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EXPLORATORY ENVIRONMENTAL TESTS OF SEVERAL HEAT SHIELDS

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SUMMARY

Exploratory tests have been conducted with several conceptual radiative heat shields of composite construction. Measured transient temperature distributions were obtained for a graphite heat shield without insulation and with three types of insulating materials, and for a metal multipost heat shield, at surface temperatures of approximately 2,000°F and 1,450°F, respectively, by use of a radiant-heat facility. The graphite configurations suffered loss of surface material under repeated irradiation. Temperature distribution calculated for the metal heat shield by a numerical procedure was in good agreement with measured data.

Environmental survival tests of the graphite heat shield without insulation, an insulated multipost heat shield, and a stainless-steel-tile heat shield were made at temperatures of 2,000°F and dynamic pressures of approximately 6,000 lb/sq ft, provided by an ethylene-heated jet operating at a Mach number of 2.0 and sea-level conditions. The graphite heat shield survived the simulated aerodynamic heating and pressure loading. A problem area exists in the design and materials for heat-resistant fasteners between the graphite shield and the base structure. The insulated multipost heat shield was found to be superior to the stainless-steel-tile heat shield in retarding heat flow. Overlapped face-plate joints and surface smoothness of the insulated multipost heat shield were not adversely affected by the test environment.

The graphite heat shield without insulation survived tests made in the acoustic environment of a large air jet. This acoustic environment is random in frequency and has an overall noise level of 160 decibels.

INTRODUCTION

Some basic approaches to the design of heat-resistant structures for application to high-speed vehicles subject to aerodynamic heating are unprotected structures made of high-temperature materials which are capable of radiating part of the heat input, protected structures employing transpiration cooling or an external layer of ablative material which absorbs heat as it is consumed, heat sink depending on mass...
of material to provide adequate heat capacity, and insulated structures in which the load-carrying members are kept cool by insulation held in place by an outer radiative heat shield. These design approaches are discussed more fully in reference 1. The insulated-structure approach is investigated in references 2 and 3.

The present paper presents data obtained from exploratory tests of several conceptual radiative heat shields in the category of the insulated-structure approach. Radiative heat shields of three types of construction are considered. The outer surface of these heat shields dissipates part of the heat input. The remainder of heat flowing through the heat shield may be partially blocked by bulk insulation and reflective foils. Small conduction areas in the heat-shield supporting material and fastening devices assist in retarding heat flow. These methods of retarding heat flow have been incorporated in the heat shields considered. Provisions have been made to permit relative expansion of the heat shields and underlying primary structure by use of oversize holes. The heat-shield constructional concepts investigated are a graphite heat shield in thin-flat-plate form, attached with ceramic fasteners to a metal base plate representing the primary structure; a metallic sandwich-type heat shield employing multipost construction; and thin-gage metal tiles attached to the primary structure with rigidly fastened flexible strip supports.

Unconventional structural configurations and material applications in these heat-shield assemblies have prompted exploratory investigation. A radiant-heat facility at the Langley Research Center was used to obtain temperature distributions for a graphite heat shield without insulation and with three types of insulating material, and for a metallic sandwich-type heat shield of multipost construction, at surface temperatures of approximately 2,000°F and 1,450°F, respectively. Simulated environmental survival tests of a graphite heat shield without insulation, an insulated multipost heat shield, and a metal-tile heat shield were made, at approximately 2,000°F, in the ethylene-heated high-temperature jet located at the NASA Wallops Station. The tests were conducted at a Mach number of 2.0 and a stagnation temperature of 3,000°F. Exploratory acoustic tests of a basic graphite heat shield were conducted in an acoustic environment of a large air jet at the Langley Research Center. This acoustic environment is random in frequency and has an overall noise level of 160 decibels.

DESCRIPTION OF TEST PANELS

Graphite Heat Shield

The basic graphite heat shield is machined from grade AGR graphite into thin-flat-plate form 6- by 6-inches square. Figures 1(a) and 1(b)
are dimensional sketches of the basic graphite heat shield. Integral bosses are provided at each corner and at the center to serve as supports. The boss-type supports provide space for insulation between the flat surface of the graphite and a 1/8-inch-thick base plate of SAE 1020 steel representing the primary structure. The thin-flat-plate heat shield is attached to the base plate at the corners of the 6- by 6-inch square through oversize holes in the boss-type supports. Allowance for thermal expansion is made by use of the oversize holes. The flat-plate portion of the configuration is 0.20 inch thick for all panels fabricated except one. For this one the flat-plate portion is made of 0.30-inch-thick graphite to provide a survival test panel in the event of strength failure of the thinner test panel. Grade AGX graphite was used for this panel because grade AGR was not available. All graphite surfaces have a smooth machine finish. Molded zirconium dioxide fasteners were used to minimize heat flow to the base plate and to obtain large contact area with the brittle graphite. Conventional steel bolts were used with the zirconium dioxide fasteners as illustrated in figure 1(b). The heat shield of 0.20-inch-thick graphite weighs 2.34 lb/sq ft, not including the base plate. Oxidation-resistant surface coatings were not employed on any test panels. Typical thermocouple locations are shown in figure 1(c).

In addition to the basic graphite panel, three modified heat-shield configurations were obtained by installing various insulating materials in the air chamber of the basic graphite heat shield. Graphite test panels which have insulation in the space provided by boss-type supports also have insulation installed between the supports and the base plate. Insulation between the supports and the base plates consists of two 0.04-inch-thick layers of a fibrous ceramic material compressed to a total thickness of 0.04 of an inch. The three modified heat-shield configurations are as follows:

**Bulk insulation.** - A fibrous ceramic material was used for the bulk insulation. The approximate density of the insulation is 12.0 lb/cu ft; total weight of the assembly is 2.81 lb/sq ft, not including the base plate. Figure 1(c) is a sketch of the basic graphite heat shield with bulk insulation.

**Radiation shields.** - The radiation shield consists of two 0.001-inch-thick gold sheets formed into 3/32-inch-high corrugated sheets placed in the air chamber with corrugations horizontal and mutually perpendicular. The total weight of the assembly is 2.65 lb/sq ft, not including the base plate. Figure 1(d) is a sketch of the basic graphite heat shield with radiation shields.

**Composite blanket.** - The composite blanket consists of one 0.001-inch-thick sheet of gold sandwiched between two 1/32-inch-thick layers of fibrous glass compressed in felt form. The total weight of the assembly
is 2.47 lb/sq ft, not including the base plate. Figure 1(e) is a sketch of the basic graphite heat shield with the composite-blanket insulation.

Multipost Heat Shield

Figure 2 is a schematic representation of the multipost heat shield. The heat shield consists of a face plate and supporting posts in a 1/4- by 1/4-inch-square array. The heat shield is mounted on a sandwich-type structure, which represents the basic structure and is made of two face plates with a corrugated sheet as core material. The entire assembly is made of AISI stainless steels and is resistance welded.

All face plates and the corrugated sheet are made of 347 stainless steel and are 0.011 inch thick. The posts are made of 310 stainless-steel wire and are 0.035 inch in diameter. Nominal size of the test panel is 3/4 by 6 by 6 inches. The multipost heat shield, consisting of posts and a face plate supported by them weighs 0.7 lb/sq ft.

Surface roughness of the face plate of the heat shield, due to resistance welding, is 0.031 inch as indicated by the difference in highest and lowest points on the surface. Thermocouple locations are shown in figure 3.

Insulated Multipost Heat Shield

A photograph, dimensional cross section, and thermocouple locations of the insulated multipost heat shield are shown in figure 4. The heat shield consists of four 6- by 6-inch panels of multipost construction, fasteners for attachment to the basic structure, and insulating material. The fasteners are welded to the multipost panels and extend through oversize holes in the basic structure which is represented by the sandwich-type panel of corrugated construction. Five fasteners per 6- by 6-inch panel are used, one at each corner and one in the center. Conventional steel nuts hold the heat shield in place. Adjacent edges of the face plates of the multipost heat shield are overlapped to allow for thermal expansion.

The face plates of the insulated multipost construction are 0.0075-inch-thick 302 stainless steel. The posts are 0.035 inch in diameter and are made of 310 stainless steel. The corrugated panel is made of 0.011-inch-thick 347 stainless steel as shown in figure 4, and the fasteners are made of the same material. Insulation between the multipost heat shield and the corrugated panel is 1/4 inch thick, 12- by 12-inch Min-K 1301. The insulated multipost heat shield weighs 1.4 lb/sq ft, excluding the basic structure. Surface roughness after
fabrication as indicated by the maximum difference in high and low points on the surface was 0.028 inch.

**Stainless-Steel-Tile Heat Shield**

A dimensional cross section and thermocouple locations of the stainless-steel-tile heat shield are shown in figure 5. More details of the heat shield are shown in a subsequent photograph. The heat shield consists of 0.015-inch-thick, 2- by 2-inch tiles of 321 stainless steel and 0.020-inch-thick, 3/8-inch-wide support strips of the same material. Ceramic-fiber insulation in felt form, 1/16 inch thick, prevents contact of the tiles with the support strips and contact of the support strips with the base plate. Steel rivets are used throughout for fastening. The heat shield, excluding the base plate, weighs 1.3 lb/sq ft.

**DESCRIPTION OF TESTS**

**Radiant-Heater Tests**

A radiant-heat facility at the Langley Research Center was employed to obtain measured temperature distributions of the graphite heat shields and the multipost heat shield. This facility consists of two bus bars with a single bank of 3/8-inch-diameter quartz lamps supported between them by lead wires. The bus bars are slotted for 3/4-inch uniform spacing of the lamps. Figure 6 is a schematic sketch of a test setup indicating the arrangement of lamps and bus bars. The test facility has provisions for programming the specimen temperature as a function of time. More detailed information on quartz-lamp radiant heaters may be found in reference 4.

**Graphite heat shield.**- Measured temperature-time histories were obtained for four graphite heat-shield assemblies previously described as basic graphite heat shield, graphite heat shield with bulk insulation, graphite heat shield with radiation shield, and graphite heat shield with composite blanket. The four assemblies were individually mounted in support frames and irradiated simultaneously. The panels were located 2 inches from the face of the lamps and each exposed surface was parallel to the bank of lamps in order to obtain equal incident radiant heat flow for all panels. A control thermocouple was installed in the basic graphite panel (without insulation) for programming temperature-time histories. The temperature rise was programmed for a rate of 40°F/sec, at the control thermocouple location, from room temperature to levels of 600°F, 1,200°F, and 1,800°F. At levels of 600°F, 1,200°F, and 1,800°F the temperatures of the irradiated face plate were held approximately constant until the temperature
of the base plate reached a near equilibrium condition. Irradiation of the panels under the same plan was repeated for a temperature rise at the rate of 80°F/sec, making a total of six exposures for each panel.

Chromel-alumel thermocouples were used. The bimetallic thermocouple wires were formed into weldment beads and lightly pressed into holes drilled in the graphite. Thermocouples numbers 1 and 2 for all panels were installed at a depth of 0.05 inch from the irradiated surface and the back surface, respectively. Thermocouple number 3 was resistance welded to the interior surface of the steel base plate. Thermocouple number 4 was resistance welded to the exterior surface of the base plate, in the area below a boss-type support.

Multipost heat shield. - The face plate supported by multipost construction was exposed to radiant heat flux corresponding to surface temperature rises of 20°F/sec for one test and 170°F/sec for a second test. The edges of the multipost heat-shield assembly were covered with U-channels to support the heat shield and prevent outside air from flowing through the assembly during tests. Chromel-alumel thermocouples were installed by resistance welding. The thermocouples were located near the center of area of the 6- by 6-inch panel to minimize edge effects. Five thermocouples were used to measure the temperature distribution and for convenience were numbered 1, 5, 11, 20, and 25 as shown in figure 3. The thermocouples are referred to in this paper in regard to a numerical method for calculating temperature distribution. A control thermocouple was located near thermocouple number 1 on the back surface of the irradiated face plate for programming the temperature-time history of the face plate.

Survival Tests

Survival tests were made in the ethylene-heated high-temperature jet located at the NASA Wallops Station. This facility is a blowdown-type jet with characteristic running conditions of a Mach number of 2.0, a dynamic pressure of 6,000 lb/sq ft, and a stagnation temperature of 3,000°F. Jet stream temperature may be varied up to 3,300°F by controlling the quantity of ethylene fuel introduced in the jet stream. Motion pictures at 3,000 frames per second were taken during each test. A detailed description of this facility is contained in reference 5.

Basic graphite heat shield. - Survival tests were made for the basic graphite panel without insulation. Panels were mounted flush with the surface of a wedge-shaped support stand.
Figure 7 shows the setup of a typical ethylene-jet survival test. A thermal expansion gap of 0.03 inch was provided between the edges of the graphite panel and the support stand. Instrumentation consisted of two thermocouples in proximity installed in the thin flat-plate portion of the basic graphite panel, 0.05 inch below the graphite surface. The survival tests are summarized in Table I.

**Insulated multipost heat shield.** The insulated multipost heat shield was mounted for a survival test in the same manner as that shown in Figure 7. The support stand and test assembly were fixed at an angle of attack of 30°, leading edge down, with respect to the jet center line. Temperature distribution through the overall thickness of the assembly was measured by chromel-alumel thermocouples, resistance welded to the face plates. The ethylene-jet test conditions for a duration of 45 seconds are given in Table I.

**Stainless-steel-tile heat shield.** The stainless-steel-tile heat shield was mounted in a wedge-shaped support stand and held in place by retaining flanges fastened to the support stand. The support stand and assembled tile surface were inclined at an angle of attack of 50° for this test. Temperature distribution through the overall thickness of the test panel was measured by chromel-alumel thermocouples resistance welded to the test panel at three locations. Ethylene-jet test conditions during the test run of 40 seconds are given in Table I.

### Acoustic Test

A large air jet at the Langley Research Center was employed as a noise generator to conduct acoustic tests of the basic graphite heat shield without insulation. The jet exit is circular in cross section and has a 12-inch diameter. The test area is located just downstream of the jet exit and around the periphery of the jet exhaust. Noise levels of approximately 160 decibels are generated in this area. More information on this facility is given in Reference 6.

Exposure of a basic graphite panel, with 0.20-inch-thick flat-plate section, to an intense acoustic environment was made at two positions in the vicinity of the jet exit as is shown in Figure 8. Tests were made consecutively at positions A and B. The graphite panel was rigidly attached to an aluminum plate and mounted on supporting structural framework near the jet exit. Air impingement was not experienced by the panel since in each test position the panel was mounted outside the jet stream approximately parallel to the stream divergent boundaries. A diaphragm crystal-type microphone was used for measuring the noise environments at the two test-panel positions prior to the tests. The measured signals
were fed into a sound-level meter and octave-band analyzer to obtain the noise spectrum at each panel position. Noise spectra are presented in figure 9.

RESULTS AND DISCUSSION

Radiant-Heater Tests

Graphite heat shields.- Measured temperature-time histories of the four graphite heat-shield configurations tested at a rate of temperature rise of approximately 40° F/sec to a maximum face-plate temperature of 1,800° F are shown in figures 10 to 13. The figures give data only for the first 2 minutes of test time. Measured data for all tests are tabulated in tables II and III.

Comparison of figures 10 to 13 shows that the insulating materials were nearly equally effective in producing significant reductions in temperatures through the shields. The rate of temperature rise indicated by thermocouple number 1 on each of the four panels tested is approximately the same, and, the maximum temperatures of the exposed graphite plates are within 200° F. As indicated by thermocouple number 3 on each of the modified panels, very little difference is noted in the insulating value of the modified panels.

Photographs of the four graphite heat-shield configurations after each had six exposures to radiant heat flow are shown in figures 14 to 17. Total exposure time for six exposures of each heat shield was 1 hour and 47 minutes of which approximately 59 minutes were at a temperature greater than 1,200° F. The thickness of the graphite plate was 0.20 inch prior to tests. The graphite surface was initially flush with the top surface of ceramic fasteners. Loss of graphite material is noticeable in the photographs. Average thickness of the four panels after tests was 0.15 inch. Several of the ceramic fasteners showed slight evidence of fractures and spalling at the exposed surface.

Multipost heat shield.- Measured temperature-time histories for the multipost heat shield are shown in figure 18 for a face-plate temperature rise of approximately 20° F/sec. The maximum temperature of the irradiated face plate as indicated by thermocouple number 5 is approximately 1,400° F at 68 seconds. Thermocouple number 26 indicates a temperature of approximately 230° F at 68 seconds. The temperature rise as indicated by thermocouple number 26 is increasing whereas that of thermocouple number 5 is essentially constant. Figure 19 shows measured temperature-time histories of the multipost heat shield for a temperature rise of approximately 170° F/sec, on the irradiated face plate. In comparison to the temperature rise of 20° F/sec, this type assembly would provide a relatively
short time of thermal protection at 170°F/sec input. Although the assembly with insulation was not tested in this facility, results of the aforementioned tests of the graphite heat shield indicate that insulation would have a marked effect on extending the protection period of multipost-type heat shields. Figure 20 is a photograph of the multipost heat shield after exposure to face-plate temperature rises of 20°F/sec and 170°F/sec. Surface distortion, as indicated by the difference in maximum and minimum measurements on the 6- by 5-inch exposed face plate, was 0.025 inch. This roughness is slightly less than that measured prior to tests.

A calculated temperature distribution was made by the method described in appendix A. The measured temperature rise of approximately 20°F/sec at the location of thermocouple number 1 was employed in the calculation. Variations of temperature with time at the locations of thermocouple numbers 5, 11, 20, and 26 were calculated and are shown in figure 18 for comparison with measured data. Good agreement of calculated temperature distribution with measured data was obtained. It appears that transient temperature distributions through this type of complex structure can be satisfactorily predicted, at least for the low rates of temperature rise employed.

Survival Tests

Basic graphite heat shield. - Ethylene-jet test number 1 (table I) of the basic graphite heat shield with zirconium dioxide fasteners resulted in destruction of the heat shield. The motion pictures revealed spalling of the exposed surface of the two downstream zirconium dioxide fasteners eventuating in destruction of both fasteners. Flutter of the basic graphite panel was observed after loss of the fasteners for a period of 4.5 seconds prior to disintegration of the panel. Total test time from injection of the panel into the ethylene-jet stream to destruction was approximately 6.4 seconds.

Ethylene-jet test number 2 was a repeat of test number 1 with an identical basic graphite panel having the zirconium dioxide fasteners replaced with geometrically identical fasteners made of 347 stainless steel. This test was conducted in order to determine survival capabilities of the basic graphite panel per se. Inspection of the panel after ethylene-jet test number 2 revealed no visual damage other than a change in graphite surface texture which was probably due to oxidation. Maximum temperature of the flat-plate graphite as indicated by a chromel-alumel thermocouple was about 1,700°F, and the total test run time was 30 seconds.

Test numbers 3 and 4 at angles of attack of 3° and 8°, respectively, were satisfactory. Measured temperature-time histories are shown in figure 21 for the basic graphite panel with 0.20-inch-thick flat plate
at an angle of attack of \(3^\circ\). Maximum temperature as indicated by the thermocouples is approximately \(1,770^\circ F\). The initial rate of temperature rise estimated from figure 21 is \(200^\circ F/\text{sec}\). Surface pressure, estimated from two-dimensional wedge theory was 17.0 psia. Measured temperature-time histories are shown in figure 22 for the basic graphite panel having a 0.30-inch-thick flat plate at an angle of attack of \(8^\circ\). Maximum temperature is approximately \(1,675^\circ F\). The initial rate of temperature rise estimated from figure 22 is \(250^\circ F/\text{sec}\). The estimated surface pressure for an angle of attack of \(8^\circ\) was 22.0 psia.

It is noteworthy that the graphite structure tested survived the aerodynamic loading and heat flow of the ethylene jet. The present tests also show that a problem area exists on the fasteners and that more work is required in this area.

**Insulated multipost heat shield.** Temperature-time histories at four thermocouple locations in the insulated multipost heat shield are shown in figure 23. The heat shield survived the high temperature rise indicated by thermocouple number 1. The apparent improvement in resistance to heat flow in this assembly appears to be due to the large amount of insulation between the heat shield and the corrugated panel.

Figure 24 is a photograph of the insulated multipost heat shield after ethylene-jet tests. Surface measurements on the exposed face plate after testing indicated a maximum difference of 0.069 inch between high and low points. The condition of the heat shield was generally good. Surface distortion and overlapped joints of the face plates were not adversely affected by the temperature and dynamic pressure. Surface pressure experienced by the insulated multipost heat shield at an angle of attack of \(3^\circ\) was calculated to be 17.0 psia.

**Stainless-steel-tile heat shield.** Measured temperature-time histories for the stainless-steel-tile heat shield are shown by the data in figure 25. The maximum temperature of the tiles measured by thermocouple number 1 is \(1,550^\circ F\). Exposure of the stainless-steel-tile heat shield to the ethylene jet resulted in conditions shown by the photographs of figures 26 and 27.

Damage to the trailing-edge row of tiles may have been due to loss of confinement of the tile trailing edges by the retaining flange. Concavity and derangement of the tiles indicate inadequate strength and stiffness of the tiles for a temperature of \(1,350^\circ F\) and a calculated surface pressure of approximately 19.0 psia at an angle of attack of \(5^\circ\). Aerodynamic loads obtained in the ethylene-jet facility are severe as compared to loads experienced at high altitudes and Mach numbers. Flutter of individual 2- by 2-inch tiles was revealed by high-speed motion pictures of the tile heat shield during the ethylene-jet test.
The insulated multipost heat shield, shown in figure 23, was found to be superior to the stainless-steel-tile heat shield in retarding heat flow to the base plate when tested in the ethylene jet.

Acoustic Test

The noise environment for the acoustic tests is random in frequency and has an overall noise level of about 160 decibels. Detail noise-frequency spectra are shown in figure 9 for the two test positions. This figure shows that the overall sound pressure level in position B was 161 decibels whereas the overall sound pressure level of position A was 157 decibels. The panel was tested at position A for a period of 3 minutes and at position B for 6 minutes. Visual inspection of the graphite panel after tests revealed no structural damage.

CONCLUDING REMARKS

Exploratory tests have been conducted with several conceptual radiative heat shields of composite construction.

Radiant-heater tests of a graphite heat shield without insulation, with bulk insulation, with an insulating radiative shield, and with an insulating composite blanket shield showed that the insulating materials were nearly equally effective in producing significant reductions in temperatures through the shields. Radiant-heater tests of the graphite configurations showed that the shields lost surface material under repeated irradiation. The basic graphite heat shield survived the aerodynamic loadings of an ethylene-heated jet and the noise levels of an acoustic facility. The survival tests also showed that a problem area exists in the design and materials for the heat resistant fasteners between the graphite shield and base plate.

The insulated multipost heat shield was found to be superior to the stainless-steel-tile heat shield in retarding heat flow to the base plate when tested in the ethylene jet. Tiles of the latter shield fluttered and became distorted under the ethylene-jet loading and temperature conditions. Overlapped thin-face-plate joints and surface smoothness of the insulated multipost heat shield were not adversely affected by the test environment.

The calculated temperature distribution through the multipost heat shield was in good agreement with measured temperatures obtained from
radiant-heater tests. The numerical method used appears to be adequate for predicting the temperatures through complex structures, at least for low rates of heat input.

Langley Research Center,
National Aeronautics and Space Administration,
APPENDIX A

METHOD OF CALCULATING TEMPERATURE DISTRIBUTION

The calculated transient temperature distribution shown in figure 18, for comparison with measured temperature-time histories, was calculated by a numerical method similar to the procedure of reference 7. The conducting body of reference 7 is divided into small geometrical shapes and a heat-balance equation is written for each shape. Solution of the set of simultaneous equations is made by an iterative process for small time increments.

The symbols used in this appendix are as follows:

\begin{align*}
A & \quad \text{area of conduction path or radiating surface, sq ft} \\
c & \quad \text{specific heat, Btu/(lb)(°R)} \\
F & \quad \text{configuration factor for radiant interchange (1.0)} \\
k & \quad \text{thermal conductivity, Btu/(ft)(sec)(°R)} \\
l & \quad \text{length of conduction path, ft} \\
q & \quad \text{heat input, Btu/sec} \\
T & \quad \text{temperature, °R} \\
\Delta T & \quad \text{increment in temperature} \\
\Delta t & \quad \text{increment in time} \\
V & \quad \text{volume, subdivisions of heat-transfer element, cu ft} \\
\varepsilon & \quad \text{emissivity} \\
\rho & \quad \text{weight density, lb/cu ft} \\
\sigma & \quad \text{Stefan-Boltzmann constant, Btu/(sq ft)(sec)(°R)^4} \\
\text{Subscript:} \\
a & \quad \text{conductivity of air}
\end{align*}

Numerical subscripts indicate number of subdivision blocks in heat-transfer element.
An elemental section of the multipost heat shield is shown in figure 28. This section was used as a basic heat-transfer element to calculate the temperature distribution through the depth. Subdivision of the heat-transfer element into geometrical shapes is indicated by the numbered blocks in figure 28. Detail dimensions of the heat-transfer element are given in figure 3. For a small increment of time, heat-balance equations were written for each subdivision by considering heat loss and gain. In setting up heat-balance equations, net radiation exchange between the interstitial post of the heat-transfer element and that of surrounding posts was neglected. Configuration factors for radiant interchange were assumed to equal one for subdivisions in the face plates and corrugated sheet. Areas for subdivisions of the corrugated sheet were used as areas projected parallel to the face plates. A constant emissivity, \( \epsilon = 0.46 \), was assumed for stainless steel.

The following heat balance was used for each subdivision:

\[
\frac{c_p V \Delta T}{\Delta t} = \sum q_{\text{gained}} + \sum q_{\text{lost}}
\]

The heat-balance equation for subdivision number 4 of figure 28 is given as follows as a typical equation:

\[
\Delta T_4 = \frac{\Delta t}{c_p V} \left[ q - \epsilon \sigma (T_4)^4 A_4 + k \frac{A_{1-4}}{l_{1-4}} (T_1 - T_4) + k \frac{A_{4-5}}{l_{4-5}} (T_5 - T_4) + k \frac{A_{4-13}}{l_{4-13}} (T_{13} - T_4) + \frac{1}{\epsilon_4} + \frac{1}{\epsilon_{13}} - 1 \right]
\]

The first term inside the brackets of the typical equation represents the heat input. The second term is the heat lost by block 4 by radiation from the outer surface. Conduction heat transfer with adjacent blocks is represented by the third and fourth terms. The air column between blocks 4 and 13 was assumed to be a conductor path. Conduction by air in this column is represented by the fifth term. Radiation exchange of blocks 4 and 13 is accounted for by the sixth term.

Twenty-nine equations are obtained from the heat-transfer element of figure 28. Since the variation of heat input with time was unknown, temperature-time history of block number 1 was measured in order to perform the calculations. A time increment of \( \Delta t = 0.25 \) seconds was found by trial calculations to be satisfactory for solution of the
equations. A simultaneous solution of these equations, for successive small increments of time, was made on an IBM 704 electronic data processing machine.

Equations approximating the temperature-time history of block number 1 are given in table IV. Variation of material properties with temperature used in solution of the heat-balance equations was approximated by the following equations:

For stainless steel 347

\[ k = 0.001676 + 1.35 \times 10^{-6} \times T \]

\[ c = 0.1088 + 20.0 \times 10^{-6} \times T \]

\[ \rho = 494.2 \]

For stainless steel 310

\[ k = 0.001434 + 0.96527 \times 10^{-6} \times T \]

\[ c = 0.1088 + 20.0 \times 10^{-6} \times T \]

\[ \rho = 501.1 \]

For air

\[ k_a = 0.03437 \times 10^{-6} + 0.00828 \times 10^{-6} \times T - 1.2656 \times 10^{-12}T^2 \]
REFERENCES


<table>
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<th>Test panel</th>
<th>Ethylene-jet test number</th>
<th>Thickness of flat-plate graphite, in.</th>
<th>Grade of graphite</th>
<th>Fastener material</th>
<th>Angle of attack, deg</th>
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<td>Stagnation temp. = 2,240°F Mach no. = 2.0 Static press. = 14.9 psia Dynamic press. = 5,590 lb/sq ft</td>
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<td>347 stainless steel</td>
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<td>Stagnation temp. = 1,840°F Mach no. = 2.0 Static press. = 14.8 psia Dynamic press. = 5,927 lb/sq ft</td>
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### TABLE II. - MEASURED TEMPERATURE-TIME HISTORIES DURING RADIANT-HEATER TESTS FOR GRAPHITE HEAT SHIELDS

[Programed temperature rise, +40°F/sec]

(a) Tests made from room temperature to levels of 600°F

<table>
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<tr>
<th>Time, sec</th>
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<th>With radiation shields</th>
<th>With composite blanket</th>
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<td>920 910 94 100</td>
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Temperature, °F, at thermocouples -
**TABLE II. - MEASURED TEMPERATURE-TIME HISTORIES DURING RADIANT-HEATER TESTS FOR GRAPHITE HEAT SHIELDS - Continued**

(b) Tests made from room temperature to levels of 1,200 \(^\circ\)F

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<th>With composite blanket</th>
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**TABLE II.** MEASURED TEMPERATURE-TIME HISTORIES DURING RADIANT-HEATER TESTS FOR GRAPHITE HEAT SHIELDS - Concluded

(Progrnmed temperature rise, 400°F/sec)

Tests made from room temperature to levels of 1,000°F

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Temperature, °F, at thermocouples:
TABLE III. - MEASURED TEMPERATURE-TIME HISTORIES DURING RADIANT-HEATER TESTS FOR GRAPHITE HEAT SHIELDS

<table>
<thead>
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<th>Time, sec</th>
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(a) Tests made from room temperature to levels of 600°F
TABLE III.- MEASURED TEMPERATURE-TIME HISTORIES DURING RADIANT-HEATER TESTS FOR GRAPHITE HEAT SHIELDS - Continued

[Programed temperature rise, 80°F/sec]

(b) Tests made from room temperature to levels of 1,200°F

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<td>822 824 184 180</td>
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<table>
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<tr>
<th>Temperature, °F, at thermocouples</th>
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<tr>
<td>With insulation</td>
</tr>
<tr>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>152 151 170 169</td>
</tr>
<tr>
<td>156 158 177 175</td>
</tr>
<tr>
<td>151 150 176 174</td>
</tr>
<tr>
<td>148 151 161 160</td>
</tr>
<tr>
<td>With bulk insulation</td>
</tr>
<tr>
<td>0 1 2 3 4</td>
</tr>
<tr>
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<tr>
<td>156 158 176 175</td>
</tr>
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<td>150 150 176 174</td>
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<td>148 150 161 160</td>
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<tr>
<td>With radiation shields</td>
</tr>
<tr>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>160 150 170 169</td>
</tr>
<tr>
<td>156 158 176 175</td>
</tr>
<tr>
<td>150 150 176 174</td>
</tr>
<tr>
<td>148 150 161 160</td>
</tr>
<tr>
<td>With composite blanket</td>
</tr>
<tr>
<td>0 1 2 3 4</td>
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<td>192 275 172 171</td>
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<tr>
<td>290 231 178 178</td>
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<td>57 382 178 176</td>
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<td>170 170 165 164</td>
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<tr>
<td>197 191 167 167</td>
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<tr>
<td>227 214 169 170</td>
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</table>
TABLE IV.- MEASURED TEMPERATURE-TIME HISTORY OF MULTIPOST HEAT SHIELD

AT THERMOCOUPLE NUMBER 1, BLOCK NUMBER 1

\[ T_l, \text{temperature of block no. 1, } ^\circ\text{R; } t, \text{time in seconds} \]

<table>
<thead>
<tr>
<th>Time, sec</th>
<th>Equation of straight line approximating measured temperature-time variation of block no. 1</th>
</tr>
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<tbody>
<tr>
<td>0 to 8</td>
<td>( T_l - 22.825t - 542 = 0 )</td>
</tr>
<tr>
<td>8 to 60</td>
<td>( T_l - 20.813t - 558.092 = 0 )</td>
</tr>
<tr>
<td>60 to 66</td>
<td>( T_l - 17.383t - 763.900 = 0 )</td>
</tr>
<tr>
<td>66 to 67</td>
<td>( T_l - 12.8t - 1666.4 = 0 )</td>
</tr>
<tr>
<td>67 to 68</td>
<td>( T_l - 1924 = 0 )</td>
</tr>
</tbody>
</table>
Figure 1.- Basic graphite heat shield. Dimensions in inches.
(c) Sectional view A-A. Basic graphite heat shield with bulk insulation. Thermocouple locations are typical for graphite heat shields.

(d) Sectional view A-A. Basic graphite heat shield with radiation shields.

(e) Sectional view A-A. Basic graphite heat shield with composite blanket.

Figure 1.- Concluded.
Figure 2. - Schematic sketch of the multi-post heat shield. Dimensions in inches.

(a) Perspective sketch.

(b) Cross section.

Post spacing

.035 Diam.

posts

0.11

3.72

- .775

63°

6
Figure 3.- Structural element of multipost heat shield showing thermocouple locations. Dimensions in inches.
(a) Photograph of insulated multipost heat shield.

Figure 4. - Insulated multipost heat shield. Dimensions in inches.
Figure 5.- Cross section of stainless-steel-tile heat shield. Dimensions in inches.
Figure 6: Schematic sketch of radiant-heater test setup.
Figure 7.- Photograph of typical test setup for ethylene-jet survival tests. Test setup for basic graphite heat shield illustrated.
Figure 8.- Schematic sketch of acoustic test setup of basic graphite heat shield.
Figure 9.- Noise spectra. Acoustic facility; basic graphite heat shield.
Figure 10. - Measured temperature-time histories for the basic graphite heat shield without insulation. Radiant-heater test.
Figure 11.- Measured temperature-time histories for the basic graphite heat shield with bulk insulation. Radiant-heater test.
Figure 12.- Measured temperature-time histories for the basic graphite heat shield with radiation shields. Radiant-heater test.
Figure 13.- Measured temperature-time histories for the basic graphite heat shield with composite blanket. Radiant-heater test.
Figure 14.- Photograph of basic graphite heat shield without insulation, after six radiant-heater exposures.
Figure 15.- Photograph of basic graphite heat shield with bulk insulation, after six radiant-heater exposures.
Figure 16.- Photograph of basic graphite heat shield with radiation shields, after six radiant-heater exposures.
Figure 17.- Photograph of basic graphite heat shield with composite blanket, after six radiant-heater exposures.
Figure 18.- Comparison of calculated and measured temperature-time histories for the multipost heat shield. Radiant-heater test.
Figure 19. - Measured temperature-time histories for the multipost heat shield. Radiant-heater test.
Figure 20.- Photograph of the multipost heat shield after radiant-heater tests.
Figure 21.- Measured temperature-time history for basic graphite heat shield without insulation. 0.20-inch-thick flat plate; ethylene-jet survival test.
Figure 22.- Measured temperature-time history for basic graphite heat shield without insulation. 0.30-inch-thick flat plate; ethylene-jet survival test.
Figure 23.- Measured temperature-time histories for the insulated multipost heat shield. Ethylene-jet survival test.
Figure 26. - Photograph of stainless-steel-tile heat shield mounted in ethylene-jet support stand, after survival test.
Figure 27.- Photograph of stainless-steel-tile heat shield after ethylene-jet survival tests.
Figure 28.- Heat-transfer element used in temperature-distribution calculations for the multipost heat shield.