thermocouples were compared with the responses of a reference thermocouple.

The results show that errors in temperature measurements of several hundred degrees can result if the thermocouple lead wires are oriented parallel to the direction of heat flow. This type of installation allows a significant amount of heat to be conducted along the lead wires away from the junction and thus the thermocouple indicates temperatures which are considerably lower than would exist at the location of the junction if the thermocouple were not present. Errors of as much as 800° K were obtained from configuration A thermocouples made from 24-gage wire (referred to as 24-A thermocouples). The conduction error can be reduced to some extent by using very small thermocouples. However, large errors (as much as 600° K) were obtained with 36-A thermocouples. The data also indicate that large errors result even when using a 40-A thermocouple. Therefore it would appear that a configuration A thermocouple is undesirable for measuring temperatures within charring ablators or in any material which has a very low thermal conductivity and in which large temperature gradients exist.

The conduction errors can be minimized by using thermocouples with lead wires perpendicular to the direction of heat flow. However, large errors due to the uncertainties in the locations of the thermocouple junctions are possible. Therefore the locations of the thermocouple junctions must be determined very accurately if reliable temperature measurements are to be made. For this reason very small thermocouples are desirable even for installation perpendicular to the direction of heat flow.

The results also indicate that at low heating rates (about 0.75 MW/m^2) the response of a thermocouple does not depend to a great extent upon the size of the thermocouple wire if the lead wires are oriented perpendicular to the direction of heat flow. At the higher heating rates, the thermocouples made from the larger wires respond more slowly than do those made from the smaller wires. However, thermocouples made from very small wires (e.g., 49 and 40 gage) may be subject to breaking, especially if there is considerable difference between the thermal expansion characteristics of the thermocouple material and the specimen material.

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TABLE I.- THERMOCOUPLE WIRE SIZES

Wire gage number	Wire diameter, cm
24	0.051
30	.025
36	.013
40	.008
49	.003

TABLE II.- SPECIMENS AND TEST CONDITIONS

Specimen number	Cold-wall heating rate, MW/m^2	Thermocouple wire size and configuration	Thermocouple junction location (distance from initial front surface), cm
1A	1.03	24-A	1.16
		30-A	.75
		36-A	.94
		40-A	1.16
		49-R	.54
		49-R	.63
		49-R	.79
		49-R	.92
		49-R	1.07
2A	1.03	24-A	0.76
		30-A	.76
		36-A	.76
		40-A	.83
		49-R	.56
		49-R	.64
		49-R	.79
		49-R	.89
		49-R	.99
1B	0.75	24-B	0.70
		40-B	.98
		49-R	.49
		49-R	.65
		49-R	.76
		49-R	.92
		49-R	1.04
2B	1.27	24-B	0.66
		40-B	.92
		49-R	.53
		49-R	.65
		49-R	.77
		49-R	.89
		49-R	1.00

TABLE II.- SPECIMENS AND TEST CONDITIONS – Concluded

Specimen number	Cold-wall heating rate, MW/m^2	Thermocouple wire size and configuration	Thermocouple junction location (distance from initial front surface), cm
3B	1.36	24-B	0.69
		40-B	.85
		49-R	.50
		49-R	.63
		49-R	.74
		49-R	.88
		49-R	1.01
4B	0.76	30-B	0.89
		36-B	.65
		49-R	.50
		49-R	.66
		49-R	.77
		49-R	.91
		49-R	1.05
5B	1.29	30-B	0.89
		36-B	.63
		49-R	.53
		49-R	.67
		49-R	.76
		49-R	.89
		49-R	1.02
6B	1.66	30-B	0.86
		36-B	.61
		49-R	.50
		49-R	.66
		49-R	.78
		49-R	.90
		49-R	1.03

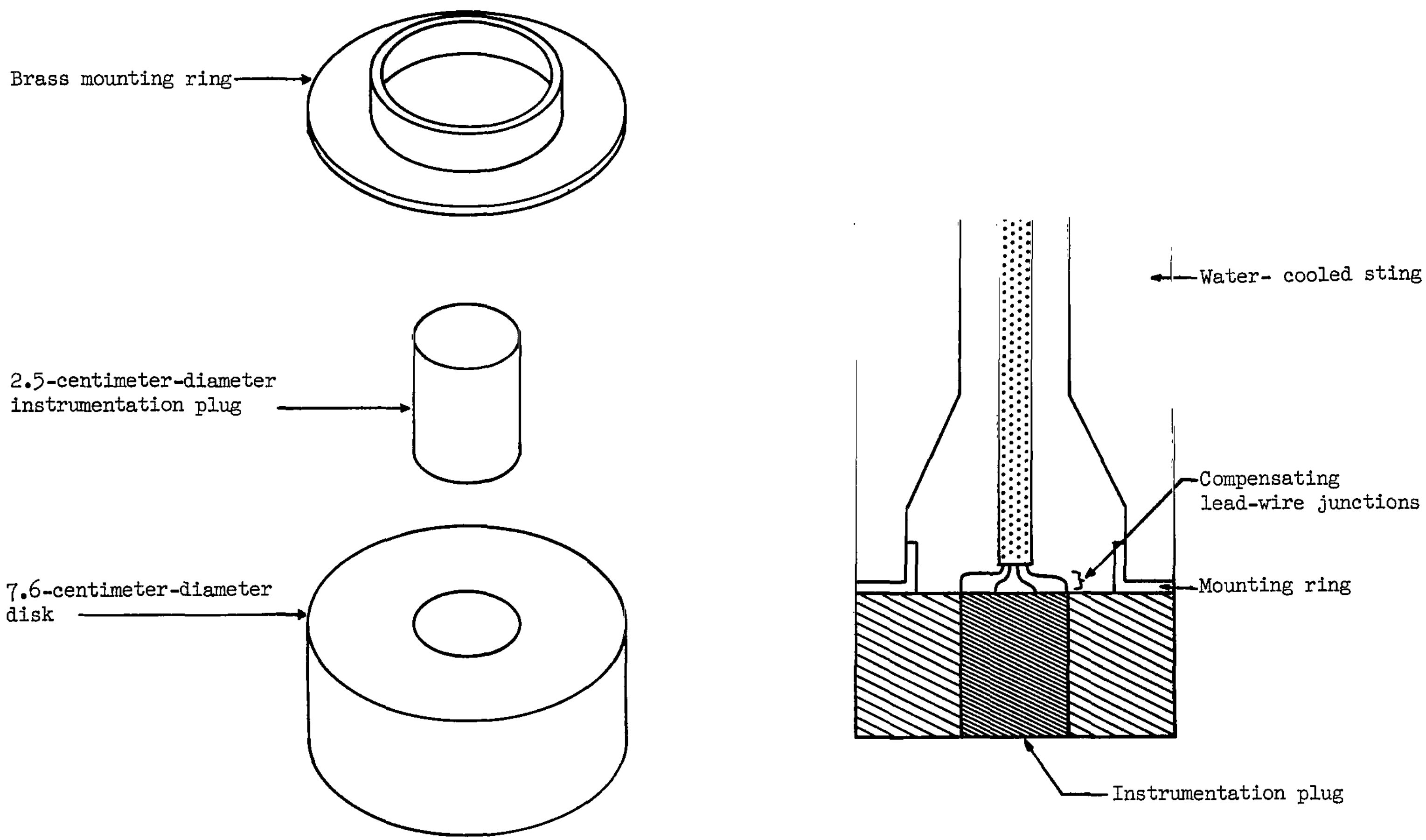


Figure 1.- Schematic diagram of test specimen assembly.

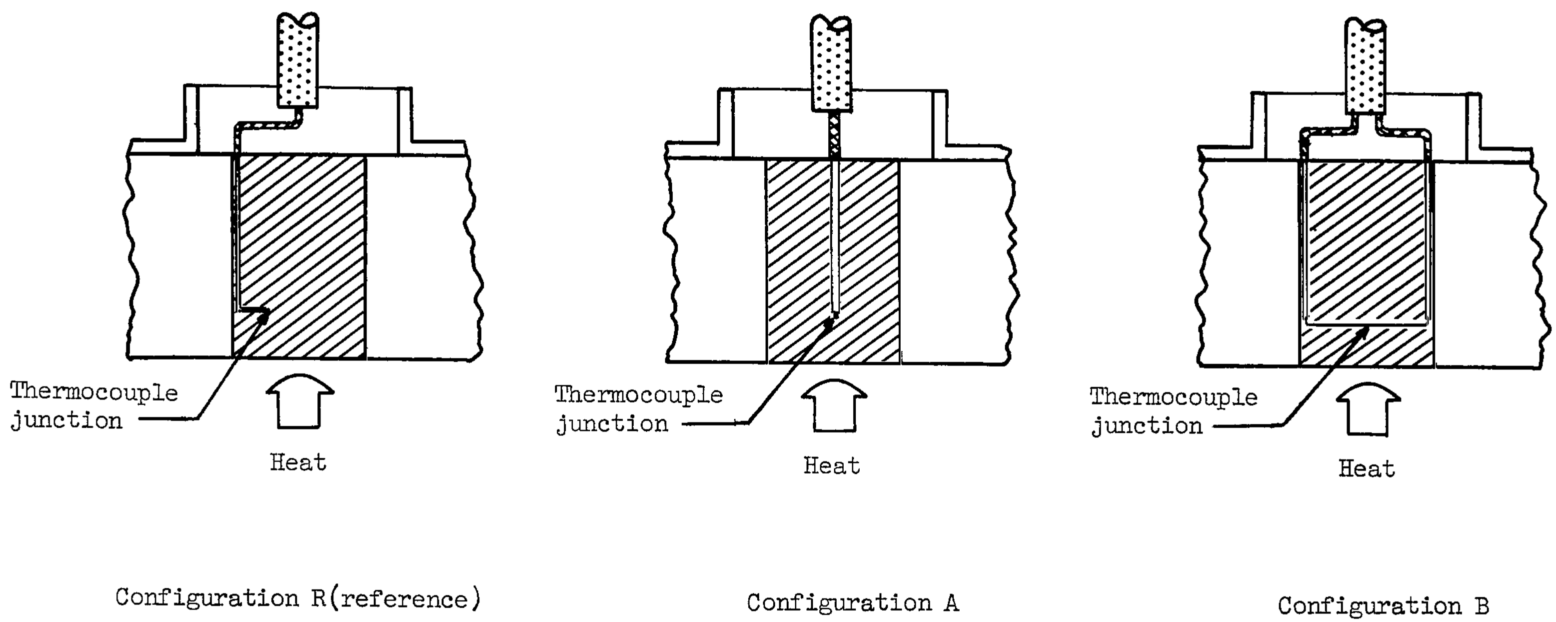


Figure 2.- Schematic diagram of thermocouple installations.

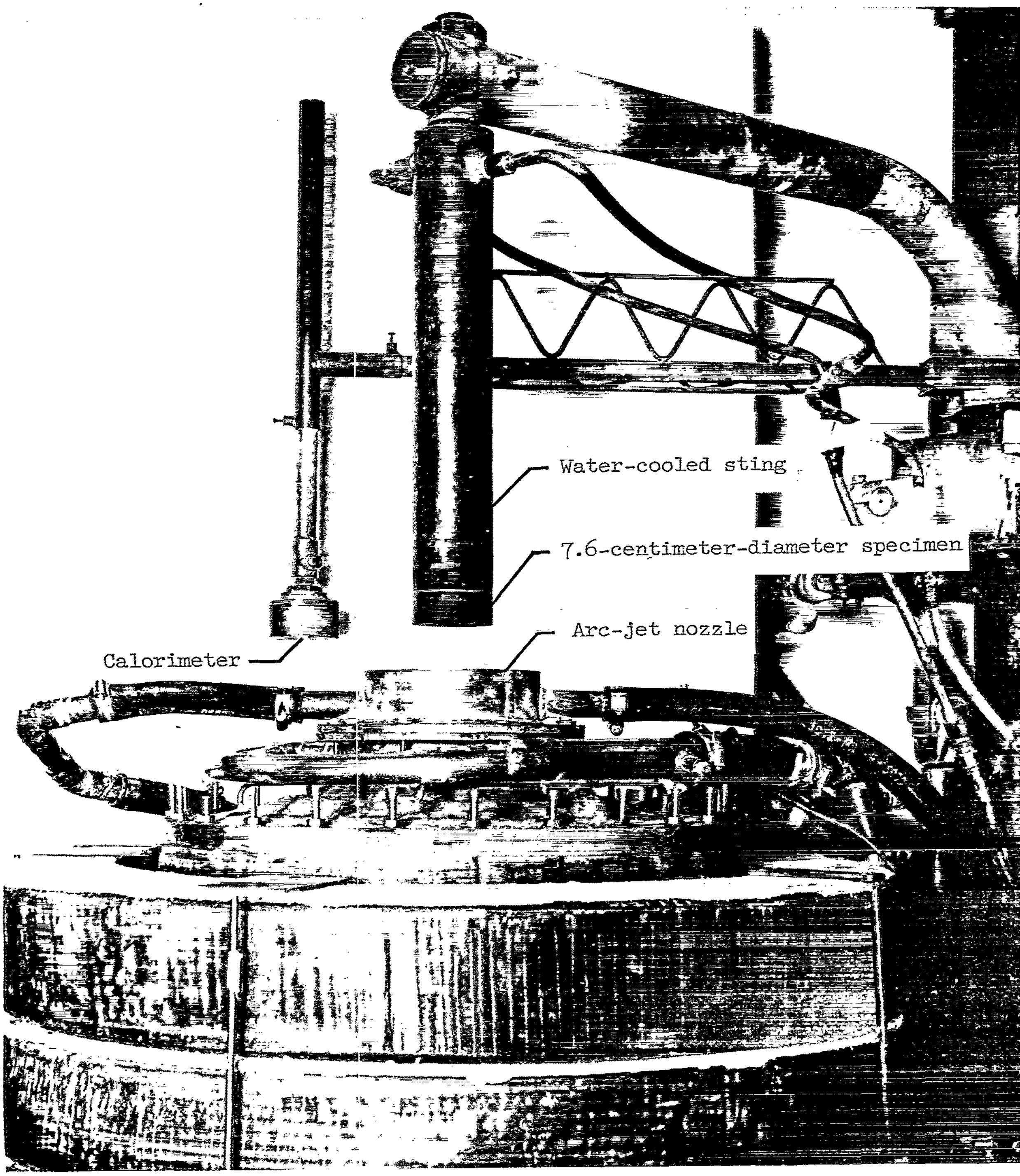


Figure 3.- The 2.5-megawatt arc jet at the Langley Research Center. Specimen in test position. L-63-10026.1

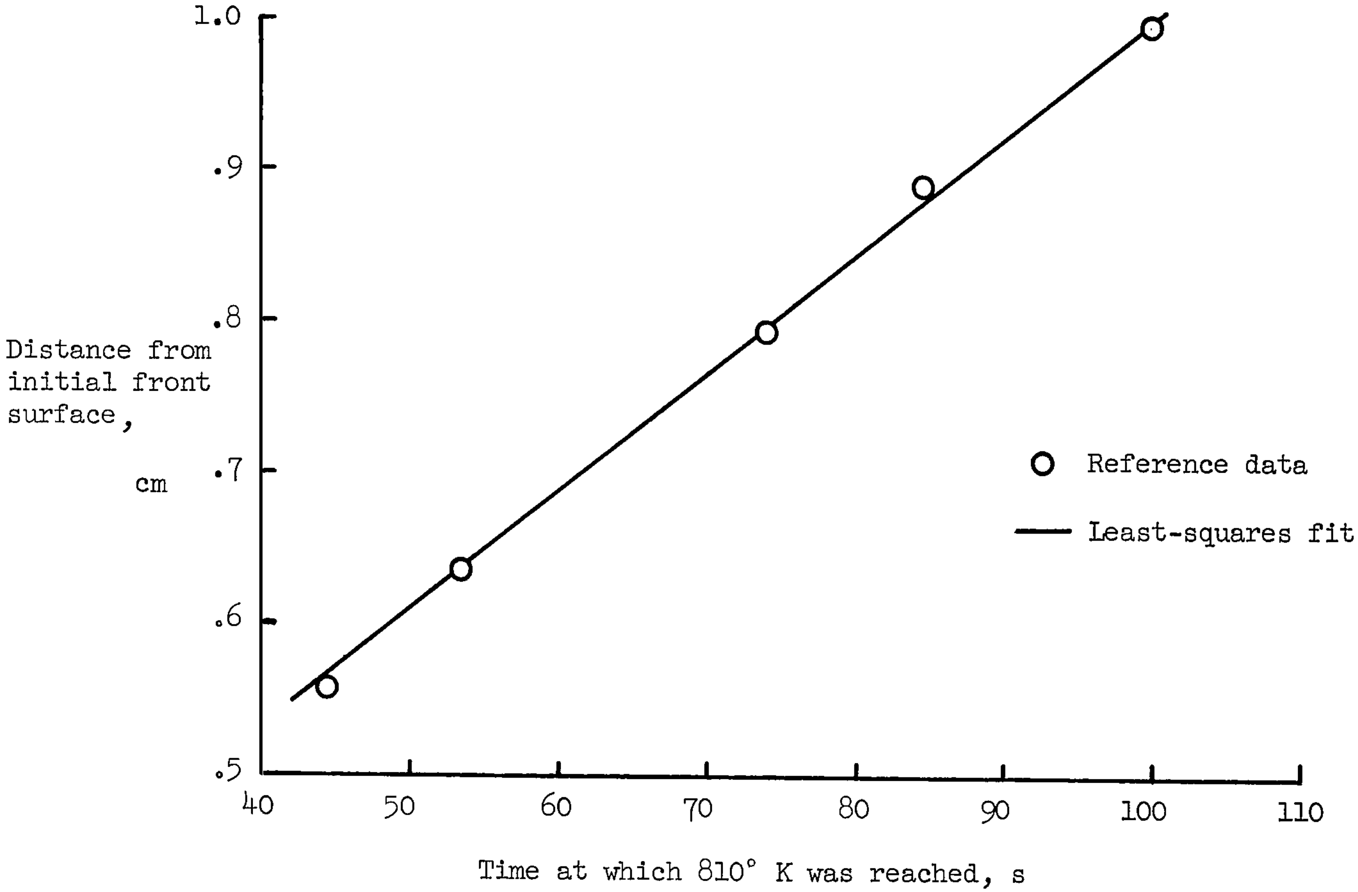


Figure 4.- Movement of 810^0 K isothermal plane through specimen 2A.

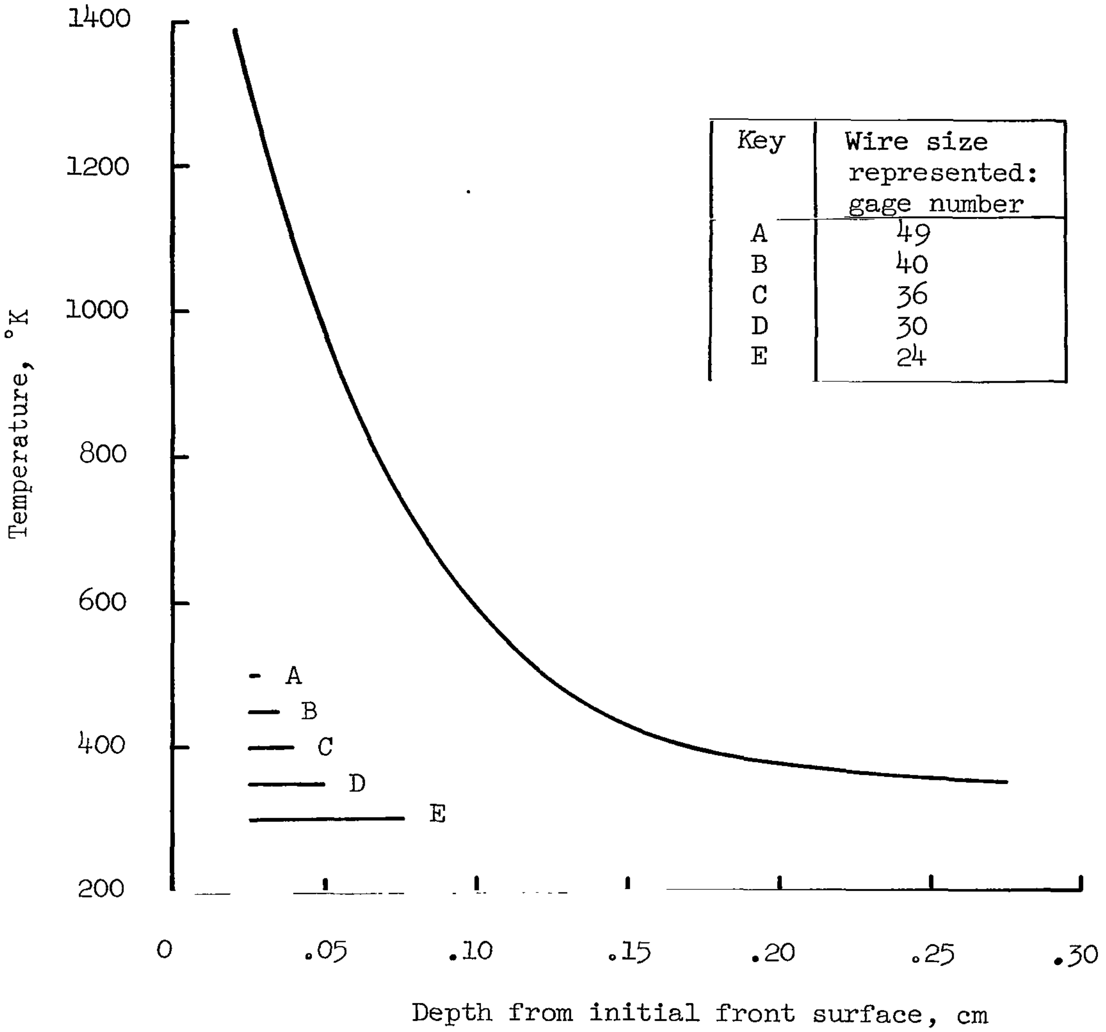


Figure 5.- Typical temperature profile in charring ablator obtained from reference thermocouple data. Cold-wall heating rate = 1.03 MW/m^2.

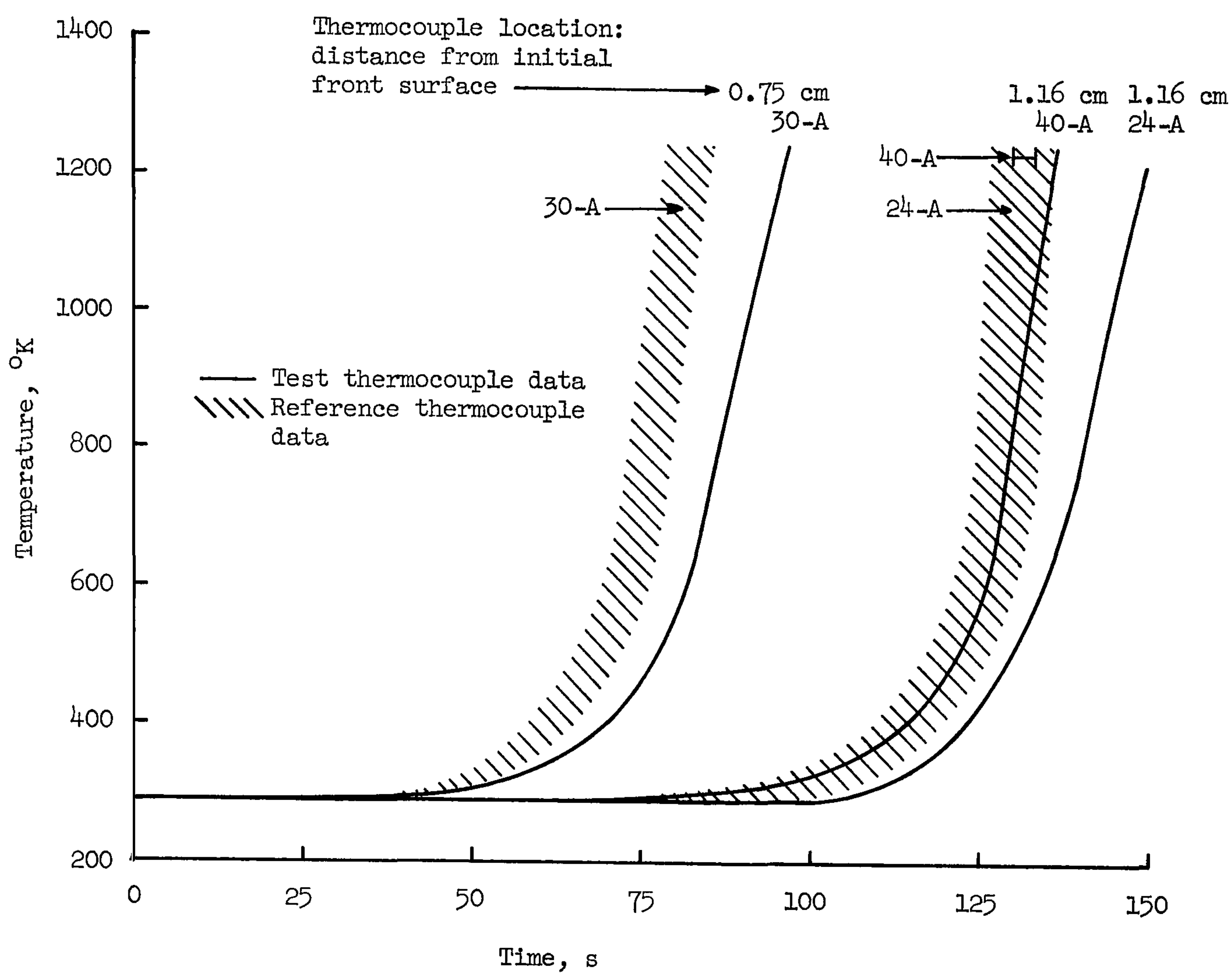


Figure 6.- Comparison of 24-A, 30-A, and 40-A thermocouple responses with reference data. Specimen 1A; cold-wall heating rate = 1.03 MW/m^2.

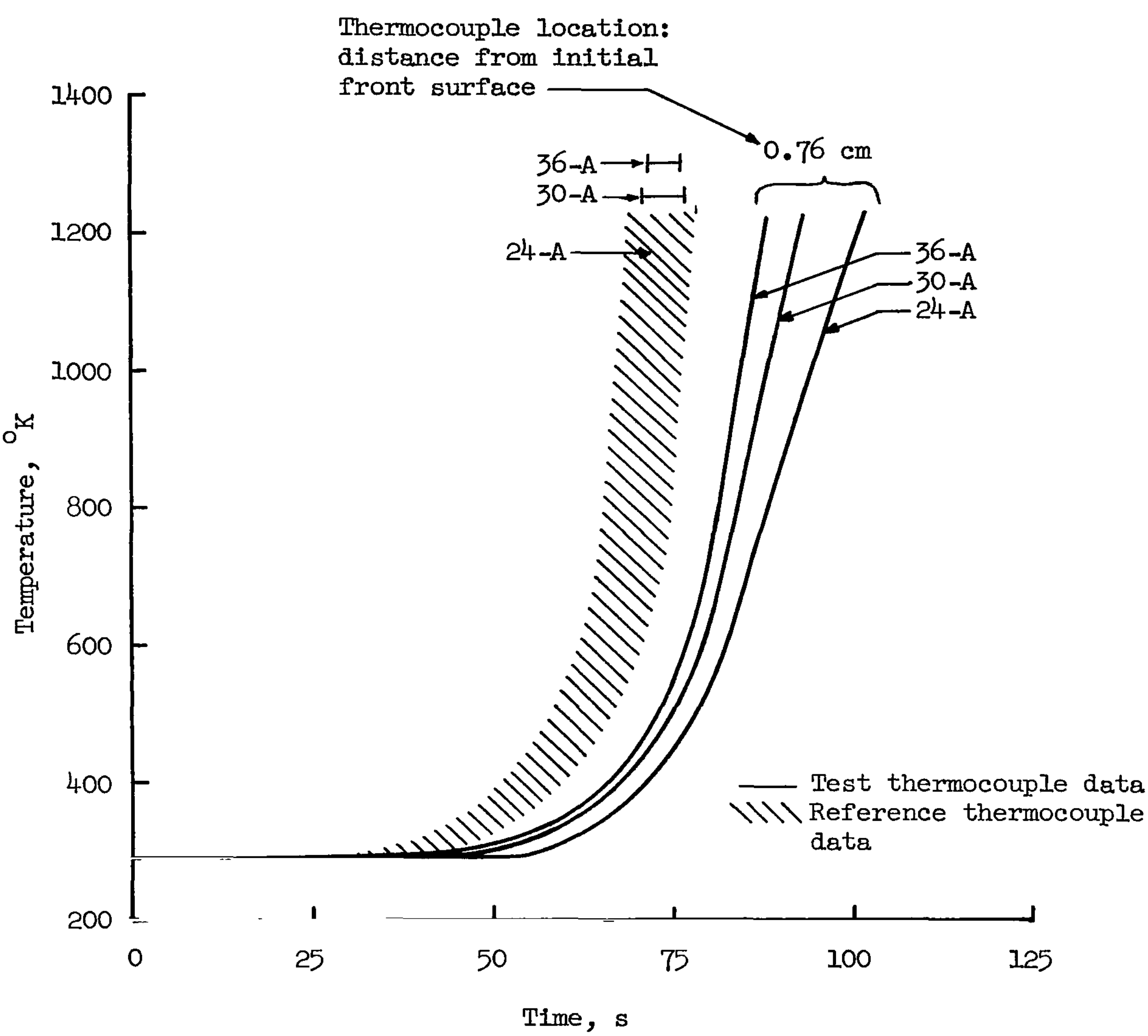


Figure 7.- Comparison of 24-A, 30-A, and 36-A thermocouple responses with reference data. Specimen 2A; cold-wall heating rate = 1.03 MW/m^2.

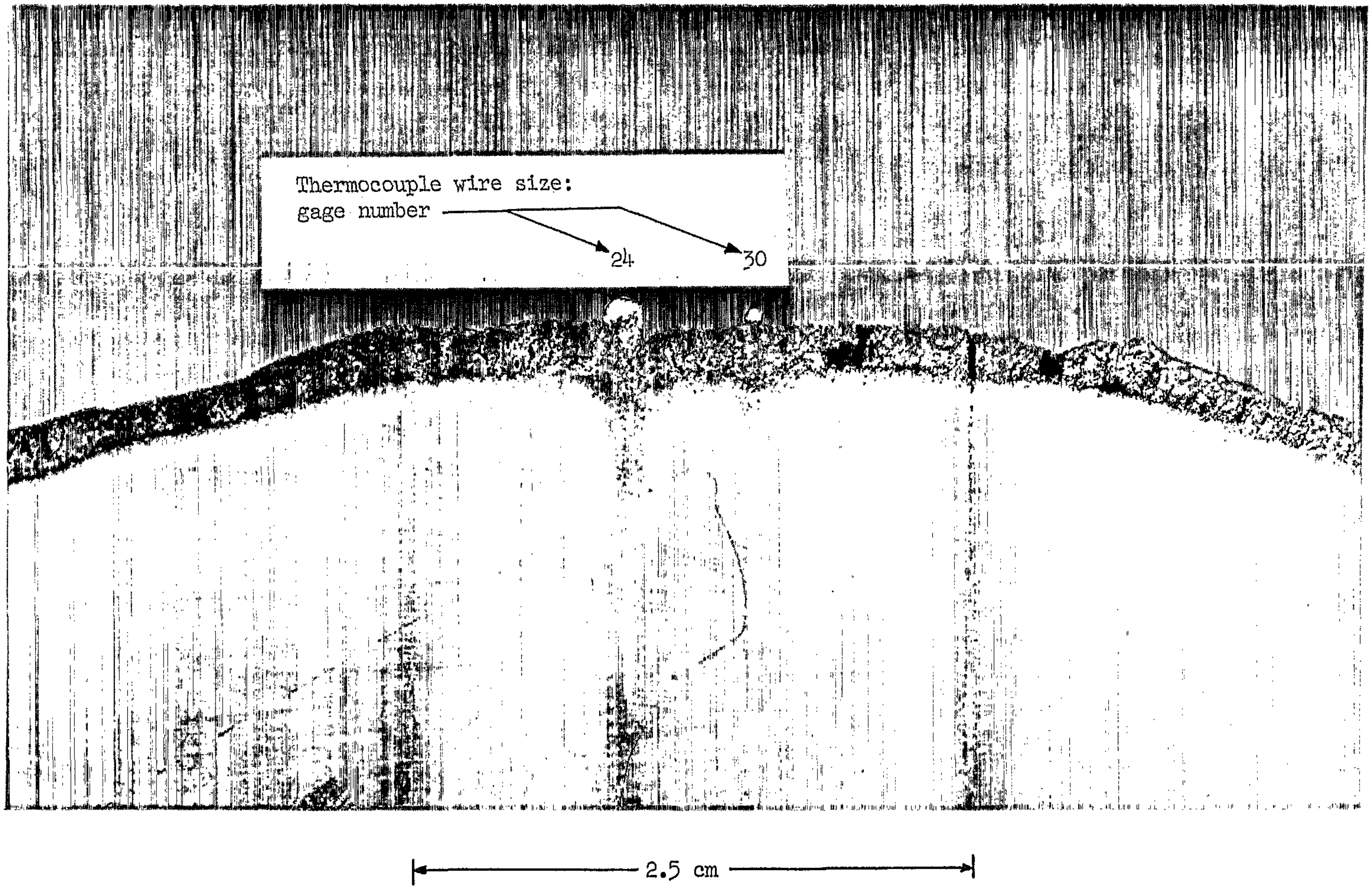
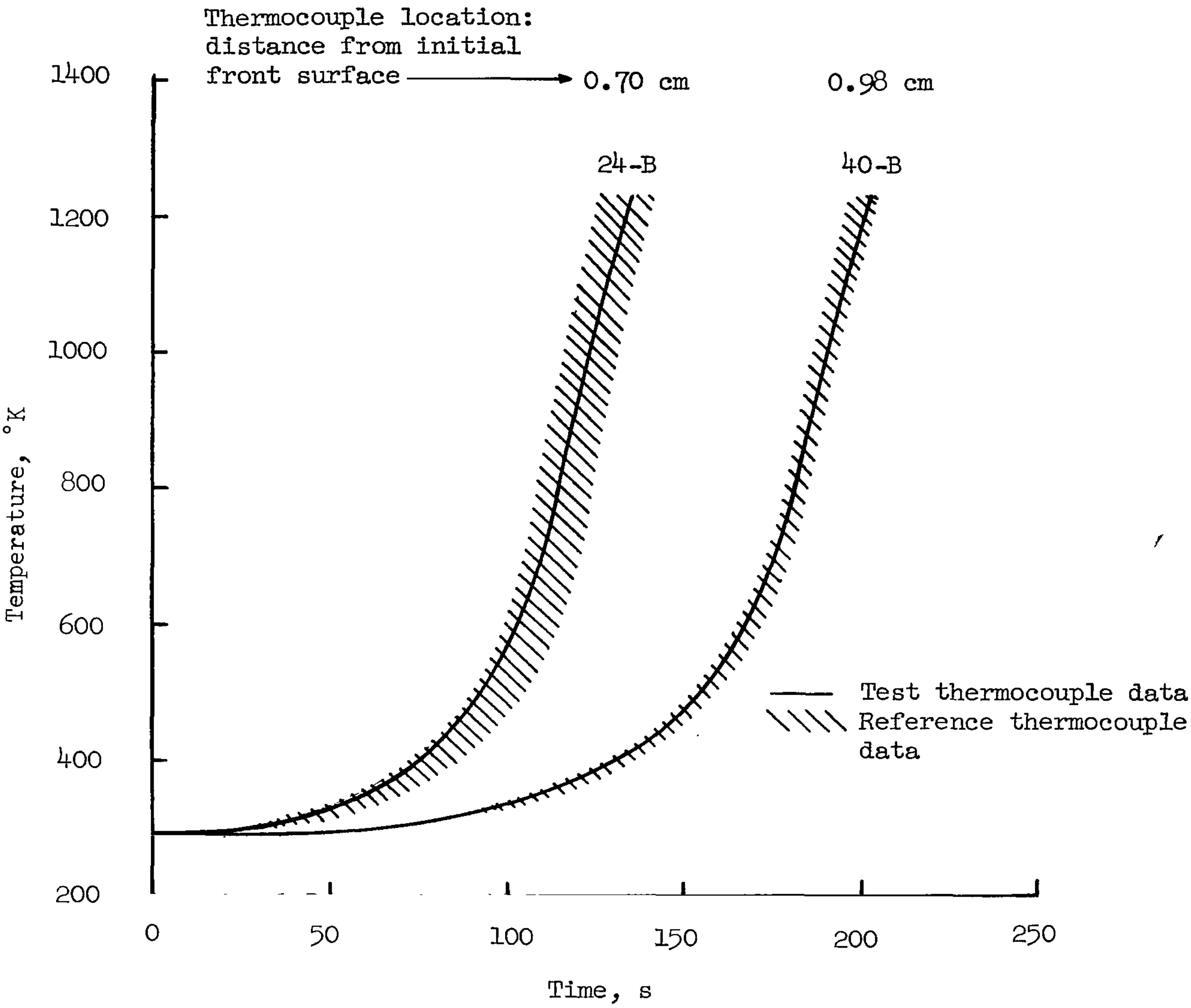


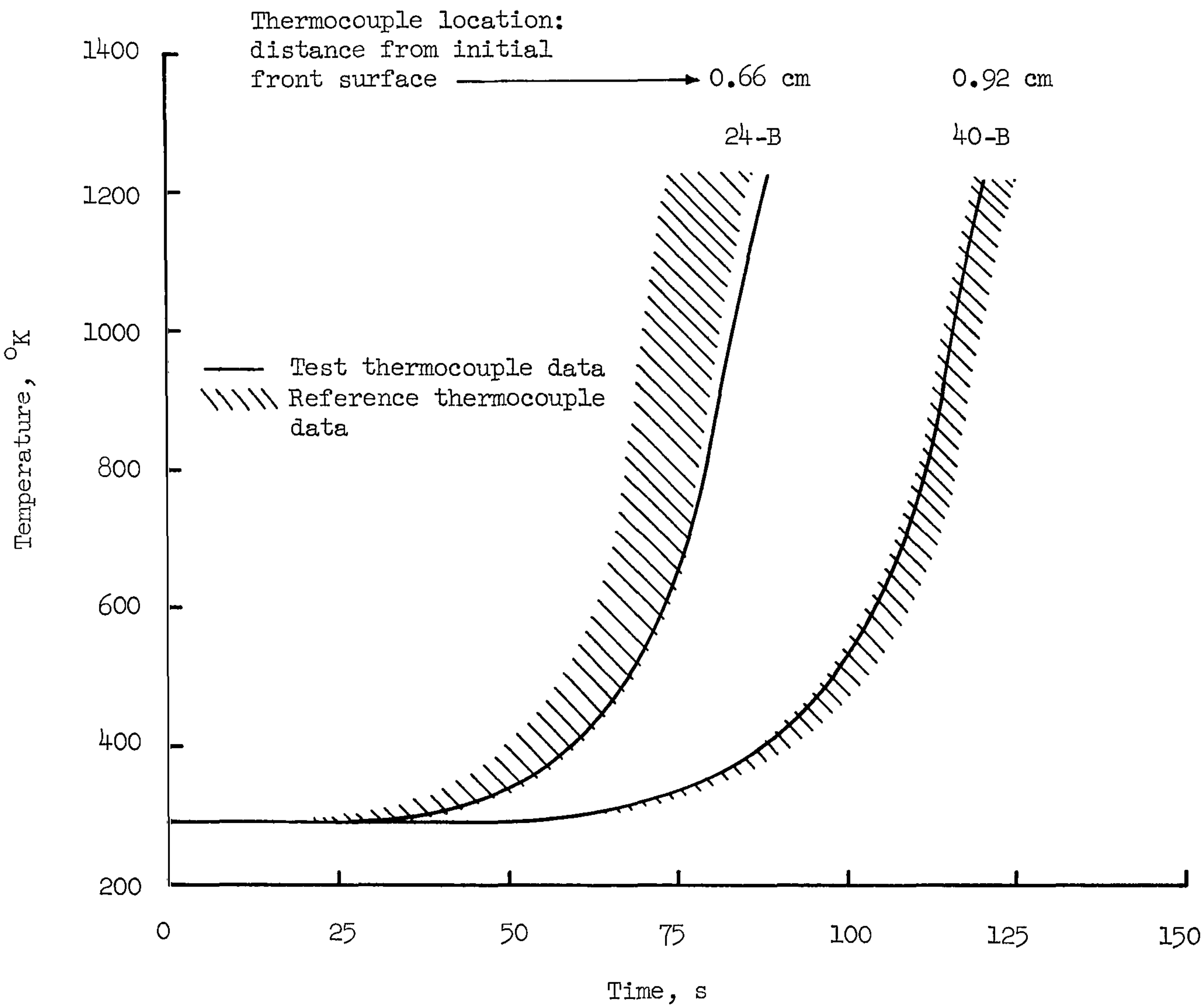
Figure 8.- Sectioned view of specimen 2A after testing.

L-64-7871.1



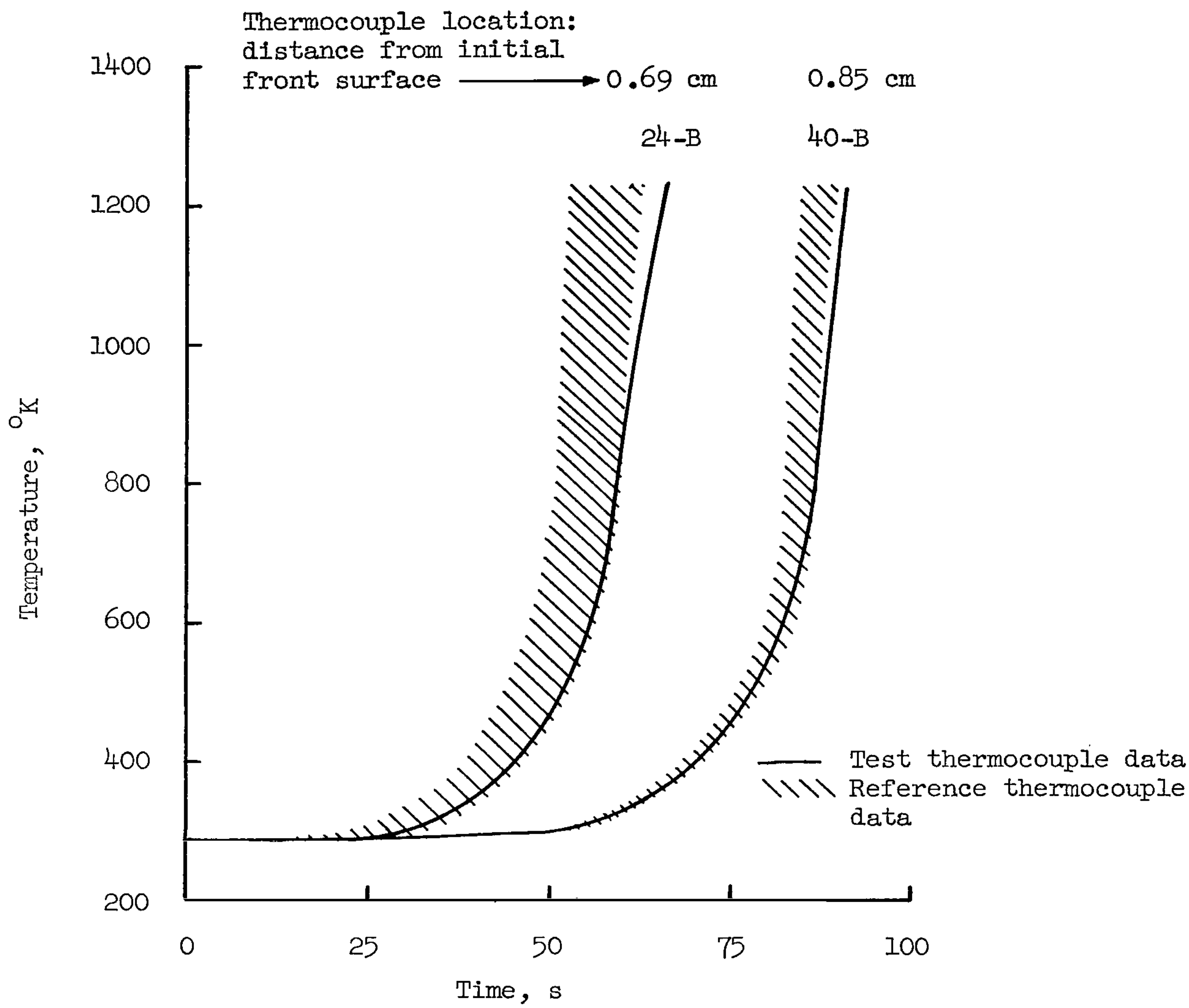
(a) Specimen 1B; cold-wall heating rate = 0.75 MW/m^2.

Figure 9.- Comparison of 24-B and 40-B thermocouple responses with reference data.



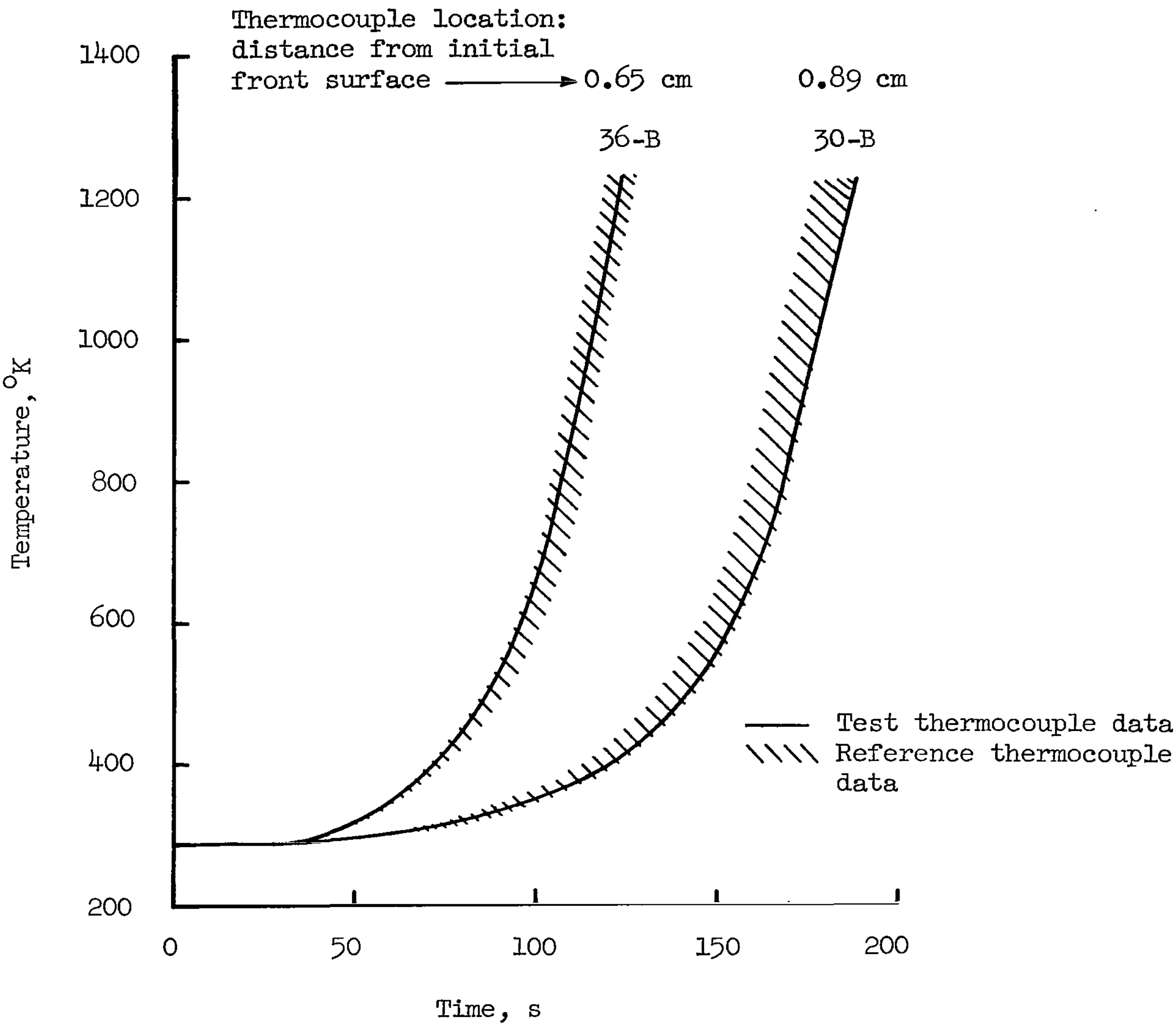
(b) Specimen 2B; cold-wall heating rate = 1.27 MW/m^2.

Figure 9.- Continued.



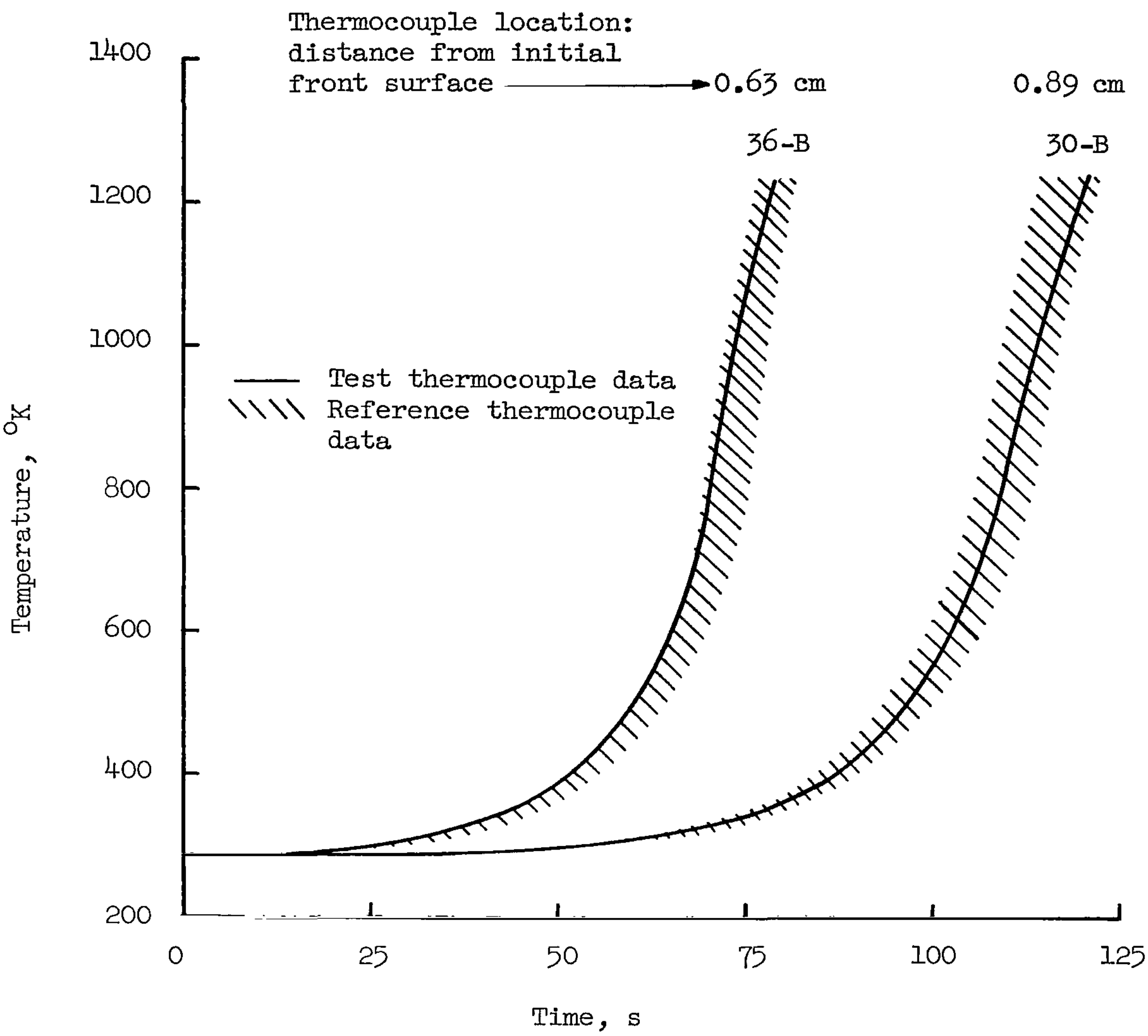
(c) Specimen 3B; cold-wall heating rate = 1.36 MW/m^2.

Figure 9.- Concluded.



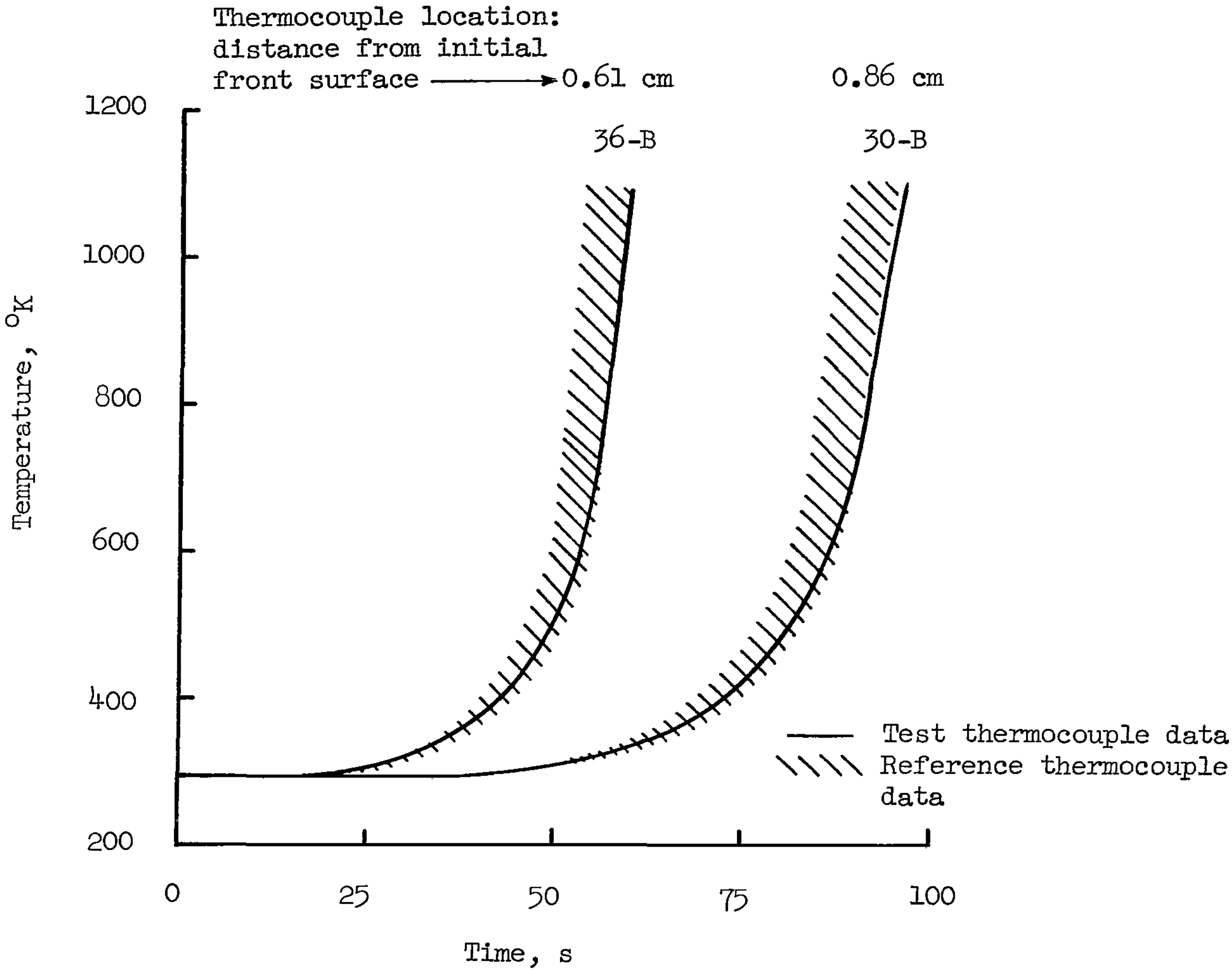
(a) Specimen 4B; cold-wall heating rate = 0.76 MW/m^2.

Figure 10.- Comparison of 30-B and 36-B thermocouple responses with reference data.



(b) Specimen 5B; cold-wall heating rate = 1.29 MW/m^2.

Figure 10.- Continued.



(c) Specimen 6B; cold-wall heating rate = 1.66 MW/m^2.

Figure 10.- Concluded.

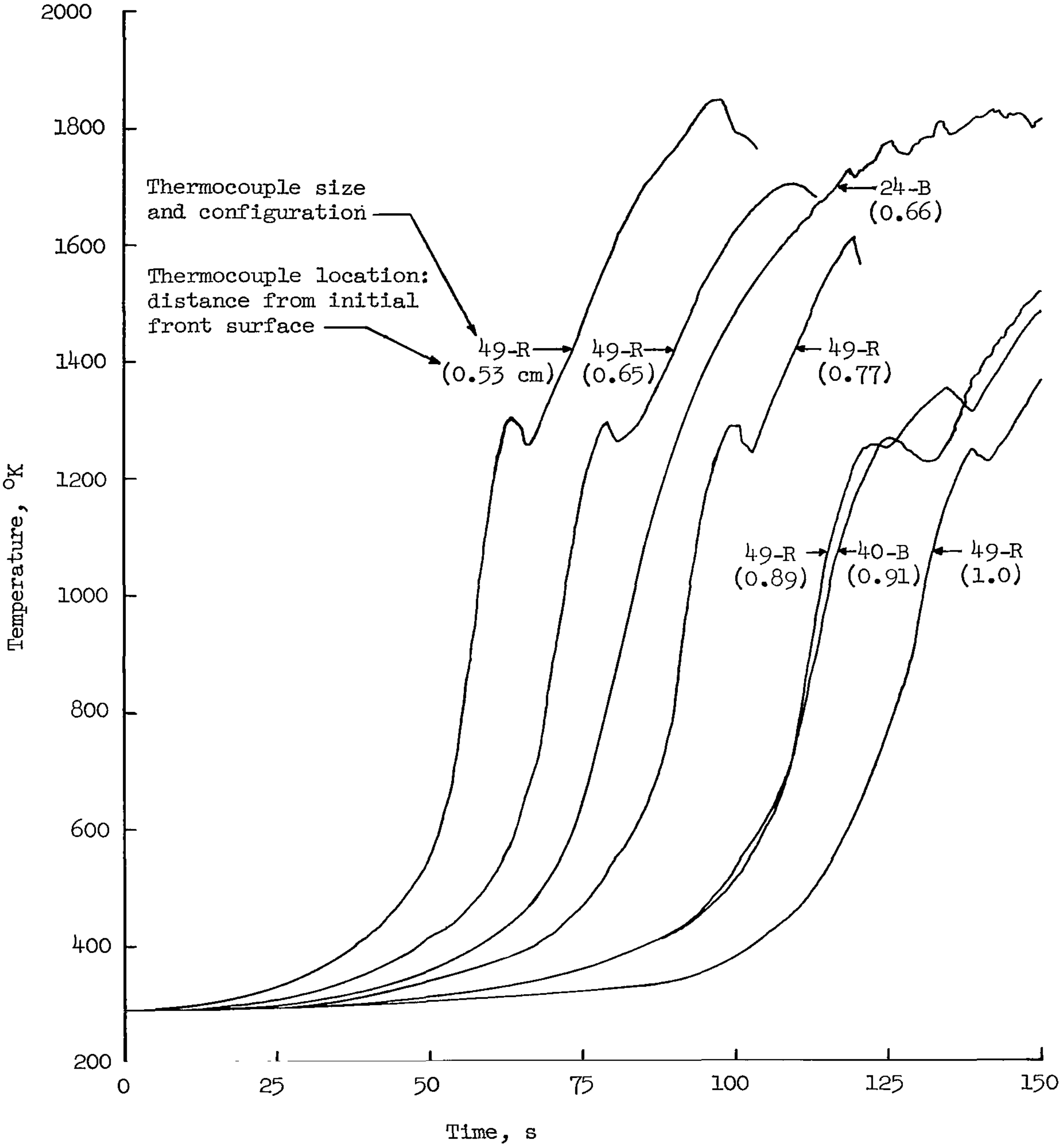


Figure 11.- Temperature-time histories for thermocouples within specimen 2B.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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