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SUMMARY

The internal temperatures measured by various thermocouple configurations in a charring ablator and in a porous ceramic subjected to severe heating in an electric-powered arc jet are presented and discussed. The results show that measurement errors of several hundred degrees can result from the conduction of heat from the hot junction of the thermocouple by the thermocouple lead wires. The measurement of internal temperatures in materials with low values of thermal conductivity subjected to severe heating by thermocouples requires that the thermocouple produce a minimum temperature disturbance within the material.

A comparison was made of several thermocouple sensors designed to minimize internal temperature disturbances caused by heat conduction from the hot junction by the sensor material. These thermocouple sensors had short lengths of the sensor lead wire in the isothermal plane of the hot junction. This comparison showed that the temperatures indicated by these thermocouple sensors agreed reasonably well.

INTRODUCTION

The flight-test and ground-test evaluation of ablation materials, subjected to severe heating, often requires a history of the rapidly changing temperature at an interior point in the material. The validity of analytical procedures for determining the temperature distribution within an ablation material depends upon a comparison with experimental measurements. The experimental temperature history may be obtained from a thermocouple sensor in the interior of the ablating material, but attention must be paid to the method of installing the sensor.

The objective in using thermocouple sensors to measure temperatures within materials is to measure the temperature that would exist in the region of measurement if the thermocouple sensor were not present. Temperature measurements obtained from sensors which cause significant temperature disturbances in the region of measurement are therefore erroneous measurements. This error follows despite the fact that the temperature of the hot junction of the thermocouple sensor may be correctly measured.

Experiments (ref. 1) and analysis (ref. 2) indicate that considerable error in the measurement of internal temperatures may be introduced by the thermocouple sensor itself if heat is carried from the place of measurement by the sensor material. The temperature disturbance is particularly severe when there is a large difference in the thermal conductivity of the thermocouple sensor and the surrounding material and when the thermocouple lead wires are parallel to the direction of heat flow within the material.

Because ablation materials have low values of thermal conductivity compared with those of the thermocouple wire, it has been found that certain methods of installing thermocouple sensors can produce significant errors in the measurement of internal temperatures. The present paper presents the results of an experimental investigation to determine the magnitude of temperature disturbances within a charring ablation material subjected to severe heating, when thermocouple sensors are installed with the lead wires parallel to the direction of heat flow. A comparison is also made of several thermocouple sensor configurations designed to minimize heat conduction from the hot junction in the manner suggested in references 1 and 2. The results were examined to determine whether certain thermocouple-sensor-assembly configurations were susceptible to electrical shorting by the conducting char layer formed by thermal degradation of some plastic ablation materials.

Temperatures were measured within a charring ablation material and within a low-density porous ceramic material. Specimens of these materials were exposed to the hot gas stream produced by an electric-powered arc jet. The tests of the porous ceramic material were performed to obtain data from a material of low thermal conductivity which does not pyrolyze and form a char layer when exposed to severe heating.

SYMBOLS AND NOMENCLATURE

The units used for the physical quantities defined herein are given both in the U.S. customary units and in the International System of Units, SI (ref. 3). An appendix is included for the purpose of explaining the relationships between these two systems of units.

$\bar{H}$	dimensionless enthalpy of test stream
k	thermal conductivity, Btu/ft-sec-$^{\circ}$R (W/m-$^{\circ}$K)
x	distance from thermocouple-sensor hot junction to original front or unheated surface of specimen, in. (m)
K	Instrument Society of America (ISA) symbol for chromel—alumel thermocouples

R	ISA symbol for platinum—platinum 13-percent rhodium thermocouples
S	ISA symbol for platinum—platinum 10-percent rhodium thermocouples

TEST SPECIMEN MATERIALS AND INSTRUMENTATION

Materials

Charring ablator.- The material used in the fabrication of the charring ablation specimens was composed of 55-percent epoxy resin, 30-percent phenolic microballoons and 15-percent silica fibers by weight. The pertinent physical and thermal properties of this material are listed in table I.

Porous ceramic.- The material used in the fabrication of the porous ceramic specimens contained 99.8-percent fused silica with aluminum oxide as the major impurity. The pertinent physical and thermal properties of this material are presented in table I.

Instrumentation

Charring ablator specimens.- The specimens were 3-inch (7.62-cm) diameter flat-faced cylinders with a thickness of 1 inch (2.54 cm). The specimens were purchased fully instrumented.

Each specimen was instrumented by installing several types of thermocouple sensors into flat-bottomed blind holes drilled on a 7/8-inch (2.2-cm) diameter circle about the center of the 3-inch (7.62-cm) specimen as shown in figure 1. Care was exercised to insure that the hot junctions were at the same depth relative to the heated surface of the test specimens. The depth of the blind holes was mechanically measured after drilling. After insertion of the thermocouple sensors, X-ray photographs of the specimens were made to insure that the hot junctions were properly located. The hot junctions of the thermocouple sensors in the completed specimens were determined to be within ±0.002 inch (±0.05 mm) of the measured depths of the blind holes.

Premium quality commercial duplex thermocouple wire of types R and S was used in specimen instrumentation. The duplex thermocouple wire had silicone-resin impregnated double-glass wrap on each wire and a silicone-resin impregnated glass braid overall. This insulation will hereafter be referred to as resin-glass insulation. The ceramic tubing used in specimen instrumentation was 99-percent-pure aluminum oxide (alumina) with silica dioxide as the major impurity. Approximate values of the thermal conductivity of the materials used in instrumentation are given in table I.

The various thermocouple sensors used to instrument the specimens are as follows: (Details of each sensor are shown in fig. 1.)

(1) Sensor 1 was constructed with a 0.25-inch (0.64-cm) diameter plug of the charring ablation material. Slots were machined across one end and along

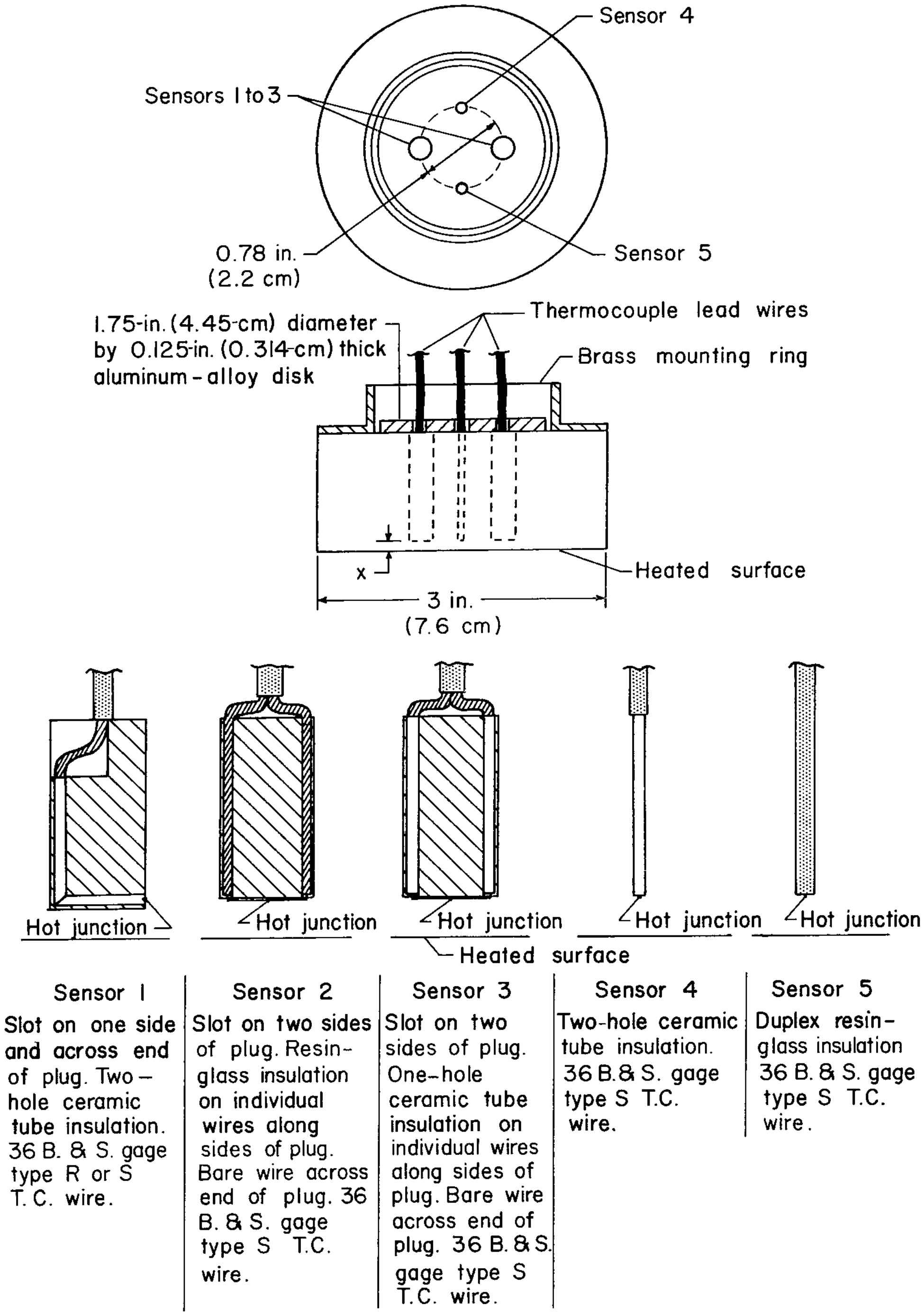


Figure 1.- Details of thermocouple sensors used in charring ablator specimens. Plugs 1 to 3 are made of the same ablation material as that used in the test specimens. All plugs are 0.25-in. (0.635-cm) diameter.

one side of the plug. A short length of the resin-glass insulation was removed from one end of a duplex thermocouple wire and the individual wires were inserted into a two-hole alumina tube. The protruding wires were resistance welded to form a hot junction and flattened against the end of the alumina tube. The alumina tube was then bonded with a ceramic adhesive into the slots in the plug. The hot junction was located at the end and flush with the outside diameter of the plug. The plug was then coated with the same epoxy resin contained in the charring ablation material and inserted and bonded into a blind hole in the specimen. (See fig. 1.) The diameter of the blind hole drilled for installation of this sensor was not more than 0.004 inch (0.102 mm) larger than the plug diameter. This sensor had approximately 0.20 inch (0.51 cm) of sensor wire across the end of the plug. The alumina tube gave the lead wires electrical insulation with a high-temperature capability.

(2) Sensor 2 also was constructed by using a 0.25-inch (0.64-cm) diameter plug of the charring ablation material. Two diametrically opposed slots were machined along the length of the plug to position the thermocouple wire. A short length of the outer resin-glass insulation was removed from one end of a duplex thermocouple wire to separate the individual wires. The two wires were welded to form a hot junction and the resin-glass insulation was stripped from each wire a distance of 0.125 inch (0.32 cm) from the hot junction. The thermocouple wire was positioned in the slots on the plug as shown in figure 1 and the plug was bonded into a blind hole in the specimen in the same manner as sensor 1. Sensor 2 had approximately 0.10 inch (0.25 cm) of uninsulated wire extending both ways from the hot junction across the end of the plug.

(3) The plug for sensor 3 was identical to the plug used for sensor 2. Sensor 3 had uninsulated wire extending from the hot junction across the end of the plug in the same manner as for sensor 2. Sensor 3 differed from sensor 2 in that the resin-glass insulation was completely removed from the individual wires along the sides of the plug and the wires were inserted into one-hole alumina tubes before forming the hot junction. The alumina tubes were bonded into the slots on the sides of the plug with the same epoxy resin as that used to bond the plug into the specimen.

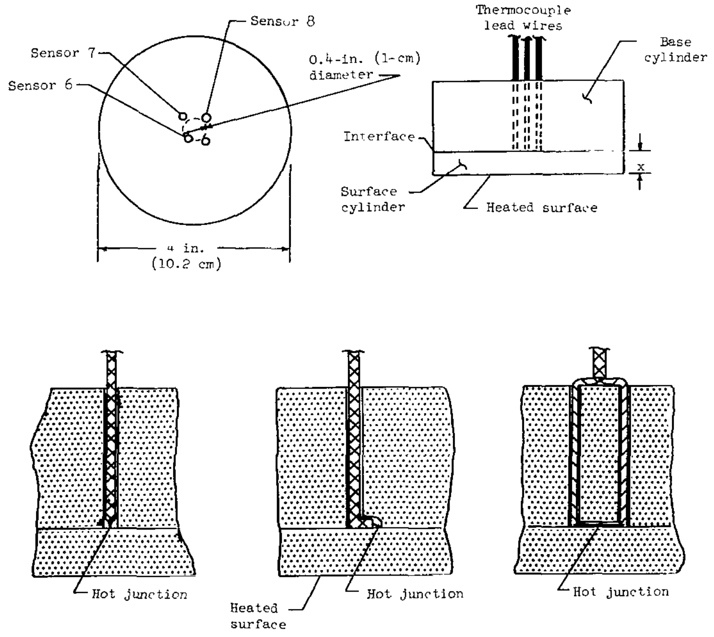
(4) Sensor 4 was constructed by removing the resin-glass insulation from a short length of duplex thermocouple wire and inserting the individual wires into a two-hole alumina tube. The protruding wires were resistance welded to form a hot junction and flattened against the end of the alumina tube. The sensor was bonded into a 0.035-inch (0.8-mm) diameter blind hole in the specimen with the same epoxy resin as that contained in the specimen material. The lead wires of this sensor extended directly from the hot junction parallel to the 1-inch (2.54-cm) depth of the specimen. There was no lead wire in the plane of the hot junction parallel to the 3-inch (7.62-cm) diameter faces of the specimen.

(5) Sensor 5 merely consisted of commercial duplex thermocouple wire with resin-glass insulation. A minimum of the resin-glass insulation was removed to permit forming the hot junction. The sensor was bonded into a 0.07-inch (1.6-mm) diameter blind hole in the specimen in the same manner as sensor 4. The only difference between sensors 4 and 5 was the use of different insulation material on the thermocouple lead wires within the specimen.

The lead wires for the sensors were 12 inches (30.5 cm) long. These lead wires were attached to temperature-compensated copper-alloy duplex lead wires 15 feet (4.6 m) long.

Each of the charring ablation specimens contained at least two of the different plug type of thermocouple sensors (1, 2, and 3). The purpose of this arrangement was to obtain a direct comparison of the temperature histories obtained from these sensors all of which were designed to minimize conduction errors. However, some of the sensors were damaged prior to testing or malfunctioned during the test and this comparison could not be made.

Porous ceramic specimens.- Two 4-inch (10-cm) diameter flat-faced cylinders of the porous ceramic material were used to construct each specimen as shown in figure 2. A 1.5-inch (3.8-cm) thick base cylinder containing the instrumentation was used for both specimens. The second cylinder, hereafter referred to as the surface cylinder, was 0.5 inch (1.27 cm) thick for one specimen and 0.1875 inch (0.47 cm) thick for the other specimen.



Sensor 6
Duplex resin-glass insulation. 30 B & S gage type K T. C. wire.

Sensor 7
Duplex resin-glass insulation. 30 B & S gage type K T. C. wire.

Sensor 8
Resin-glass insulation on individual wires along depth of holes in ceramic. Bare wire along interface. 30 B & S gage type K T. C. wire.

Figure 2.- Details of thermocouple sensors used in porous ceramic specimens.

Each of the specimens was instrumented with three thermocouple sensors which were spaced on a 0.4-inch (1-cm) diameter circle about the center of the specimen as shown in figure 2. The thermocouple sensors were representative of the types used in the charring ablator specimens. Premium quality commercial duplex thermocouple wire of type K was used in instrumentation. The wire insulation was the resin-glass insulation described previously.

The types of thermocouple sensors used to instrument the specimens are as follows: (Details of each sensor are shown in fig. 2.)

(1) Sensor 6 was similar to the sensor 5 in the charring ablator specimens. The sensor was bonded by using ceramic cement into a hole drilled through the base cylinder perpendicular to the 4-inch (10.2-cm) diameter faces. The hot junction was located in the plane of one face of the specimen base cylinder.

(2) Sensor 7 merely consisted of commercial duplex thermocouple wire. A minimum of the resin-glass insulation was removed for the formation of a hot junction. The sensor was inserted into a hole drilled through the base cylinder. The duplex thermocouple wire was then bent 90° approximately 0.25 inch (0.64 cm) from the hot junction. The 0.25-inch length of the sensor thus formed was positioned in a prepared groove in the face of the specimen base cylinder. The sensor was then bonded in place with ceramic cement. The hot junction was located in the plane of the face of the base cylinder, and approximately 0.25 inch of thermocouple lead wire was located parallel to the face of the base cylinder.

(3) Sensor 8 was also fabricated from commercial duplex thermocouple wire. A short length of the outer resin-glass insulation was removed from one end of the duplex wire and the individual wires were then inserted into two holes drilled through the base cylinder. The protruding wires were welded to form a hot junction and the resin-glass insulation on each individual wire was removed for a distance of 0.25 inch (0.64 cm) from the hot junction. The 0.5-inch (1.27-cm) length of uninsulated wire was positioned in a prepared groove in the face of the specimen base cylinder. The sensor was then bonded in place with ceramic cement. The hot junction was located in the plane of the face of the base cylinder midway between the through holes for the thermocouple lead wires.

The depth of the three thermocouple sensors was kept uniform by placing the hot junctions at the surface of the 1.5-inch (3.8-cm) thick base cylinder which had been ground flat. After installation of the sensors, the surfaces were again ground lightly to insure flatness. Then the surface cylinder which also had ground faces was placed in contact with the base cylinder containing the thermocouple sensors. The two cylinders comprising a specimen were bonded together with ceramic cement applied around the periphery.

TEST EQUIPMENT AND PROCEDURES

Equipment

The specimens were exposed to the high-temperature gas stream produced by the 2500-kilowatt arc jet at the Langley Research Center. This facility is described in reference 4. It produces a subsonic gas stream at atmospheric pressure having a static temperature of about 6400° F (3810° K) and a constant enthalpy of approximately 3000 Btu/lb (6.97 MJ/kg). The photograph of figure 3 shows the arc-jet facility with a specimen in the test position.

The output from the thermocouple sensors installed in each specimen was recorded on magnetic tape at discrete time intervals by the Langley central digital data recording facility. The data were reduced to time-temperature tabulations by means of a digital computer program.

Procedures

Tests were performed by exposing the flat face of the cylindrical specimens to the high-temperature gas stream produced by the arc-jet facility. The specimens were positioned in the test stream by the water-cooled sting shown in figure 3. The arc-jet nozzle had a smaller diameter than the specimens which resulted in splash tests in which the hot gas heated the specimen front surface but was deflected away from the sides so that little heating occurred on the specimen sides.

Measurements of the cold-wall stagnation-point heat-transfer rate in the arc-jet stream were made by using the flat-faced metal calorimeter shown in figure 3. Unpublished experimental measurements of cold-wall heating rates in the stream of the arc jet used in the present investigation show that the heating-rate distribution is nearly uniform over a 1-inch (2.54-cm) diameter circle at the center of a 3-inch (7.62-cm) diameter calorimeter. Within the accuracy of the measurements, the heating-rate values over the 1-inch-diameter circle varied less than 10 percent from the stagnation-point values.

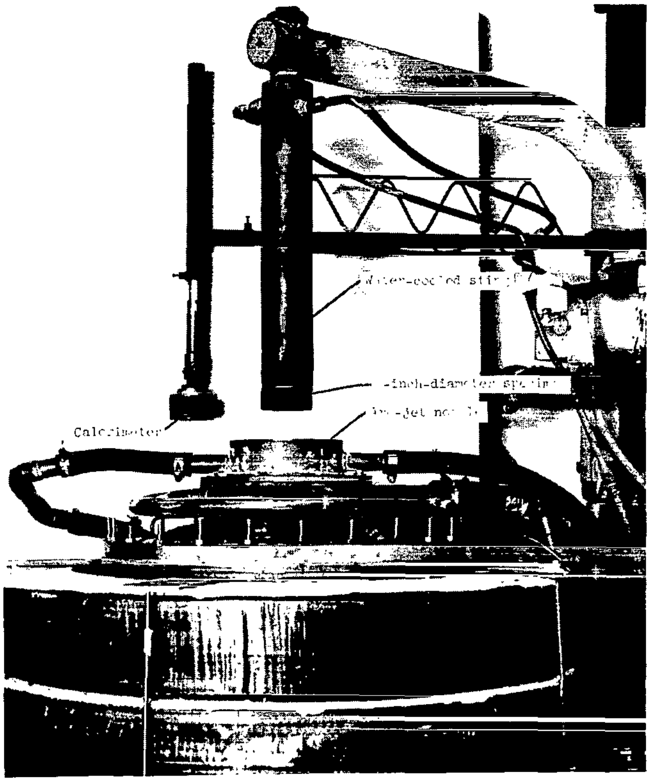


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Figure 3.- Test setup for charring ablator specimens.

The lead wires of the thermocouple sensors were routed through the water-cooled sting to a cold-junction terminal. The connection between the type R lead wires and the compensated lead wires were within the water-cooled sting. The cold-junction terminal was located a sufficient distance from the arc-jet nozzle so that ambient temperature conditions at the cold junction were not affected by operation of the arc-jet facility.

The gas supply for the arc jet was controlled to permit operation with varying percentages of oxygen and nitrogen. The charring ablator specimens were tested in gas streams of air, nitrogen, and 5-percent air and 95-percent nitrogen by weight. The stream composition was varied to obtain data at different rates of char formation and removal. The porous ceramic specimens were tested only in air.

RESULTS AND DISCUSSION

Table II is a summary of the specimens tested in the present investigation and shows the various thermocouple sensors in each specimen, the type of thermocouple wire used, and the depth x of each hot junction. (See figs. 1 and 2.)

The test conditions, that is, stream composition, heating rate, and enthalpy for each specimen are also summarized in table II.

Charring Ablator Specimens

Figure 4 shows a charring ablation specimen after testing. The flat regular surface of the char was typical of all specimens. The appearance of the tested specimen indicates that in the region where the thermocouple-sensor assemblies were located, one-dimensional heating perpendicular to the 3-inch (7.62-cm) diameter face of the specimen was obtained.

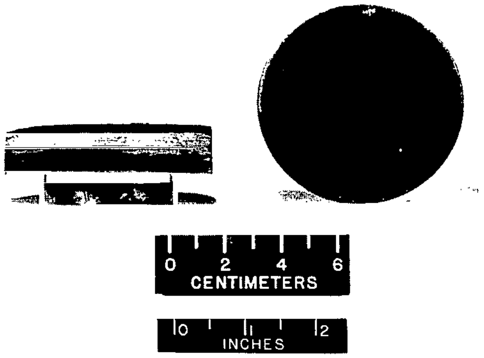

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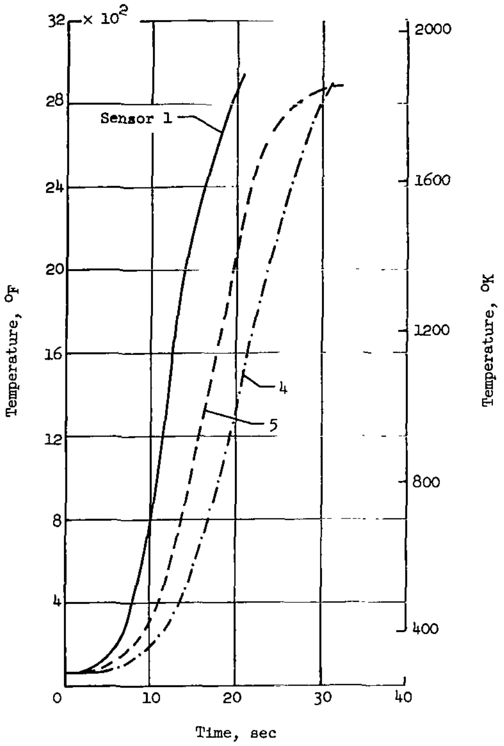
Figure 4.- Charring ablator specimen after testing.

The results of tests of charring ablation specimens are shown as temperature histories in figure 5. Figure 5(a) shows a comparison of the temperature histories obtained from thermocouple sensors 1, 4, and 5 in specimen A tested in an air arc-jet stream. The major point of interest in figure 5(a) is the large variations in the measured temperature that were obtained at a particular time from the different thermocouple sensors. Note that at an exposure time of 15 seconds, sensor 4 which had alumina-tube insulation indicated a temperature approximately 1600° F (1145° K) lower than sensor 1. Similarly sensor 5 which had resin-glass insulation indicated a temperature approximately 1100° F (868° K) lower than sensor 1.

Thermocouple sensors 4 and 5 were installed in the specimens so that the lead wires would be parallel to the direction of heat flow. (See fig. 1.) Since the thermocouple material, including the wire and its insulation, had a considerably higher thermal conductivity than the charring ablation material, heat from the hot-junction region was conducted along the wires to the cooler region within the ablation material during testing. This initiated a temperature disturbance because the heat conducted by the wires had to be transferred from the material surrounding the thermocouple hot junction. This heat transfer resulted in the large temperature drops of 1600° F and 1100° F in the low-thermal-conductivity charring ablation material surrounding the hot junctions of sensors 4 and 5, respectively.

Thermocouple sensor 1 in specimen A had a length of the lead wires equal to several wire diameters in the same isothermal plane as the hot junction. Thus the temperature disturbance which occurred at the point where the direction of the lead wires became parallel to the direction of heat flow was a relatively long distance from the hot junction and caused a minimal temperature disturbance at the hot junction. The plug type of sensor assemblies such as sensors 1, 2,



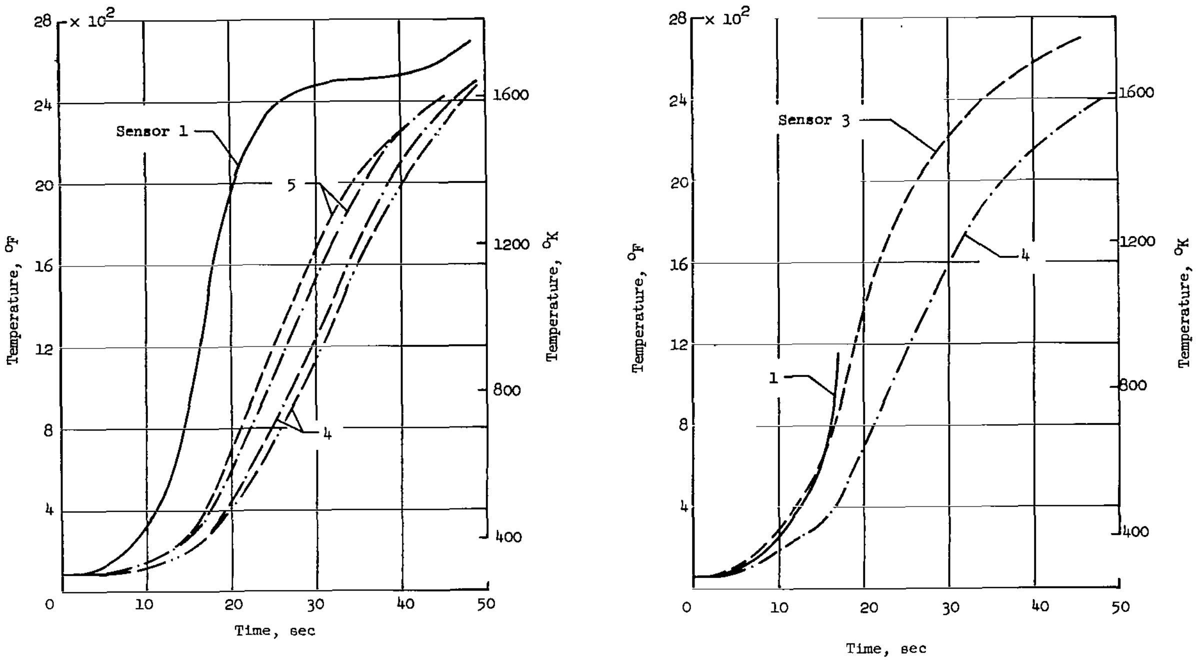
(a) Specimen A.

Figure 5.- Response of various thermocouple sensor assemblies in charring ablator.

and 3 are an approach to the desired condition of having infinitely long thermocouple lead wires in the isothermal plane of the hot junction.

A comparison of the temperature histories obtained from thermocouple sensors 1, 4, and 5 in specimen B tested in an arc-jet stream of 95-percent nitrogen and 5-percent oxygen is shown in figure 5(b). This specimen contained two each of sensors 4 and 5. This specimen developed a thicker char layer than the specimen tested in air because less char was oxidized at the reduced oxygen content. Also, the highly heated outer surface of the char moved toward the hot junctions of the sensors at a slower rate than for the tests in air (fig. 5(a)). The slope of the temperature-history curve of sensor 1 shows a considerable decrease after a temperature greater than 2400° F (1590° K) was reached. The change in slope may indicate the approach to an equilibrium temperature before oxidation of the char layer caused a significant increase in the temperature-rise rate at the sensor location. The change in slope may also have been caused by loss of thermal contact with the char layer due to separation. The temperature disturbances in specimen B caused by thermocouple sensors 4 and 5 were equal in severity to those produced in specimen A tested in air. A comparison of the temperature histories for sensors 4 and 5 in figures 5(a) and 5(b) indicates that the sensors with alumina tube insulation on the lead wires caused larger temperature disturbance than the sensors with resin-glass insulation on the lead wires. This difference is probably due to the higher thermal conductivity of the alumina materials.

Figure 5(c) shows a comparison of the temperature histories obtained from thermocouple sensors 1, 3, and 4 in specimen C tested in an arc-jet stream of nitrogen. Because of a malfunction in sensor 1, a comparison with sensor 3 was not obtained over the full temperature range. A comparison of the temperature histories obtained from sensors 3 and 4 shows that at a particular time the temperature indicated by sensor 4 was considerably lower than the temperature indicated by sensor 3 although the variation was not as large as the variation between sensors 1 and 4 shown in figures 5(a) and 5(b). The less severe temperature variation shown in figure 5(c) was probably due to the nonoxidizing arc-jet stream which resulted in the formation of a thicker char layer and a correspondingly less severe temperature gradient through the char than existed in the tests of specimens A and B.



(b) Specimen B.

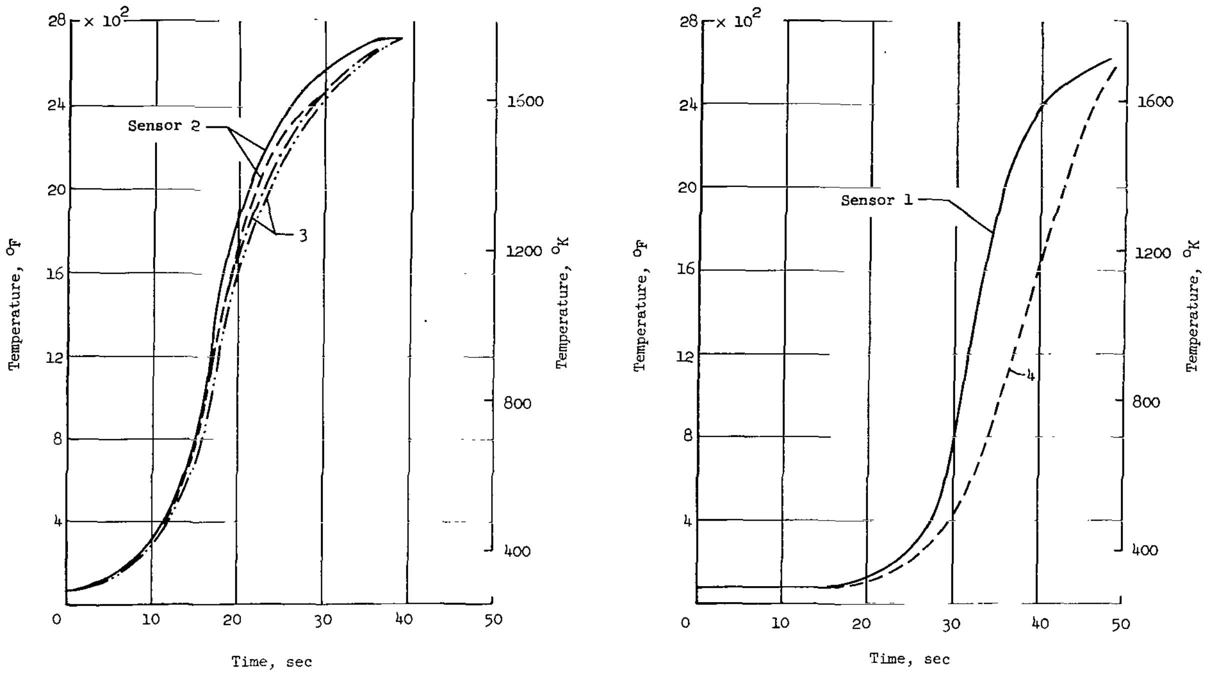
(c) Specimen C.

Figure 5.- Continued.

The possibility of electrical shorting of thermocouple lead wires not protected by alumina tubes was investigated in the test of specimen D, the temperature histories of which are shown in figure 5(d). Specimen D contained two each of thermocouple sensors 2 and 3 and was tested in an arc-jet stream of 95-percent nitrogen and 5-percent oxygen. The temperature histories obtained from sensors 2 and 3 show reasonable agreement, with the temperatures indicated by sensors 2 being somewhat higher than the temperatures indicated by sensors 3. Sensors 2 which had the lead wires along the sides of the 0.25-inch (0.64-cm) plug insulated with resin-glass did not appear to be affected by electrical shorting through the carbonaceous char layer.

Because of damage to thermocouple sensors prior to testing, a direct comparison of the temperature histories of sensors 1 and 2 and sensors 1 and 3 in the same specimen was not obtained. However, a comparison of the temperature histories of specimen D (fig. 5(d)) with the temperature history of sensor 1 in specimen B (fig. 5(b)) shows reasonable agreement. Specimens B and D were exposed to the same test conditions.

Data furnished by R. A. Cocozella of AVCO Corp. are given in figure 5(e) which show a comparison of the temperature histories obtained from thermocouple sensors 1 and 4 in a specimen tested in air at higher values of cold-wall heating rate and enthalpy than were used in tests of specimens A, B, C, and D. These data also indicate a large variation in the temperatures measured by thermocouple sensors 1 and 4.



(d) Specimen D.

(e) Specimen E.

Figure 5.- Concluded.

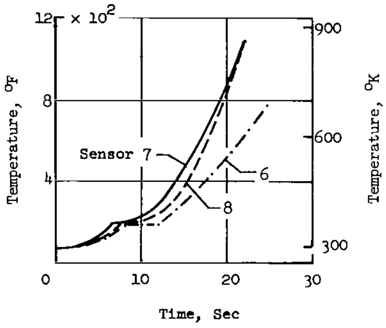
The test results shown in figure 5 indicate that the variations in temperatures measured by the plug type of sensors (1, 2, and 3) and sensors 4 and 5 reach maximum values and that the variations then decrease with continued heating. This effect is probably due to two causes: First, the thermal conductivity of the charring ablation material changes during thermal degradation. Pyrolysis of charring ablators produces a carbonaceous char layer which at elevated temperatures has larger values of thermal conductivity than the unpyrolyzed material. (See table I.) The effect of the increase in the thermal conductivity of the ablation material is to decrease the mismatch in thermal-conductivity values of the material whose temperature is being measured and the temperature sensor; second, the temperature-rise rate in the vicinity of the thermocouple-sensor hot junction decreases as the ablation material pyrolyzes and the char layer reaches highly elevated temperatures. Thus the temperatures indicated by the various thermocouple sensors tend to indicate the variations that would exist with a steady-state temperature gradient through the ablation material. The approach to a steady-state temperature gradient is demonstrated by thermocouple sensors 3 and 4 of specimen C (fig. 5(c)) which was tested in nitrogen. Removal of the char layer by oxidation is a further complication in that the highly heated surface is a moving boundary which approaches the thermocouple hot junction at a rate dependent on the oxygen content of the test stream. The effect of char removal is to increase the temperature-rise rate so that there is no approach to a steady-state temperature gradient. This type of behavior is demonstrated by specimen A (fig. 5(a)) which was tested in air. Chemical reactions between the thermocouple-sensor materials and the pyrolyzed charring ablation material are possible at elevated temperatures. These reactions, if present, could affect the homogeneity of the thermocouple wire and alter the temperature indications. However, in view of the short time period during which measurements were made, it does not appear that homogeneity effects would be significant.

Porous Ceramic Specimens

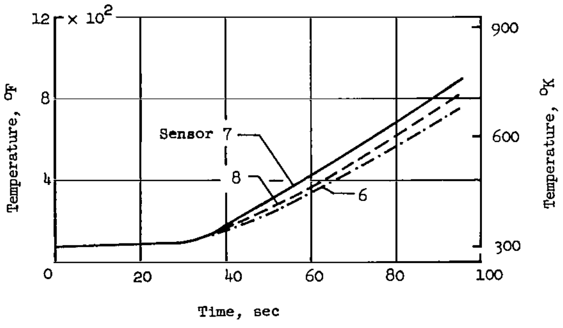
The results of the tests of the two porous ceramic specimens are shown as temperature histories in figure 6. Thermocouple sensor 6 was similar to sensor 5 in the charring ablator specimens. Sensor 7 resembled sensor 1 in the charring ablation specimens in that both thermocouple lead wires were extended side by side from the hot junction a distance of approximately 0.25 inch (0.64-cm) parallel to the circular face of the specimen and then extended out of the specimen normal to the circular face. Sensor 7 differed from sensor 1 in that sensor 7 was not constructed with a plug of the specimen material and the thermocouple lead wires were insulated with duplex resin-glass instead of alumina tubing. Sensor 8 resembled sensor 2 in the preparation and the positioning of the thermocouple hot junction and lead wires. Sensor 8 differed from sensor 2 in that sensor 8 was not constructed with a plug of the specimen material.

Figure 6(a) shows a comparison of the temperature histories obtained from thermocouple sensors 6, 7, and 8 in specimen F tested in an air arc-jet stream. The surface cylinder of specimen F was 3/16 inch (0.48 cm) thick. It is not known what caused the disturbance in the temperature histories at a temperature of approximately 200° F (367° K). The disturbance may have been caused by unevaporated water in the ceramic adhesive used to bond the thermocouple sensors into the base cylinder of the specimen. At temperatures above 200° F (367° K), thermocouple sensor 6 indicates temperatures which are lower than those indicated by sensors 7 and 8 which had lead wire in the isothermal plane of the hot junction in the same manner as for the tests of the charring-ablator specimens.

Figure 6(b) shows a comparison of the temperature histories obtained from thermocouple sensors 6, 7, and 8 in specimen G tested in an air arc-jet stream. The surface cylinder of specimen G was 1/2 inch (1.27 cm) thick and



(a) Specimen F.



(b) Specimen G.

Figure 6.- Response of various thermocouple sensor assemblies in porous ceramic.

therefore the temperature-rise rate at the location of the sensor hot junction was less than that for specimen F (fig. 6(a)). Figure 6(b) shows that at the lower temperature-rise rates thermocouple sensor 6 again indicated the lowest temperatures.

The measurement of internal temperatures in an ablation material subjected to severe heating is inherently difficult. In addition to the problems previously discussed, other potential difficulties are the obtaining and maintaining of good thermal contact between the material and the temperature sensor, material shrinkage and expansion during heating, and separation of the char layer from the unpyrolyzed material. Inherently, the most accurate measurements of internal temperature should be obtained with temperature sensors which produce a minimum disturbance in the measurement region. The temperature sensors which most nearly meet this requirement are those which have bare wire in the plane of the hot junction of sufficient length to minimize conduction errors. Examples of this type of temperature sensor are sensors 2, 3, and 8 of the present investigation. Also electrical shorting of the sensor by a conducting char layer is a potential source of measurement error. Therefore, the high-temperature electrical insulation provided by the alumina tubes of sensor 3 (fig. 1) would appear advisable.

CONCLUDING REMARKS

The internal temperatures measured by various thermocouple sensors in a charring ablator and in a porous ceramic exposed to severe heating are presented and discussed. The test results show that internal temperature measurement errors of several hundred degrees are possible unless heat conduction away from the hot junction of the sensor by the sensor materials themselves is minimized. Thermocouple sensors installed parallel to the direction of heat flow which have no sensor material in the isothermal plane of the hot junction permit the most heat conduction away from the hot junction. Therefore, it would appear that this type of thermocouple installation is inadequate for measuring internal temperatures in ablation materials or any material which has values of thermal conductivity significantly different from that of the thermocouple sensor material.

The test results also show that the various thermocouple sensors designed to minimize heat conduction from the hot junction do not indicate the same internal temperature at an isotherm in the test material. It is felt that a thermocouple sensor having a sufficient length of bare wire in the isothermal plane of the hot junction to minimize conduction errors will produce the minimum temperature disturbance in the measurement region and thus give the most nearly correct temperature measurements. The tests reported herein show that certain methods of installing temperature sensors can produce large measurement errors. However, the tests do not establish that any of the various temperature sensors indicate the correct internal temperature. Further investigation would be necessary to determine which of the various sensors indicates the most nearly correct temperature. Further investigation should also include the effect of thermocouple-wire size on internal-temperature-measurement errors.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 7, 1964.

APPENDIX

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in resolution 12 (ref. 3). Conversion factors required for units used herein are:

Physical quantity	U.S. customary unit	Conversion factor (*)	SI unit
Enthalpy	Btu/lb	2.32×10^3	Joules/kilogram (J/kg)
Heating rate	Btu/ft^2-sec	1.135×10^4	watts/meter^2 (W/m^2)
Length	in.	0.0254	meters (m)
Temperature	($^\circ$F + 460) $^\circ$R	5/9 5/9	degrees Kelvin ($^\circ$K) degrees Kelvin ($^\circ$K)
Thermal conductivity . . .	Btu/ft-sec-$^\circ$R	6.24×10^3	watts/meter-degree Kelvin (W/m-$^\circ$K)

*Multiply value given in U.S. customary unit by conversion factor to obtain equivalent value in SI unit.

Prefixes to indicate multiples of units are:

milli (m)	10^{-3}
centi (c)	10^{-2}
kilo (k)	10^3
mega (M)	10^6

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2. Beck, J. V.: Study of Thermal Discontinuities and Associated Temperature Disturbances in a Solid Subject to a Surface Heat Flux. Part III - Effect of Sensors in Low Conductivity Material Upon Temperature Distribution and Its Measurement. Tech. Rep. RAD-TR-9(7)-59-26 (Contract Nos. AF04(647)-305 and AF04(647)-258), AVCO Corp., Aug. 3, 1960.

3. Anon.: International System of Units, Resolution No. 12. NASA TT F-200, 1964.

4. Chapman, Andrew J.: An Experimental Evaluation of Three Types of Thermal Protection Materials at Moderate Heating Rates and High Total Heat Loads. NASA TN D-1814, 1963.

TABLE I.- MATERIAL PROPERTIES

Charring Ablator

Uncharred material.-

Specific gravity 0.92

Thermal conductivity, k	Btu/ft-sec-°R	W/m-°K
at 540° R (300° K)	2.5×10^{-5}	0.156

Charred material.-

Specific gravity 0.40

Thermal conductivity, k	Btu/ft-sec-°R	W/m-°K
at 1500° R (834° K)	2×10^{-5}	0.125
at 2500° R (1390° K)	1×10^{-4}	.624
at 4000° R (2222° K)	1×10^{-3}	6.24

Porous Ceramic

Specific gravity 0.72

Thermal conductivity, k	Btu/ft-sec-°R	W/m-°K
at 760° R (423° K)	1.7×10^{-5}	0.106
at 1260° R (700° K)	3	.187
at 1760° R (978° K)	3.5	.218
at 2260° R (1256° K)	4.9	.306

Thermocouple Materials

Thermal conductivity, k	Btu/ft-sec-°R	W/m-°K
for chromel-alumel	9.6×10^{-3}	59.86
for platinum	11.5	71.71
for alumina	3	18.71
for resin-impregnated glass cloth	.25	1.56

TABLE II.- SPECIMENS AND TEST CONDITIONS

Specimen	Instrumentation					Heating rate		Dimensionless enthalpy, $\bar{H}$
	Sensor assembly	x, in.	x, cm	Type of thermocouple wire	Test-stream composition	Btu/ft^2-sec	MW/m^2	
Charring ablation material								
A	1	[a]0.102	0.259	R	Air	160	1.82	88.5
	4	.104	.264	R				
	5	.101	.256	R				
B	1	0.103	0.262	R	5 percent O_2 95 percent N_2	160	1.82	88.5
	4	.104	.264	R				
	4	.104	.264	R				
	5	.103	.262	R				
	5	.103	.262					
C	1	0.102	0.259	R	100 percent N_2	160	1.82	88.5
	3	.104	.264	R				
	4	.104	.264	R				
D	2	0.103	0.262	R	5 percent O_2 95 percent N_2	160	1.82	88.5
	2	.103	.262	R				
	3	.103	.262	R				
	3	.103	.262	R				
[b]E	1	[c]0.250	0.635	S	Air	250	2.84	100
	4	.250	.635	S				
Porous ceramic material								
F	6	0.1875	0.476	K	Air	100	1.13	148
	7	.1875	.476	K				
	8	.1875	.476	K				
G	6	0.50	1.27	K	Air	100	1.13	148
	7	.50	1.27	K				
	8	.50	1.27	K				

[a] Depth accurate within ±0.002 in. (0.051 mm) for specimens A to D.
[b] Data from R. A. Cocozella of AVCO Corp.
[c] Depth accurate within ±0.004 in. (0.102 mm) for specimen E.

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