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Experimental Assessment of a Computer Program Used in Space Shuttle Orbiter Entry Heating Analyses

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SUMMARY

A high-temperature reusable surface insulation (HRSI) tile taken from the Space Shuttle orbiter was subjected to a nominal heating rate of 60 kW/m^2 in the laboratory. The surface-temperature response to this heating was measured and used as input to a computer program which computed the applied heating rate. The program is part of a software system that is used to infer convective heating rates to the orbiter thermal protection system during entry. During the test transient period, when heat was first applied to the tile, the computed heating rate was about 98 percent of the measured value. As the tile surface temperature approached a steady-state value, the computed heating rate decreased to about 92 percent of the measured value. The steady-state value could be brought into agreement with its transient-period value, however, by accounting for free-convection losses. The results of this investigation confirm the applicability of this program to the determination of flight heat-transfer rates from flight-measured surface-temperature data.

INTRODUCTION

The thermal protection system (TPS) of the Space Shuttle orbiter consists primarily of thermally insulative tiles which cover most of the orbiter windward surface and some of the leeward surface. Many of these tiles are instrumented to provide in-flight measurement of surface pressures and temperatures. Thermocouples provide time histories of tile surface temperatures throughout the entry trajectory. These temperature measurements are used after the flight to infer convective heating rates and thereby define the orbiter entry heating environment.

A computer program developed by Pittman and Brinkley (ref. 1) provides a one-dimensional analysis of the transient thermal response of multilayer insulative systems. Given the heating rate applied to a material surface, the program is used to compute the temperature distribution through the thickness of the material (materials). Bradley (ref. 2) modified the program to allow computation of the heating rate when the surface-temperature history was provided. In reference 2, this method was applied to the orbiter TPS, and an error analysis was carried out to determine the effect of uncertainties in the knowledge of material properties on the derived heating rate.

The modified version of the program, herein referred to as SINK, has been incorporated (ref. 3) in a software system being used to determine heating rates from orbiter in-flight temperature measurements. An experimental assessment of the applicability of the program to the flight data-reduction problem was desirable to provide a higher degree of confidence in the results derived from flight data. The purpose of this paper is to report the results of laboratory tests in which an orbiter TPS tile was subjected to a measured heating rate and in which the measured thermal response was used as input to the flight data analysis software (SINK). The measured and derived heating rates were then compared.

SYMBOLS

A area, m^2

$\bar{C}$ tile surface coating parameter, equal to $\rho c x$

c heat capacity, W-sec/kg-K

F fractional portion of total radiative energy that falls within wavelength band from 0 to λ

h heat-transfer coefficient (see eqs. (6))

k thermal conductivity, W/m-K

L characteristic length (see eqs. (6))

m mass, kg

P perimeter (see eq. 6(c))

$\dot{q}$ heating rate, W/m^2

$\dot{q}_f$ free-convection heating rate (see eqs. (6))

$\dot{q}_{SINK}$ heating rate computed by SINK program, W/m^2

$\dot{q}_{slug}$ heating rate absorbed by slug calorimeter, W/m^2

$\dot{q}_{tile}$ heating rate absorbed by tile, W/m^2

R ratio of computed to measured heating rate

T temperature, K

t time, sec

x thickness, m

α absorptivity

ε emissivity

λ wavelength, m

ρ density, kg/m^3

σ Stefan-Boltzmann constant

Subscripts:

c forced convection

R radiation

s slug calorimeter

T temperature that characterizes radiative energy distribution

t tile

λ wavelength dependent

TEST SPECIMEN

The test specimen used in this investigation was a tile taken from the lower surface of the orbiter Columbia before its first flight. This high-temperature reusable surface insulation (HRSI) tile (see fig. 1) is made of silica and has a nominal 0.389-mm-thick black waterproof coating. The dimensions of the surface exposed to the heating environment (front surface) are approximately 14 by 15 cm, and the total thickness of the tile is approximately 6.6 cm. A type-R thermocouple is embedded in the front surface and is covered by the black coating. Before the coating was applied, the 0.127-mm-diameter thermocouple wire was laid in a groove in the surface of the tile for a distance of about 1.5 cm on either side of the junction. This was done to reduce errors due to conduction along the wires. (A more detailed description of the surface thermocouple installation is contained in ref. 4.) For this experiment, a second thermocouple (type J) was attached to the silica at the tile back surface and covered with a 0.635-cm-thick piece of foamed polystyrene to protect it from changes in room temperature.

EXPERIMENTAL EQUIPMENT

The apparatus in which the tests were carried out was originally designed for the direct measurement of thermophysical properties of wind-tunnel, phase-change, heat-transfer models. The technique consisted of placing a model under a bank of high-intensity, radiant lamps so that fast-opening water-cooled shutters, which isolated the heater bank from the model, provided for the application of a step-input heating rate. The model and a calorimeter were colocated in the same plane so that the applied heating rate could be recorded. The original apparatus is described and discussed in reference 5. Some modifications were required for the experiment reported herein because of a requirement for longer test times and a different test-specimen configuration. The apparatus as used in the experiment is described in the following paragraphs.

Heat Source

Four tungsten-quartz lamps were used as the heat source. The bank of four lamps formed a rectangular source with dimensions of about 25 by 30 cm. (See fig. 2 for a sketch of a typical lamp cross section.) Each lamp contained six quartz-enclosed tungsten heating elements located between a water-cooled metal reflector and a glass window. A small constant airflow in the cavity between the reflector and window was used to keep the quartz envelopes of the heating elements from overheating. The radiant heat flux produced by the lamps was controlled by regulating the electrical current supplied to the heating elements. Extensive measurements reported in reference 6 indicate that the heating distribution under the lamps at the test plane could be approximately represented by a rather flat parabola. The heat flux at the perimeter of the test plane was about 12 percent less than at the center.

Calorimeters

Two calorimeters were used in this experiment, one to measure heating-rate level and the other to confirm that heating was steady state. The calorimeters are shown in figure 3.

Copper slug.- The heating rate at the test plane was measured with a slug-type calorimeter. The wafer-shaped slug was 3.81 cm in diameter and 0.64 cm thick. The side and back surfaces were covered with metalized plastic film to reduce radiant losses. A type-K thermocouple was peened into the back surface. The front surface was painted with a black paint which has diffuse emission characteristics (ref. 7).

Gardon foil.- A Gardon foil calorimeter was used to verify that the applied heating rate remained constant throughout the test. This calorimeter consisted of a 2.54-cm-diameter water-cooled housing and a 1.59-mm-diameter foil sensor mounted in the center of the flat surface that was painted black. The output signal in millivolts is a direct function of the heating rate. When exposed to a step input of heat flux, the response time from 0 to 95 percent of steady-state output signal was less than 2 seconds (including recorder response), but about 8 seconds were required to reach steady-state value.

Test Bed

The framework for positioning and holding the lamps, tile, and calorimeter during a test is shown schematically in figure 4. An aluminum frame held the lamp bank 14 cm above the rectangular test plane. Water-cooled copper plates shielded the two sidewalls that supported the lamps. The 2.54-cm-thick aluminum plate whose upper surface formed the test plane was water-cooled and had cutouts in which to locate and position the tile and calorimeter such that only their front surfaces were exposed to the heat flux. Two water-cooled shutters were mounted between the test plane and the lamps. The shutters were flat plates that completely covered the test plane, but were mechanically connected so they could be retracted simultaneously to expose the test plane to the heat flux. The shutters met with overlapping edges at the centerline of the test plane, and the air gap between the shutter lower surface and the test plane was 0.33 mm. The calorimeter center and the tile front-surface thermocouple were located at a radius of 3.81 cm from the center of the heating pattern, as shown in figure 5. Thus, these components were located in an area over which the heat flux varied by only about 1.5 percent.

Tile mounting.- The tile was supported by the tips of four screws located near the corners at the back surface. At the test plane, the tile surface was separated from the mounting plate by a 0.20-mm-wide air gap (fig. 6(a)), and at the back surface the gap was sealed with glass-fiber tape. The tile was modified during part of the investigation to improve the isolation of the thermocouple area. (See fig. 6(b).) The modification is discussed in a subsequent section of this paper.

Calorimeter mounting.- The slug calorimeter was mounted in a cavity which was closed at the back surface except for a small hole through which the thermocouple wires passed. The calorimeter was supported at the back surface by four special plastic-tipped screws which provided height adjustment and thermal isolation. An air gap that was about 0.25 mm wide separated the calorimeter edge from the surrounding mounting plate.

When the Gardon foil calorimeter replaced the slug calorimeter, its front surface was also located in the test plane, but thermal isolation was not important since the housing was water-cooled.

INSTRUMENTATION

A schematic of the instrumentation in relation to the rest of the apparatus is shown in figure 4. An electrical switch with an applied voltage was mounted such that shutter opening resulted in switch closure, thereby sending a signal to the data recorder to indicate the instant when heat was applied to the tile and calorimeter.

The data were recorded on two double-pen, strip-chart recorders that were operated at a chart speed of 1 cm/sec. When step input signals from the voltage source were applied to the recorders, the response time from zero to maximum signal was 0.25 second. Prerun calibrations established a pen deflection of 2.54 cm/mV input, and the deflections were linear throughout the measurement range from 0 to 10 mV.

The thermocouples attached to the tile and calorimeter utilized individual electronic 273 K (32°F) reference junctions. The Gardon foil calorimeter signals were sent directly to the recorder. All lead wires were twisted and shielded to prevent induced voltage signals from external sources. An induction-type ammeter was used to monitor the electrical current to the lamps to insure constant power input and repeatability of tests.

TEST PROCEDURE

The procedure used to perform the test was as follows. The shutters were closed, all cooling water and airflows were established, the recorders were turned on, the lamps were turned on, and the lamp current was adjusted to the desired value. After the lamp current had been established, about 3 minutes of lamp operation were required to obtain a constant heat flux. When the lamps had been in operation long enough to reach an equilibrium output, the shutters were opened. The lamps were not turned off until the shutters were closed, which occurred after a predetermined length of test time.

In addition to the usual test procedures, some other precautions were taken to assure reliable test results. For SINK, a known starting temperature distribution through the tile thickness is required. A constant temperature equal to room temperature satisfied this requirement and was assured when testing was limited to one run per day. The thermocouples on the calorimeter and on the front surface and back surface of the tile were compared with a mercury thermometer before each test and were found to agree within one degree. Since the SINK analysis is one-dimensional, steps were taken to avoid the possibility of radiant heat losses from the sides which would not be accounted for by the program. After a few tests, the tile was modified by cutting a narrow slot (0.889 mm wide) from the front surface down to about 75 percent of the tile thickness. (See fig. 6(b).) The slot was located 1.27 cm from the edge on all four sides. The slot effectively formed a high-temperature insulator around the perimeter of the main tile body. As a result, the radiant losses were minimized because of the small temperature difference across the slot. However, comparison of temperature data taken before and after the slot was cut indicated that losses from the sides of the unslotted tile were not significant.

TEST APPROACH

The level of heating for the test was selected based on several considerations. First, preflight analysis of orbiter descent (ref. 8) indicates that much of the fuselage lower surface will receive a heating rate in the range from 55 to 115 kW/m^2, although some areas will experience values that are much higher and some much lower. Second, the available test apparatus, with some modifications, could accommodate a heating level of about 60 kW/m^2. Third, preliminary tests indicated that this heating rate could produce a tile surface temperature high enough for radiation from the tile surface to be the dominant term in the surface energy balance equation. (Other terms in the equation are dominant when heat is first applied as the surface temperature rises from ambient conditions to a steady-state value.) The third consideration is commensurate with the expected conditions on the orbiter windward surface during the most critical phase of entry heating. Based on these considerations, a nominal heating rate of 60 kW/m^2 was selected for this experiment.

The length of time selected for the heating period was based on brief preliminary tests which gave the initial rise in tile-surface temperature. These results were extrapolated and input to SINK which predicted a tile back-surface temperature history. For the heating rate of interest, no appreciable temperature rise on the back surface was predicted for at least 5 minutes. Since the test configuration did not allow for easy modeling of losses through the back surface, a maximum of 5 minutes was selected for the test time.

The copper-slug calorimeter served as the standard for measuring the heating rate. The heating rate for the slug calorimeter was determined by the relation

$$\dot{q}_{slug} = \frac{mc}{A} \frac{\Delta T}{\Delta t} \tag{1}$$

where all quantities on the right-hand side could be accurately determined. The estimated accuracy of $\dot{q}_{slug}$ is ±2 percent based primarily on the determination of $\Delta T/\Delta t$. The slug calorimeter is inherently limited to short test times, because $\Delta T/\Delta t$ is not linear for more than 30 seconds at the required heating rate; therefore, it was necessary to use the Gardon foil calorimeter for the 5-minute tile tests. Prior to the tile test the relationship between $\dot{q}_{slug}$ and the output signal for the Gardon foil calorimeter was established by simultaneous exposure in several 30-second heating tests.

Original plans for the experiment were to paint both the calorimeter and the tile surfaces with the same paint, so that the absorptivities would be the same. This paint, which had previously been successfully tested to high temperatures on metals, failed to adhere to the tile surface when it was heated above 530 K. After considerable effort to alleviate the problem, this approach was abandoned, and the tile and calorimeter absorptivities were experimentally determined and subsequently taken into account. The relation between the slug-calorimeter heating rate $\dot{q}_{slug}$ and the tile heating rate $\dot{q}_{tile}$ is expressed by

$$\dot{q}_{tile} = \frac{\alpha_t}{\alpha_s} \dot{q}_{slug} \tag{2}$$

since $\dot{q}_{tile} = \alpha_t \dot{q}_i$ and $\dot{q}_{slug} = \alpha_s \dot{q}_i$, where $\dot{q}_i$ was the radiant heating rate incident to both the calorimeter and tile. For purposes of comparison with the SINK computed heating rate, $\dot{q}_{tile}$ was considered the measured heating rate.

The absorptivities in equation (2) are total hemispherical values. For opaque surfaces, the spectral hemispherical absorpivity $\alpha_\lambda(T)$ can usually be set equal to the spectral hemispherical emissivity $\varepsilon_\lambda(T)$. However, if the surface in question does not have graybody characteristics, or if the incident radiation does not have a spectral distribution that is proportional to a blackbody distribution at the same temperature as the surface, then the total quantities α and ε cannot in general be set equal. If spectral-emissivity data are available, the total absorptivity can be found from

$$\alpha = \int_0^1 \alpha_\lambda \, dF_{\lambda,T} = \int_0^1 \varepsilon_\lambda \, dF_{\lambda,T} \tag{3}$$

where F_λ is the fractional portion of the incident energy that is within the wavelength interval from 0 to λ. The subscript T is the source temperature indicative of the incident spectral distribution of radiation. In this case, the lamp is the source. In summary, the values of spectral emissivity can be used to determine the total absorptivity, but they must be weighted to that region of the spectrum where the incident energy is found.

The source temperature and its emissivity were needed to determine the spectral distribution of the incident energy. Unfortunately, radiation from the tungsten heating element had to pass through two quartz windows. One window was the element envelope and the other was the lamp housing window. These windows absorbed part of the energy radiated by the tungsten and reradiated it at longer wavelengths. Since spectral measurements of the total radiation with an infrared monochrometer were impractical, measurements of the window spectral transmission were made. As a result of these measurements, the assumption has been made that the quartz absorption would not significantly affect the weighting factor, since more than 90 percent of the tungsten radiation occurred at wavelengths less than 4.8 μm, where the quartz transmission was high. The tungsten element was then regarded as the only source. Its brightness temperature was measured with an optical pyrometer and was corrected to a true temperature of about 2000 K. The tungsten emissivity at this temperature was taken from reference 9.

The spectral emissivities or spectral absorptivities of the tile and calorimeter were needed in order to determine the total absorptivities for use in equation (3), and the tile total emissivity was needed for equation (4). The tile spectral emissivity was measured at temperatures of 800, 1100, and 1300 K by the radiometric method described in reference 10, and room-temperature values were determined by the reflectance method. The total (wavelength-integrated) values of the tile emissivity are presented in figure 7(a). The measurements were surface-normal values, whereas hemispherical values were required for computations. According to reference 11 the total hemispherical emissivity for a dielectric, such as the tile coating, is about 95 percent of the total normal value; therefore, this correction was made to the data. The derived values of tile absorptivity are shown in figure 7(b). The calorimeter spectral emissivity was measured at room temperature, since the calorimeter is never allowed to exceed a temperature of about 360 K. The value determined for the calorimeter total hemispherical absorptivity was 0.875.

ANALYTICAL TECHNIQUE

Reference 3 provides a detailed discussion of how the software system (SINK) is used to derive Shuttle orbiter inflight convective heating rates. Software-related data analysis techniques are also discussed in reference 3. A brief overview of the software analysis that is pertinent to the present test is presented in this section. The computer program was developed by Pittman and Brinkley (ref. 1) to provide a one-dimensional analysis of the transient thermal response of multilayer insulative systems and is applicable to a TPS tile such as described in this paper. Later modification by Bradley (ref. 2) allows determination of the heating rate when the temperature at the heated surface is specified. In this modified version, the following simple energy balance at the heated surface provides for determination of the applied heating rate:

$$\dot{q}_c + \alpha\dot{q}_R = -k\frac{\partial T}{\partial x} + \bar{C}\frac{\partial T}{\partial t} + \varepsilon\sigma T^4 \tag{4a}$$

Convective heating rate	Radiative heating rate	Conduction into tile body	Storage of heat in coating	Radiation from surface

Although aerodynamic heating of the Shuttle orbiter during entry is primarily convective, a radiative heating method was selected for this experiment for convenience and better control of the test environment. Consequently, $\dot{q}_c = 0$ for this experiment. Therefore,

$$\dot{q}_{SINK} = \alpha\dot{q}_R = -k\frac{\partial T}{\partial x} + \bar{C}\frac{\partial T}{\partial t} + \varepsilon\sigma T^4 \tag{4b}$$

The SINK thermal model treats the thin tile coating as a heat sink, since the thermal conductivity of the coating is large relative to the tile-body conductivity. In addition to storage in the coating, the model allows for heat transfer from the hot surface to the surroundings by radiation and into the tile body by conduction. For the conduction analysis, 40 computational points are distributed through the tile thickness. Thirty of these points are located within the first one-third of the thickness, or near the heated surface. The temperature- and pressure-dependent thermal properties used for the HRSI tile in these calculations were the same as those specified by the manufacturer and used in the flight analysis (ref. 3). Except for surface emissivity and absorptivity, tabulated values of the properties are contained in reference 2. Although the measured temperature data T were obtained in this experiment as analog signals, they were manually digitized at 1-second intervals before use as input to SINK. This is consistent with the rate at which digital data are recorded in flight.

RESULTS AND DISCUSSION

The results of a typical test are shown in figure 8. The curves indicate the tile front-surface and back-surface thermocouple response to a heating rate of 61.6 kW/m^2 as measured by the slug calorimeter. The temperature rise prior to shutter opening is due to heat transfer through the shutters during the lamp stabilization period. When the shutters were opened, the tile was exposed to a step-input heating rate that was constant throughout the 5-minute test period. The front-surface temperature exceeded 980 K about 1 minute after shutter opening, and it reached 1020 K during the remaining 4 minutes. The temperature was relatively constant over the last minute of exposure. The back-surface temperature increased by only 1 K during the full 8 minutes of lamp operation. (The back-surface temperature rise computed by SINK was less than 1 K.)

The measured heating rate absorbed by the tile (determined from eq. (2)) and the heating rate computed by the SINK program are shown in figure 9(a). The "preheating" prior to shutter opening is included in the computed results. The measured heating rate shows a step input, then a sharp decrease, and finally a gradual decrease to its steady-state value. The sharp decrease is attributed primarily to the decrease in the temperature-dependent absorptivity of the tile surface. The computed heating-rate plot has a similar profile, but the sudden decrease is more erratic, and there is a gradual rise to a steady-state value that is less than the measured value. A comparison of those data is made by expressing the heating rates as a ratio R, where

$$R = \frac{\dot{q}_{SINK}}{\dot{q}_{tile}} \tag{5a}$$

A plot of R is shown in figure 9(b), where initially the computed and measured heating rates are nearly equal ($R = 0.98$). This establishes the validity of the thermal properties used in SINK, since heat storage and conduction are the primary mechanisms of energy transfer before the surface temperature is high enough to cause significant reradiation. By the end of the test, however, the computed heating rate is about 8 percent less than the measured value ($R = 0.92$). Although measurement error could account for the difference between computed and measured values, the variation with time implies a temperature-dependent phenomenon.

Heat transfer by reradiation becomes increasingly important as the surface temperature rises and approaches its steady-state value. Since surface emissivity is temperature-dependent (fig. 7(a)), its role in the determination of R should be assessed. Figure 10 shows the computed heating rate and the portion of the computed heating rate that is accounted for by the surface reradiation ($\varepsilon\sigma T^4$ in eqs. (4)). Near the end of the test time, a steady-state condition is reached, where the surface temperature remains constant (fig. 8) and $\varepsilon\sigma T^4/\dot{q}_{SINK} \approx 0.9$. At this time, an approximation for R is

$$R = \frac{\dot{q}_{SINK}}{\dot{q}_{tile}} \approx \left(\frac{\varepsilon\sigma T^4}{\alpha}\right)_t \left(\frac{\alpha_s}{\dot{q}_{slug}}\right) \approx \left(\sigma T^4\right)_t \left(\frac{\alpha_s}{\dot{q}_{slug}}\right) \tag{5b}$$

Fortuitously, the values of ε and α for the tile are nearly equal (fig. 7) over the wavelength range of interest, so their values are not critical. This does not mean that other terms in equations (4) are not important. In this test, ε and α are unimportant only because they are expressed as a ratio and are nearly equal. It should be noted that ε is important for flight data reduction, since the heating is primarily by convection, and the results are not presented as a ratio of radiative terms as in this test.

Free convection is one form of tile heat loss not accounted for by SINK, because it is not pertinent to flight. However, free convection could be important for this test. It would also increase as the tile-surface temperature increases. To assess this contribution to the heat balance, a separate semiempirical relation was used (ref. 12). The relation is for a heated horizontal plate facing upward in air at atmospheric pressure and at sea level gravity. The relation from reference 12 is as follows:

$$\dot{q}_f = hA\ \Delta T \tag{6a}$$

where

$$h = 0.27\left(\frac{\Delta T}{L}\right)^{0.25} \tag{6b}$$

and ΔT is the temperature difference across the surface film that determines the heat-transfer or "film" coefficient h. The limits that must be satisfied before using the relation are $10 > L^3(\Delta T) > 0.10$, where L is a characteristic length of the plate. The particular characteristic length used was proposed by Goldstein et al. (ref. 13). It was later shown by Lloyd and Moran in reference 14 to correlate well for a number of shapes, namely

$$L = \frac{A}{P} \tag{6c}$$

where A is the plate surface area and P is the perimeter. (These relations and limits are shown as given in the references and require the following units: h in Btu/hr-ft^2-°R, A in ft^2, ΔT in °R, $\dot{q}$ in Btu/hr-ft^2, and P and L in ft.) The ΔT required to produce a free-convection heat loss that would account for the difference in R at the end and beginning of the test is 250 K. That is, when $\Delta T = 250$ K ($h = 3.71$ W/m^2-K), $\dot{q} = 3.03$ kW/m^2, so that R was 0.98 at the end of the test, as it was at the beginning, when the tile-surface temperature was low. The value of ΔT of 250 K seems reasonable, but an actual measurement was not available. Changing ΔT by ± 100 K results in a ± 3-percent change in R. Thus, for this experiment, agreement between computed and measured heating rate is good for the steady-state situation, as well as for the initial transient period, if the free-convection component is included.

The erratic nature in which the computed heating rate is shown to change in figure 9(a) or in figure 10 should be briefly discussed. Figure 11 presents the measured surface-temperature data digitized from the strip-chart records and used as input to SINK for the first 33 seconds of heating. Although the input temperature data appear smooth in figure 11, the inset on that figure shows that $\Delta T/\Delta t$ is not monotonic, and this results in fluctuations in the computed heating rate. Obviously, the temperature data could have been fit to a smooth curve to eliminate this problem, but it was considered instructive to present results as shown. The orbiter flight-temperature data are smoothed before use in SINK (ref. 3).

CONCLUDING REMARKS

A computer program, referred to in this paper as SINK, is used to compute the heating rate of various instrumented thermal protection system (TPS) tiles on the Space Shuttle orbiter during flight. The program requires only the material thermal properties and heated-surface temperature and time histories to compute the heating rate throughout the entry period. In the experiment reported herein, a high-temperature reusable surface insulation (HRSI) tile used for reentry thermal protection on the Space Shuttle orbiter was subjected to a heating rate of about 60 kW/m^2 in the laboratory. The surface thermocouple response to this heating rate was recorded and used as input to SINK. The computed heating rate was then compared with the measured value. A radiative source was used to apply the heat in this test.

During the transient phase of the tile-surface temperature, when heat was first applied, the computed heating rate was within about 2 percent of the measured value. However, as the surface temperature increased to its steady-state value, the computed heating rate deviated from the measured heating rate by about 8 percent (lower). This suggested a temperature-related phenomenon apart from measurement error and inaccuracies in materials property values. The program does not account for losses due to free convection, since they are not pertinent to the flight situation. It is pertinent, however, to the laboratory environment. The decrease in computed heating rate relative to the measured value during the steady-state period of the test could be accounted for by free-convection losses. These losses were determined by a separate calculation which required estimation of the air temperature rise near the heated surface. When free convection is not important, the program should accurately compute the heating rate for the steady-state thermocouple response as well as the transient response.

For this experiment, the tile-surface emissivity and absorptivity were not important to the comparison of measured and computed heating rates. This was because a ratio was used to make the comparison, and the emissivity and absorptivity were nearly equal. When a tile steady-state surface temperature of about 1000 K was reached, approximately 90 percent of the computed heating rate was accounted for by reradiation from the surface. Unlike the laboratory test, flight heating is caused by forced convection, and heat loss is primarily by radiation. Therefore, the emissivity is important.

Smoothing of the input temperature data was found to be important in order to avoid fluctuations in the computed heating rate. Flight data are smoothed before use in the program.

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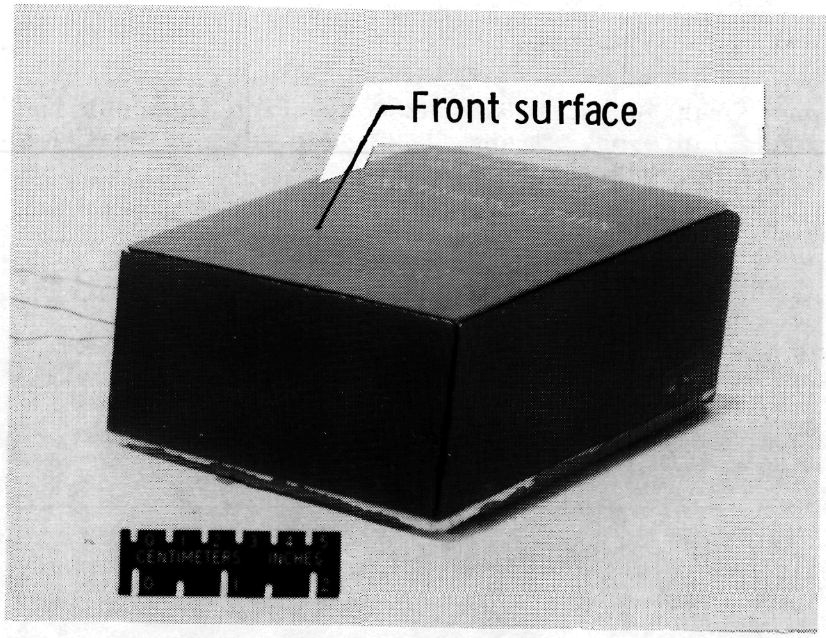
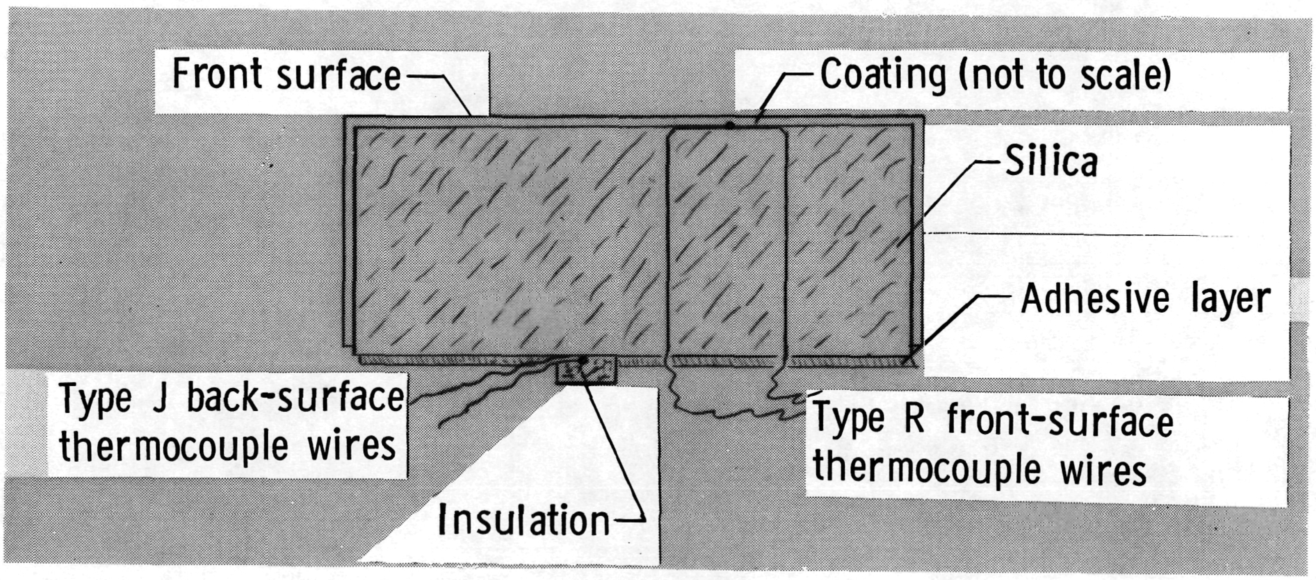


L-82-212

(a) Photograph.



(b) Cross-section sketch.

Figure 1.- High-temperature reusable surface insulation (HRSI) tile used for test.

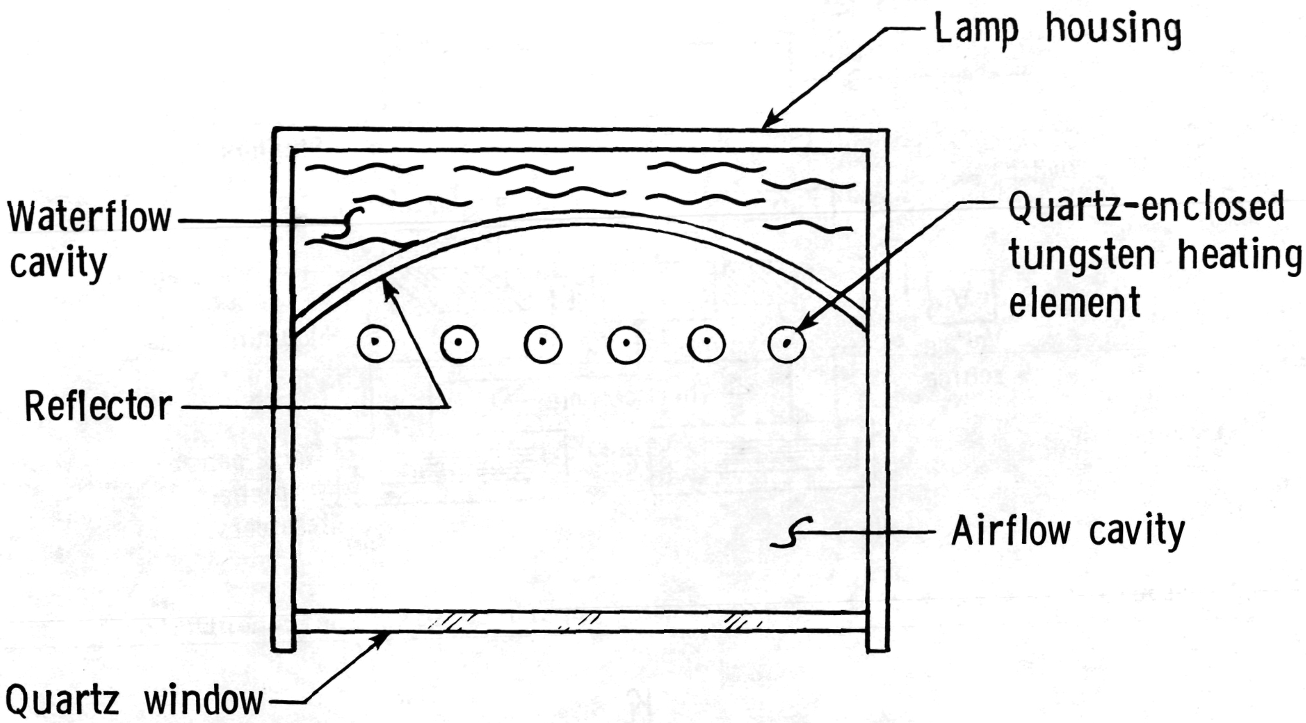
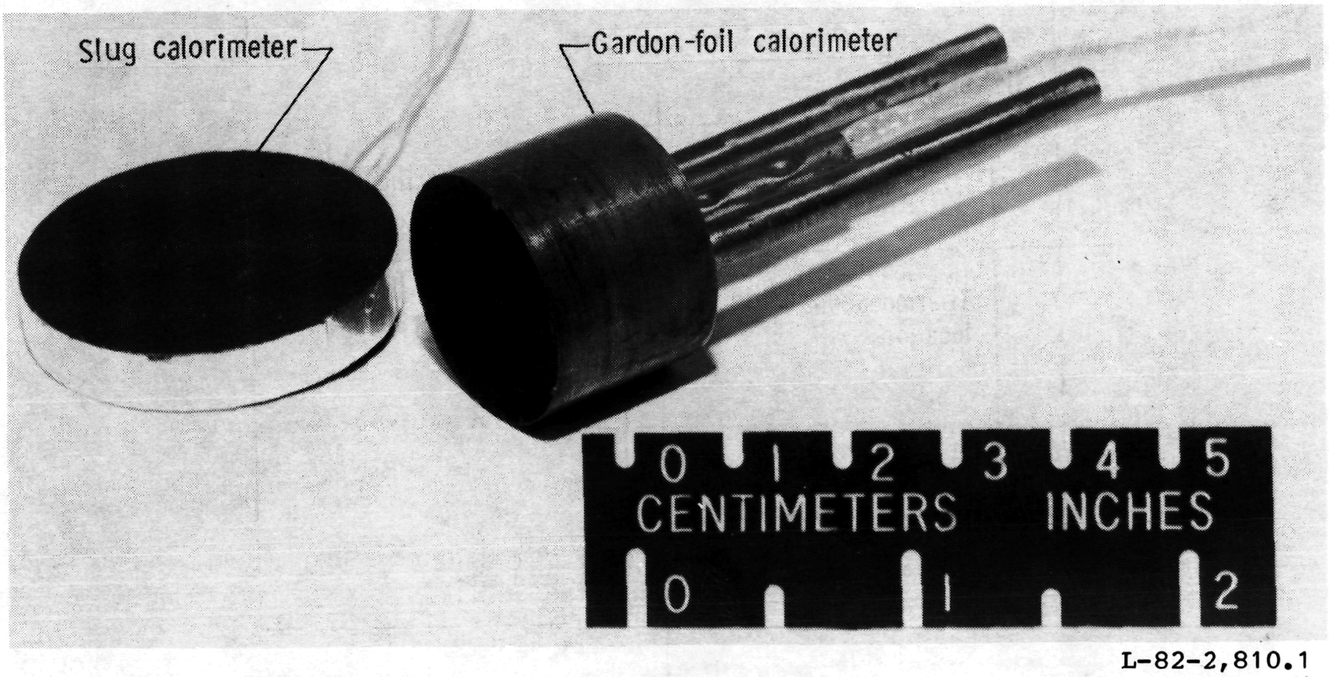


Figure 2.- Sketch of typical lamp cross section.



L-82-2,810.1

Figure 3.- Calorimeters used to measure heating rate.

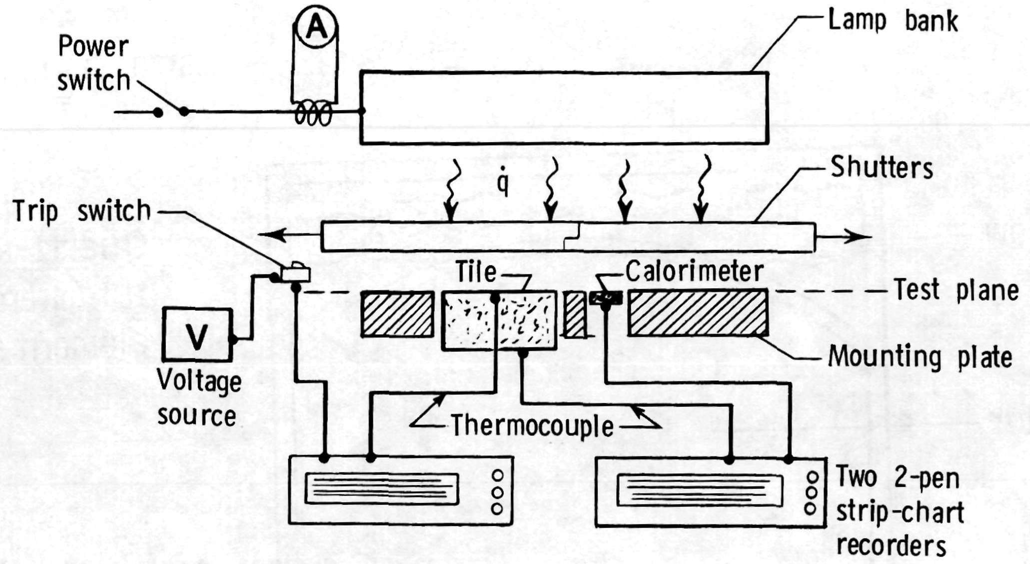


Figure 4.- Arrangement of experiment apparatus with instrumentation.

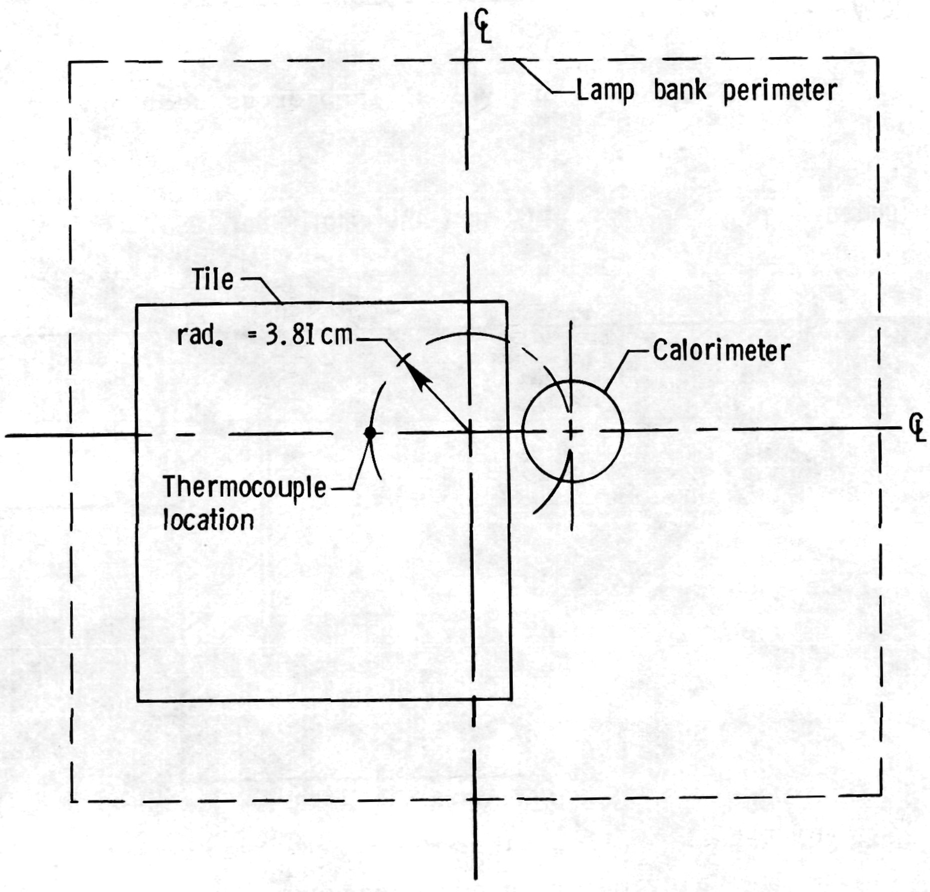
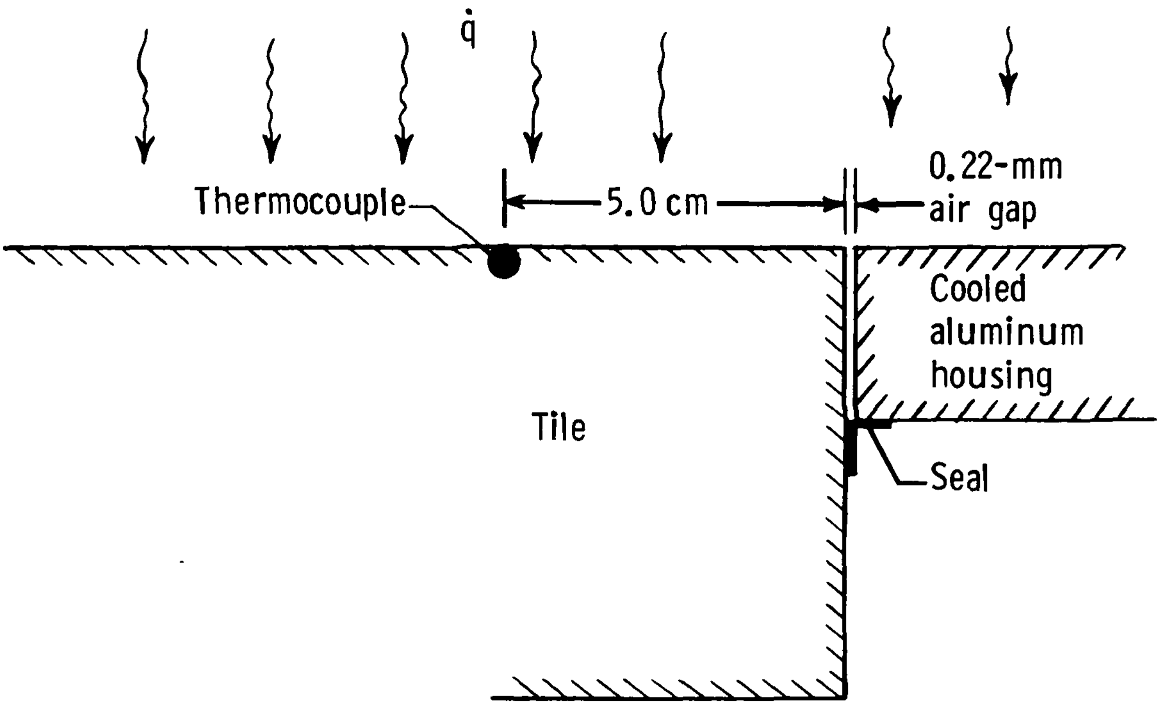
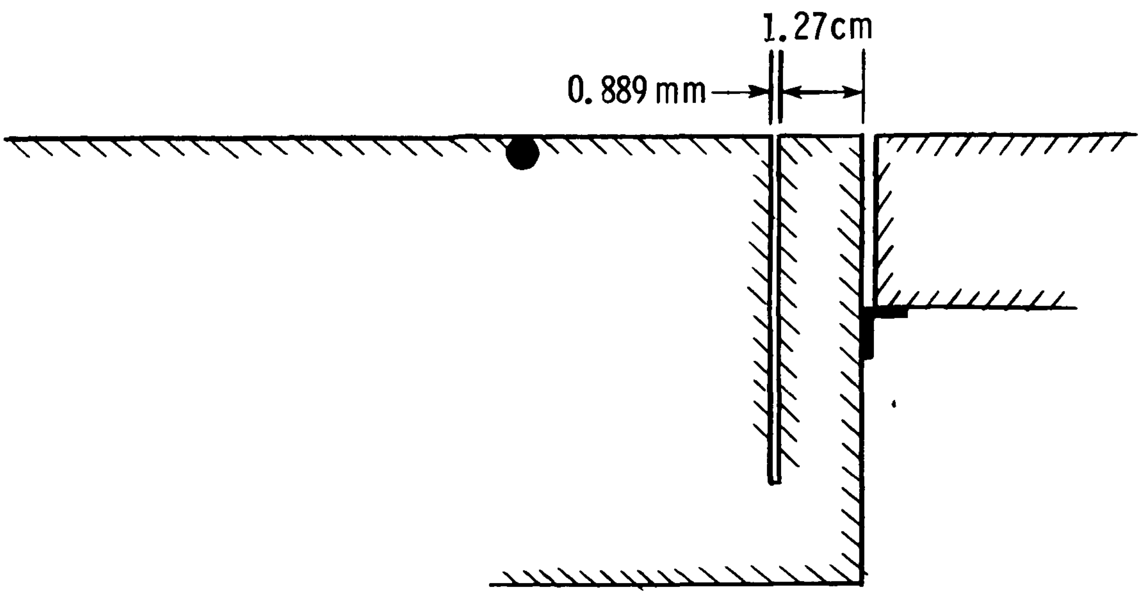


Figure 5.- Location of tile and calorimeter within heating boundary.

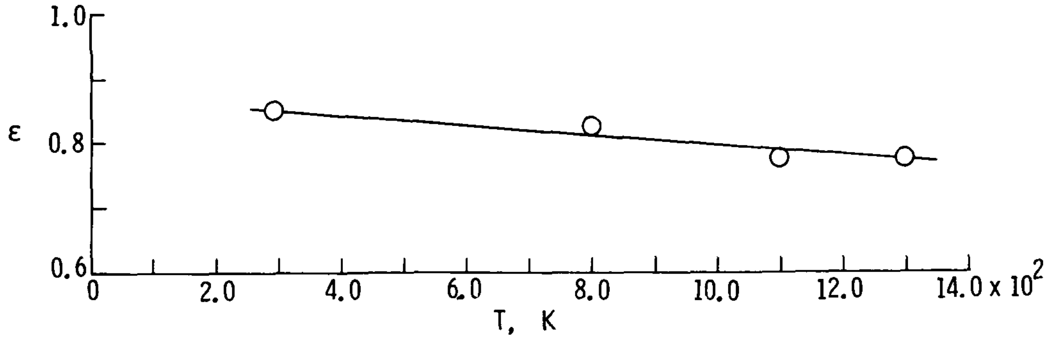


(a) Detail of air gap and seal.

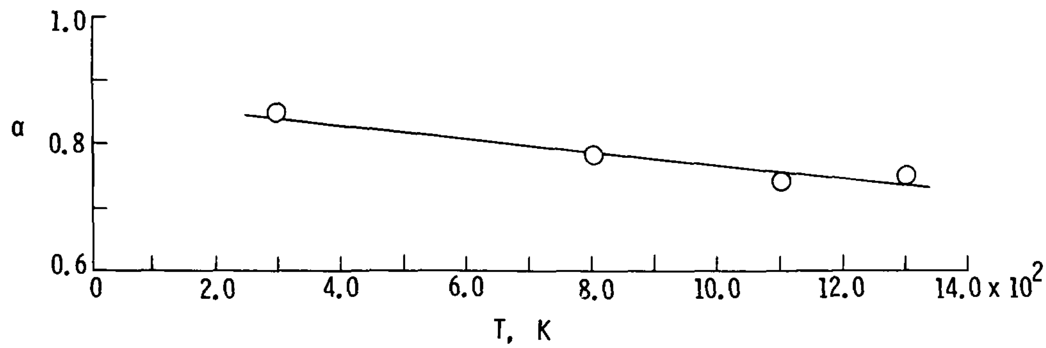


(b) Detail of slot cut in tile near perimeter.

Figure 6.- Tile isolation.



(a) Emissivity.



(b) Absorptivity weighted to lamp spectrum.

Figure 7.- Total radiative properties of tile coating.

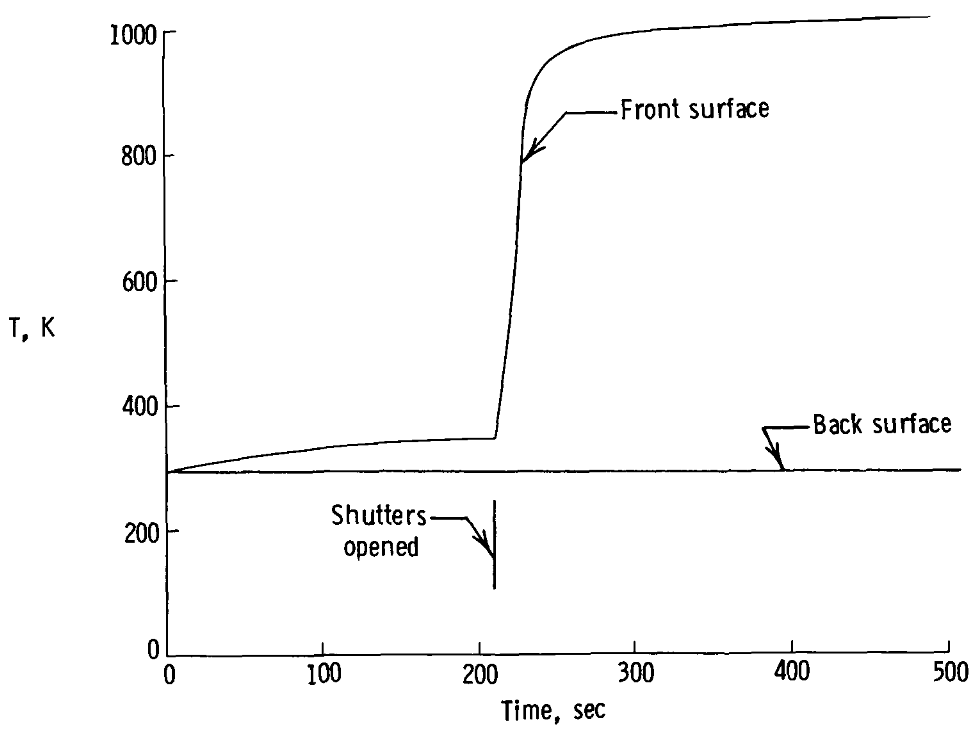
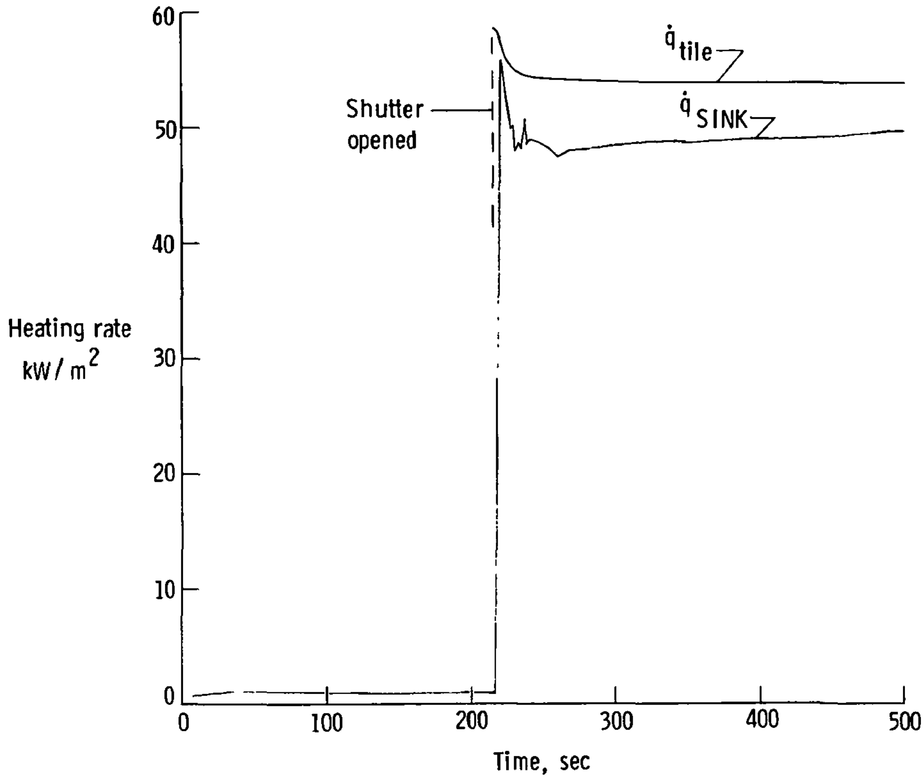
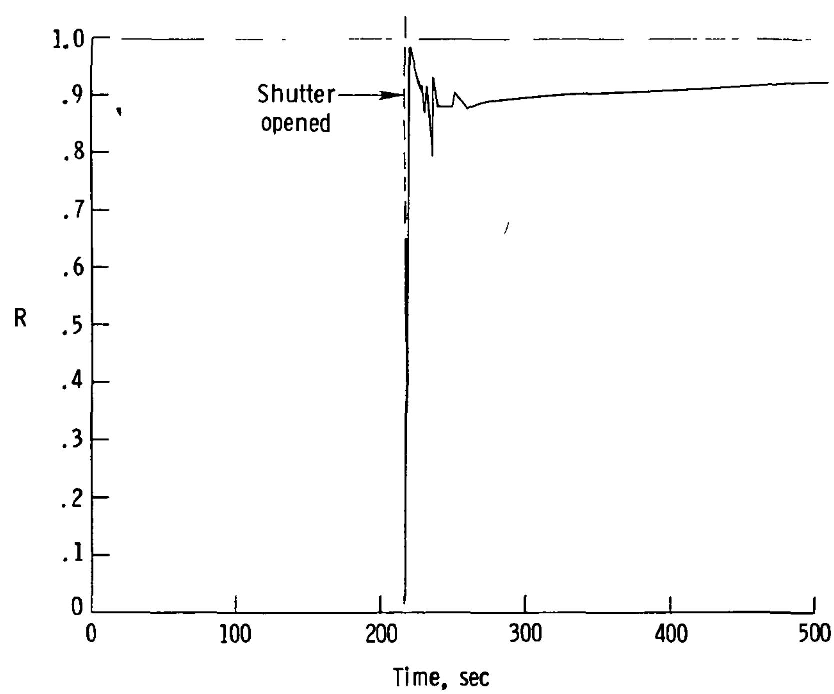


Figure 8.- Measured temperature and time histories of tile front and back surfaces during test.



(a) Separate plot of each heating rate.



(b) Ratio of computed to measured heating rates.

Figure 9.- Computed and measured heating rates into tile.

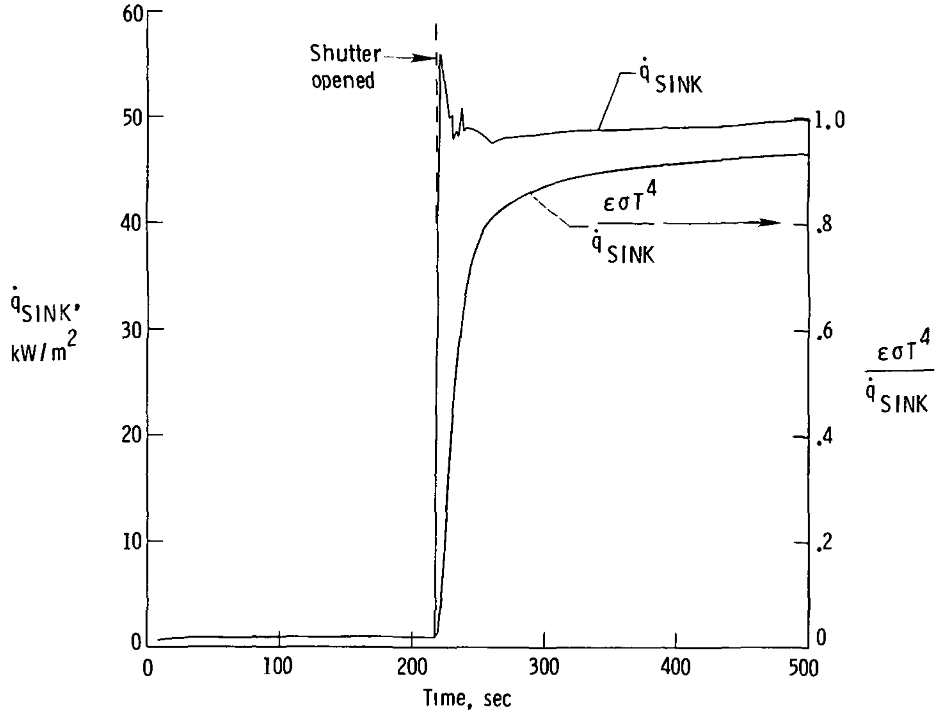


Figure 10.- Computed heating rate and percent of computed heating rate reradiated from tile surface.

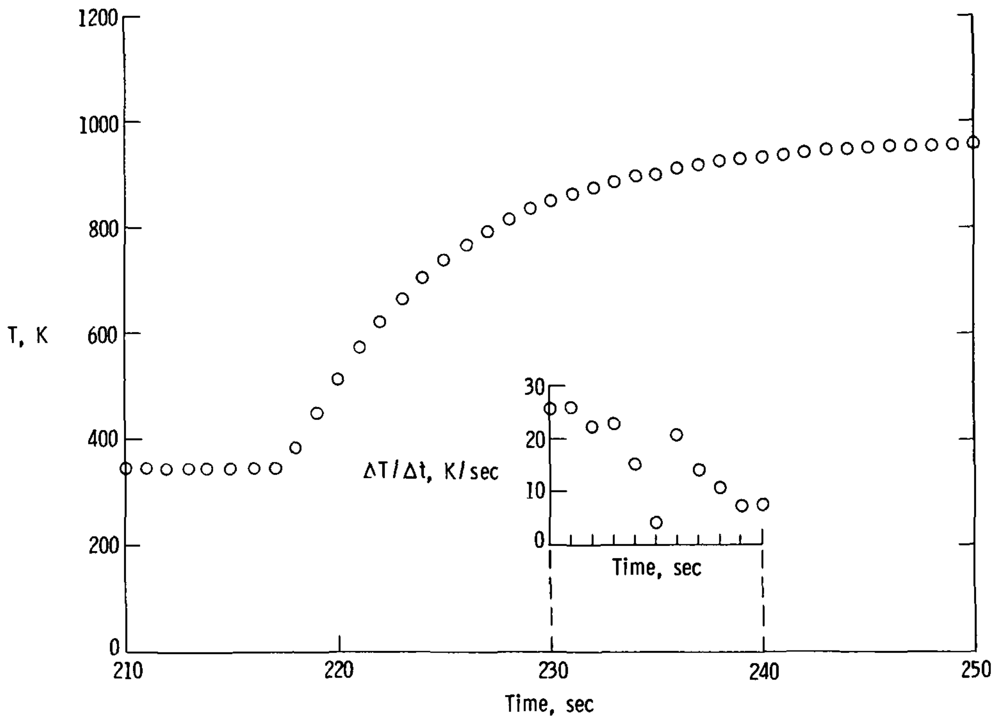


Figure 11.- Digitized temperature data used as input to computer program SINK for initial heating period. Inset shows rate of change of temperature for one 10-second interval.

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15 Supplementary Notes

16 Abstract

A high-temperature reusable surface insulation (HRSI) tile taken from the Space Shuttle orbiter was subjected to a nominal heating rate of 60 kW/m^2 in the laboratory. The surface-temperature response to this heating was measured and used as input to a computer program which computed the applied heating rate. The program is part of a software system that is used to infer convective heating rates to the orbiter thermal protection system during entry. The measured and computed heating rates are compared. The results of this investigation confirm the applicability of this program to the determination of flight heat-transfer rates from flight-measured surface-temperature data.

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