AN ANALYSIS OF
A CHARRING ABLATION
THERMAL PROTECTION SYSTEM

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SUMMARY

An analytical model is presented for predicting the transient one-dimensional thermal performance of a charring-ablator heat-protection system when exposed to a hyperthermal environment. The heat-protection system is considered to consist of an ablation material and backup structure. The ablating material is further considered to consist of three distinct regions or zones: char, reacting, and virgin material.

A FORTRAN IV digital computer program (STAB II) utilizing an implicit finite difference formulation has been written for the IBM 7094/40 computer system. The program considers one ablating material and a maximum of 12 backup materials, with conduction or radiation and/or convection allowed between materials. Thermal properties of all materials are temperature dependent, with the properties of the charring material also being state dependent.

The governing differential equations and their implicit finite difference formulation are presented. The program input and output are described in detail. The FORTRAN program statements and nomenclature are presented. Also, the theoretical and experimental results are compared.

INTRODUCTION

The analysis and design of thermal protection systems for entry into an atmospheric environment have resulted in a voluminous amount of literature on the general subject of ablation. (See refs. 1 and 2 for a survey of information on ablation.) The ablation materials may generally be classified into three categories: subliming, melting and vaporizing, and charring. The charring ablator normally provides the most efficient thermal-protection shield for the major portion of a manned entry vehicle. This report describes a method for predicting the thermal response of a typical charring-ablation material. The response of a charring material to a hyperthermal environment is extremely complex, and the mathematical model presented to analyze the transient behavior of the material contains simplifying assumptions and approximations necessary to afford even a numerical solution.
The equations derived in this analysis have been programmed in FORTRAN IV for an IBM 7094/40 computer system. The numerical formulation of this digital program, designated STAB II, is such that an implicit solution is obtained. The thermal response of a typical charring material as predicted by STAB II is compared with arc tunnel results.

A sample problem is presented in appendix A. Program usage instructions, including definitions of the input terminology, are presented in appendix B. Appendixes C and D are the program FORTRAN IV statements and definitions of the program terminology. A general flow chart of the program is presented in appendix E.

**SYMBOLS**

- **A** collision frequency
- **c_p** specific heat
- **E** activation energy
- **F** exterior view factor
- **F_env** view factor-emissivity product to cabin environment
- **H_d** heat of virgin material degradation
- **H_T** total enthalpy
- **H_w** wall enthalpy
- **H_300** enthalpy of air at 300° K
- **h** film coefficient between backup materials
- **h_env** film coefficient between last backup material and cabin environment
- **k** thermal conductivity
- **m_c** mass loss rate of char material
- **m_g** gas ablation rate
- **NP** number of nodes in ablation material
- **2**
\( n \) order of reaction

\( Q_{in} \) net heat rate into front surface

\( \dot{q}_{\text{blow}} \) hot wall convective heat flux with blowing

\( \dot{q}_{\text{comb}} \) heat flux due to combustion

\( \dot{q}_{cw} \) cold wall convective heat flux without blowing

\( \dot{q}_{\text{rad}} \) radiation heat flux

\( R \) universal gas constant

\( S \) surface recession depth

\( \dot{S} \) surface recession rate

\( T \) temperature of node at beginning of time step

\( T_{\text{env}} \) cabin environment temperature

\( T' \) temperature of node at end of time step

\( T_{\infty} \) radiation heat sink temperature

\( VL \) thickness of ablation material

\( X \) distance from surface to any point

\( \Delta H_c \) heat of combustion per unit weight of char

\( \Delta X \) thickness of a node

\( \Delta \theta \) time step (\( \theta' - \theta \))

\( \epsilon \) emissivity of material

\( \eta \) transpiration cooling efficiency

\( \theta \) initial time

\( \theta' \) final time

\( \xi \) transform for the ablation material
\( \rho \) density
\( \sigma \) Stefan–Boltzmann constant
\( \psi \) blocking effectiveness function

Subscripts:
\( c \) charred state
\( i \) node number
\( j \) material number
\( v \) virgin state

PROGRAM DESCRIPTION

The following general requirements were established before writing a digital computer program to analyze a charring ablation system:

(1) Stability of the equations for all applications.

(2) Machine running time short enough to make use of the program economically feasible (a minimum of turn around time per problem).

(3) A minimum of input per problem.

(4) A wide variety of boundary conditions for application to both trajectory data and ground or flight test data analysis.

STAB II has been formulated in FORTRAN IV to analyze the transient thermal performance of a charring ablator heat protection system. The program considers one ablating material and up to 12 different backup materials with or without air gaps. Pure conduction or radiation and/or convection between backup materials is allowed. The ablation material may be divided into a maximum of 50 nodes, and each backup material may be subdivided into a maximum of 10 nodes. The thermal properties of the materials are in tabular form and are temperature dependent. The ablation material is also dependent upon its state, that is, fully charred, partially charred, et cetera.

The following surface boundary condition options are provided:

(1) Cold-wall convective and radiative heat flux tables as a function of time. These components are specified separately, since mass transfer at the surface blocks part of the convective heating but, in general, has no effect on the radiant heating.
(2) Surface temperature as a function of time.

(3) Surface recession as a function of temperature or time. Surface recession as a function of temperature and pressure is also available.

Heat loss to the interior environment for the last node of the backup structure can be specified by two methods:

(1) Conduction into the node and radiation and/or convection loss to the interior environment.

(2) Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision, $\Delta X$. The exact values are approached more and more closely as $\Delta X$ decreases. The second kind of error is the numerical, or roundoff error. The way in which this numerical error grows or decays with time determines the stability of the difference equations.

To illustrate the differences in the explicit and implicit equation form, consider a nonablation homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is

$$\frac{\partial}{\partial X} \left( \frac{\partial T}{\partial X} \right) = \rho_c \frac{\partial T}{\partial \theta}$$

(1)

The finite difference form of equation (1) written in the conventional forward time step or explicit form for the $i$th node is

$$\frac{(T_{i+1} - T_i)}{\Delta X} \cdot \frac{(T_i - T_{i-1})}{\Delta X} = \rho_c \frac{\Delta X (T_i' - T_i)}{\Delta \theta}$$

(2)

where the prime superscript denotes values at the end of the time step

$$\Delta \theta = \theta' - \theta$$

For explicit conduction solutions, the following stability criterion has been established:

$$\frac{\rho_c}{k} \left( \frac{\Delta X)^2}{\Delta \theta} \right) \geq 2$$
which places an upper limit on the time step $\Delta t$ for a fixed truncation error. This criterion can require a prohibitive amount of machine time.

Liebmnn (ref. 3) advocated a solution of the equation which does not require this stability criterion. The finite difference equations are written in a backward time step form which affords an implicit solution.

The implicit (backward time step) difference form of equation (1) for the $i$th node is:

$$
\left( \frac{T_{i-1}^t - T_i^t}{\Delta x} + \frac{\Delta X}{2k_{i-1}} \right) - \left( \frac{T_i^t - T_{i+1}^t}{\Delta x} + \frac{\Delta X}{2k_i} \right) = \rho c_p \frac{\Delta x}{\Delta t} \left( T_{i+1}^t - T_i^t \right)
$$

Equation (3) uses the temperature differences at the end of the finite time interval instead of the beginning, as in the explicit method of equation (2). The only known temperature in equation (3) is $T_i^t$, but there are corresponding equations for each point in the system, and all are solved simultaneously to yield the temperature at each node.

Collecting all unknown temperatures on the left side of the equation and the known temperature on the right side, equation (3) becomes

$$
\left( \frac{1}{\Delta x} + \frac{\Delta X}{2k_{i-1}} \right) T_{i-1}^t - \left( \frac{1}{\Delta x} + \frac{\Delta X}{2k_i} \right) T_i^t + \left( \frac{1}{\Delta x} + \frac{\Delta X}{2k_{i+1}} \right) T_{i+1}^t = \left( \frac{\rho_i c_p \Delta X}{\Delta t} \right) T_i^t
$$

Equation (4) is of the form

$$
A{T}_{i-1}^t + B{T}_{i}^t + C{T}_{i+1}^t = D
$$

STAB II generates such an equation for each node in the system.

Since radiation is an important mode of heat transfer in charring ablative systems, a problem is encountered in any equation containing a radiation term. The radiation heat flux, written in a backward difference form is:

$$
q_{rad} = F \sigma \left( T_i^t - T_{\infty}^4 \right)
$$

6
This term cannot be used in an implicit solution since the unknown temperature \( T_f \) is to be the 4th power. The 4th power unknown can be eliminated by the following linearizations:

\[
\left( T_f^4 \right) = \left( T_i + \Delta T \right)^4 = T_i^4 \left( 1 + \frac{\Delta T}{T_i} \right)^4 \tag{7}
\]

where

\[
\Delta T = T_f - T_i
\]

let

\[
Z \equiv \frac{\Delta T}{T_i}
\]

and rewrite equation (7) as

\[
\left( T_f^4 \right) \approx \left( T_i^4 \right) \left( 1 + Z \right)^4 \tag{8}
\]

If \( Z \) has an absolute value near zero, the following is true

\[
(1 + Z)^4 \approx 1 + 4Z \tag{9}
\]

Now substituting equation (9) into equation (8)

\[
\left( T_f^4 \right) \approx \left( T_i^4 \right) \left( 1 + 4Z \right) = \left( T_i^4 \right) \left( 1 + 4 \frac{\Delta T}{T_i} \right)
\]

\[
\approx 4 T_i^3 T_f^4 - 3 T_i^4 \tag{10}
\]

Equation (10) is a linearized approximation of equation (7) in which the unknown temperature is only to the first power. The assumption in equation (10) is that \( \Delta T/T_i \) has an absolute value near zero. Figure 1 is a plot of the error obtained when \( (1 + 4Z) \) is substituted for \( (1 + Z)^4 \). For most ablation problems in which the surface temperature is high and the radiation losses are significant, the value of \( \Delta T/T_i \) can easily be controlled to values of less than \( \pm 0.1 \).

Therefore, equation (6) can now be written

\[
\dot{q}_{\text{rad}} = \Phi \sigma \left( 4 T_i^3 T_f^4 - 3 T_i^4 - T_\infty^4 \right) \tag{11}
\]
Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

\[ B_1 T_1 + C_1 T_2 = D_1 \]
\[ A_2 T_1 + B_2 T_2 + C_2 T_3 = D_2 \]
\[ A_3 T_2 + B_3 T_3 + C_3 T_4 = D_3 \]
\[ \vdots \]
\[ A_{N-1} T_{N-2} + B_{N-1} T_{N-1} + C_{N-1} T_N = D_{N-1} \]
\[ A_N T_{N-1} + B_N T_N = D_N \]

Gauss' elimination method, discussed in reference 4, is applied to solve the system of equations. This method affords a fast and accurate solution for matrices containing a dominant diagonal. The solution of this matrix gives the temperature of each node in the system for the next future time step. The entire process is repeated for each time step throughout the run, giving a time history of the temperature at each node.

Using this method of solution, residual errors in the temperature computations at the beginning of the time step are distributed throughout the entire system of nodal equations and tend to cancel out rapidly. The principal advantage in using the implicit method is a set of equations that are mathematically stable in time and distance. Therefore, the magnitude of the time step is not limited by a convergence criterion. However, care must be taken in selecting the magnitude of the time step in order to minimize truncation errors when the second derivative of temperature with respect to time is large. A similar approach is used to minimize truncation errors in distance by choosing small node dimensions in locations where large second derivatives of temperature with respect to distance are expected.

In the case of a char-forming ablative heat shield where approximately 80 percent of the heat is reradiated, instability can arise in taking large time steps. The temperature of the surface node can start oscillating on successive time steps when a balance between the radiation source and the heat sink has been achieved. Therefore, in ablation problems in which the surface node loses a large percentage of heat by radiation, oscillations of the node can be damped out by taking small time steps during conditions of high heat flux and near radiation equilibrium temperatures.

ANALYSIS

Figure 2 is a schematic of the thermal protection system to be analyzed. A receding surface has been assumed with the formation of a residual char layer and reaction zone. The thermal protection system is composed of one charring material and a maximum of 12 different backup materials with or without air gaps.
The analysis is such that the entire system may be composed of noncharring materials. The thermal properties of all materials are temperature dependent; also, the charring material properties are state dependent (fully or partially charred).

The response of charring ablation heat shields to a hyperthermal environment is extremely complex, and simplifying assumptions and approximations are necessary to afford a numerical solution. The following assumptions and approximations are utilized in the equations developed in this report:

1. The material decomposes from the virgin state to a porous char layer in the reaction zone.

2. The reaction zone can be defined by an upper and lower temperature limit.

3. The gas generated within the reaction zone is assumed to pass out of the structure with no pressure loss. No gas accumulation within a node is allowed.

4. Local thermal equilibrium is maintained between the gas and porous char matrix.

5. The gas undergoes no further chemical reaction within the residual material after having been formed.

Derivation of Equations

The equations are derived for a moving boundary coordinate system, where the front face is the moving surface (ref. 5). With this system, the ablating material is divided into a fixed number of nodes of thickness $\Delta X$ which depends on the instantaneous location of the front face. The surface recession is handled in a continuous manner, eliminating the need of throwing away or lumping off of nodes.

The physical model for the front surface, including all heating terms, is shown as follows:
The energy equation at the front char surface is

\[
\frac{d}{d\theta} \left( \frac{1}{2} \Delta X \rho_1 c_p T_1 \right) = \frac{1}{2} \Delta X \rho_1 c_p T_1 \frac{dT_1}{d\theta} + \frac{1}{2} \rho_1 c_p T_1 \frac{d(\Delta X)}{d\theta} \\
= Q_{in} + \dot{m}_2 c_p T_2' + \rho_2 c_p T_2' - \dot{m}_1 c_p T_1' \\
- \rho_1 c_p \dot{S}_1 T_1' - k_{1-2} \left( \frac{\Delta T}{\Delta X} \right)
\]  

(12)

where

\[
Q_{in} = \dot{q}_c, \text{ blow} + \dot{q}_\text{rad} + \dot{q}_\text{comb} - \rho c_s (T_1^4 - T_\infty^4)
\]

and

\[
\frac{d(\Delta X)}{d\theta} = \frac{d(\Delta X)}{d\theta} (\Delta X - S) = -\frac{\dot{S}}{NP - 1}
\]

where \(\dot{S}\) is the linear surface recession rate and \(NP\) is the total number of nodes in the ablation material of thickness \(VL\).
Rewriting equation (12) in implicit finite difference form

\[ Q_{in} + \dot{m}_2 c_{p2} T_2' - \dot{m}_1 c_{p1} T_1' - \dot{s}_{p1} c_{p1} T_1' = \left( \frac{T_1' - T_2'}{\Delta X} \right) \frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2} \]

\[ + \rho_2 c_{p2} \left( \frac{NP - 1.5}{NP - 1.0} \right) T_2' = \rho_1 c_{p1} \frac{\Delta X}{2} \left( \frac{T_1' - T_1}{\Delta \theta} \right) \]

\[ - \frac{1}{2} \rho_1 c_{p1} T_1 \left( \frac{\dot{s}}{NP - 1} \right) \] (12a)

Then, rearranging and collecting terms yield,

\[- \left[ m_1 c_{p1} \dot{s}_{p1} c_{p1} + \rho_1 c_{p1} \frac{\Delta X}{2\Delta \theta} + \frac{1}{\Delta X} \frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2} - \frac{1}{2} \rho_1 c_{p1} \left( \frac{\dot{s}}{NP - 1} \right) \right] T_1' \]

\[+ \left[ \dot{m}_2 c_{p2} + \frac{1}{\Delta X} \frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2} \right] T_2' \]

\[= -\rho_1 c_{p1} \frac{\Delta X}{2\Delta \theta} T_1 - Q_{in}. \] (12b)
The physical model for interior points in the mature char zone, including all heating terms, is shown in the following sketch:

The energy equation for interior points in the char matrix is

\[
\frac{d}{d\theta} \left( \Delta X \rho_i c_{p_i} T_i \right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i \left( \frac{\dot{S}}{NP - 1} \right)
\]

\[
= \dot{m}_{g_{i+1} c_{p_{i+1}}} T_{i+1} + k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} T_{i+1} \left( \frac{\dot{S}}{NP - 1} \right)
\]

\[
- k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_i c_{p_i}} T_i - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_{i+1}^{'}
\]

(13)
Putting equation (13) in an implicit finite difference form yields

\[
\left( \frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i} \right) T_{i-1}' - \left[ \dot{m}_i c_{p_1} + \rho_i c_{p_1} \dot{S} \left( \frac{NP - 1 + \frac{1}{2}}{NP - 1} \right) + \frac{1}{\Delta X} + \frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i} \right] T_i' \\
+ \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_i c_{p_1} \left( \frac{\Delta S}{\Delta \theta} - \frac{\rho_i c_{p_1}}{NP - 1} \right) T_i' \\
+ \left[ \dot{m}_{i+1} c_{p_{i+1}} + \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - 1 - \frac{1}{2}}{NP - 1} \right) \right] T_{i+1}' \\
= -\rho_i c_{p_1} \frac{\Delta S}{\Delta \theta} T_i.'
\]

(13a)

In the mature char zone, no internal gaseous ablation products are assumed to form. The reaction zone is the source for the formation of the internal gaseous products. Therefore, in equations (12) and (13), \( \dot{m}_i = \dot{m}_{i+1} \).

The physical model for nodes in the reaction zone is identical to schematic shown for the interior nodes in the char except for considering the energy absorbed in formation of the gaseous ablation products. The heat balance equation for a node in the reaction zone is

\[
\frac{d}{d\theta} \left( \Delta X \rho_i c_{p_1} T_i \right) = \Delta X \rho_i c_{p_1} \frac{dT_i}{d\theta} - \rho_i c_{p_1} T_i \left( \frac{\dot{S}}{NP - 1} \right) - \left( \dot{m}_i - \dot{m}_{i+1} \right) H_d
\\
= \dot{m}_{i+1} c_{p_{i+1}} T_{i+1}' + k_{i-1,i} \left( \frac{dT_i}{d\theta} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - 1 - \frac{1}{2}}{NP - 1} \right) T_{i+1}'
\\
- k_{i,i+1} \left( \frac{dT_i}{d\theta} \right) - \dot{m}_i c_{p_1} T_i' - \rho_i c_{p_1} \dot{S} \left( \frac{NP - 1 + \frac{1}{2}}{NP - 1} \right) T_i'.
\]

(14)
Rearranging,

\[
\left( \frac{1}{2k_{i-1}} + \frac{\Delta X}{2k_i} \right) T_{i-1} - \left[ m_{g_1} c_{p_1} + \rho_i c_{p_1} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \frac{1}{2k_{i-1}} + \frac{\Delta X}{2k_i} \right]
\]

\[+ \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_{i+1} c_{p_{i+1}} \left( \frac{S}{NP - 1} \right) T_i + \left[ m_{g_{i+1}} c_{p_{i+1}} \right]
\]

\[+ \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_{i+1} c_{p_{i+1}} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1}
\]

\[= -\rho_i c_{p_1} \Delta \theta T_i - \left( m_{g_1} - m_{g_{i+1}} \right) H_d \] (14a)

The physical model for the interface between the reaction zone and virgin material is illustrated as follows:
The heat balance equation for this node is

\[
\frac{d}{d\theta} \left( \Delta X \rho_1 c_p T_1 \right) = \Delta X \rho_1 c_p \frac{dT_1}{d\theta} - \rho_1 c_p T_1 T_1' \left( \frac{\dot{S}}{NP - 1} \right) - \dot{m}_{g_1} H_d
\]

\[
= k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_p T_1' \cdot \frac{\dot{S}}{NP - 1} \left( \frac{NP - i - \frac{1}{2}}{\frac{NP}{NP - 1}} \right) T_1' + k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_1} c_p T_1 - \rho_1 c_p T_1 \frac{\dot{S}}{NP - 1} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_1
\]

\[ (15) \]

Rearranging yields

\[
\left( \frac{1}{2k_{i-1}} + \frac{1}{2k_i} \right) T_1' - \left[ \dot{m}_{g_1} c_p + \frac{1}{2k_{i-1}} + \frac{1}{2k_i} + \frac{1}{2k_{i+1}} \right]
\]

\[
+ \rho_1 c_p T_1 \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho_1 c_p \frac{\Delta T}{\Delta \theta} - \rho_1 c_p \left( \frac{\dot{S}}{NP - 1} \right) T_1
\]

\[ \text{INTERFACE} \]

\[
+ \left[ \frac{1}{2k_{i+1}} + \frac{1}{2k_{i+1}} \right] \rho_{i+1} c_p T_1' + \rho_{i+1} c_p T_1' \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right)
\]

\[ (15a) \]
The physical model for an interior node in the virgin material is

\[
\begin{align*}
\dot{S}_{i-1,i} & = \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) \\
\dot{S}_{i,i+1} & = \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \\
\end{align*}
\]

The heat balance for this nonablating node is

\[
\frac{d}{d\theta} \left( \Delta X \rho_1 c_{p_1} T_1 \right) = \Delta X \rho_1 c_{p_1} \frac{dT_1}{d\theta} - \rho_1 c_{p_1} T_1 \left( \frac{\dot{S}}{NP - 1} \right)
\]

\[
= k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1} - k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right)
\]

\[
- \rho_1 c_{p_1} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_i
\]

(16)
Rearranging,

\[
\left(\frac{1}{\Delta x} + \frac{\Delta x}{2k_{i-1}}\right) T'_{i-1} = -\left[\frac{1}{\Delta x} + \frac{\Delta x}{2k_i} + \frac{\Delta x}{2k_{i+1}}\right] T'_{i} + \rho_1 c_p \left(\frac{\Delta x}{NP - 1}\right) T_{i+1}^j
\]

\[
+ \rho_1 c_p \left(\frac{\Delta x}{NP - 1}\right) T^j + \rho_1 c_p \left(\frac{\Delta x}{NP - 1}\right) T^j - \rho_1 c_p \left(\frac{\Delta x}{NP - 1}\right) T^j
\]

The physical model for the last node in the ablation material and first node in the backup structure is

\[
\begin{align*}
\hat{S}_{i-1,j} &= \rho_i c_p \left(\frac{\Delta x}{NP - 1}\right) T^j, \quad \text{for } T^j, j \\
\hat{S}_{i,j} &= \rho_i c_p \left(\frac{\Delta x}{NP - 1}\right) T^j, \quad \text{for } T^j, j \\
\hat{S}_{i,j+1} &= \rho_i c_p \left(\frac{\Delta x}{NP - 1}\right) T^j, \quad \text{for } T^j, j+1
\end{align*}
\]

For this interface, \( T'_{i,j} = T'_{i,j+1} \).
The heat balance equation for this node is

\[ \frac{d}{d\theta} \left[ \left( \frac{\Delta X_j}{2} \rho_{i,j} c_{p_{i,j}} + \frac{\Delta X_{j+1}}{2} c_{p_{i,j+1}} \rho_{i,j+1} \right) T_1 \right] \]

\[ = \left( \frac{\Delta X_j \rho_{i,j} c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2} \right) \frac{dT_1}{d\theta} - \frac{1}{2} \left( \frac{\dot{S}}{NP - 1} \right) c_{p_{i,j}} \rho_{i,j} T_1' \]

\[ = k_{i-1,j} \left( \frac{\Delta T}{\Delta X} \right) - c_{p_{i,j}} \rho_{i,j} \dot{S} \left( \frac{1}{2} \frac{1}{NP - 1} \right) T_1' - k_{i,j+1} \left( \frac{\Delta T}{\Delta X} \right) \]

Rearranging yields

\[ \left( \frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}} \right) T_1' - \left[ \frac{\Delta X_j}{2k_{i-1,j}} \frac{\Delta X_j}{2k_{i,j}} \frac{\Delta X_{j+1}}{2k_{i,j+1}} \frac{\Delta X_{j+1}}{2k_{i+1,j+1}} \right] \]

\[ + \left( \frac{\Delta X_j c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta \theta} \right) T_1' + \left( \frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}} \right) T_1' \]

\[ = - \left( \frac{\Delta X_j c_{p_{i,j}} \rho_{i,j} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta \theta} \right) T_1 \]

(17a)

The backup structure may contain up to a maximum of 12 different materials with or without air gaps between materials. Therefore, conduction or radiation and/or convection between materials is allowed. The heat balance equations for the various modes of heat transfer in the backup structure are presented in the following equations:
(1) Interior node material:

\[ \frac{\left( T'_{i-1,j} - T'_{i,j} \right)}{\Delta X_j} + \frac{\left( T'_{i,j} - T'_{i+1,j} \right)}{\Delta X_j} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} \left( T'_{i,j} - T_{i,j} \right) \]  

Rearranging, equation (18) becomes

\[ \left( \frac{\Delta X_j}{(2k_{i-1,j} + 2k_i,j)} \right) T'_{i-1,j} - \left( \frac{\Delta X_j}{(2k_{i-1,j} + 2k_i,j)} \right) T'_{i,j} + \left( \frac{\Delta X_j}{(2k_i,j + 2k_{i+1,j})} \right) T'_{i+1,j} \]

\[ = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} T_{i,j} \]  

(18a)

(2) First and last nodes of two interior materials with no gap:

\[ \frac{\left( T'_{i-1,j} - T'_{i,j} \right)}{\Delta X_j} + \frac{\left( T'_{i,j+1} - T'_{i+1,j+1} \right)}{\Delta X_j} \]

\[ = \left( \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{2(\Delta \theta)} \right) \left( T'_{i,j} - T_{i,j} \right) \]  

For this case, \( T'_{i,j} = T_{i,j+1} \)
Rearranging, equation (19) becomes

\[
\left( \frac{\Delta X_{j}}{2k_{i-1,j}} + \frac{\Delta X_{j}}{2k_{i,j}} \right) T'_{i-1,j} - \left[ \frac{1}{\Delta X_{j}} + \frac{1}{2k_{i,j}} + \frac{1}{2k_{i,j+1}} \right] + \left( \frac{\rho_{i,j} c p_{i,j} \Delta X_{j} + \rho_{i,j+1} c p_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} \right) T'_{i,j}
\]

\[= - \left( \frac{\rho_{i,j} c p_{i,j} \Delta X_{j} + \rho_{i,j+1} c p_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} \right) T'_{i,j} \tag{19a}\]

(3) **First node of interior material with an air gap between materials:**

\[
h_{j} \left( T'_{i-1,j} - T'_{i,j+1} \right) + \left( \frac{1}{\varepsilon_{j}} + \frac{1}{\varepsilon_{j+1}} - 1 \right) \left( T'_{i-1,j} - T'_{i,j+1} \right)
\]

\[= \left( \frac{T'_{i,j+1} - T'_{i+1,j+1}}{\Delta X_{j+1}} + \frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}} \right) \left( T'_{i,j+1} - T'_{i,j+1} \right) \tag{20}\]

Equation (20) may be linearized by using the approximation

\[T'^{h} \approx 4T'^{h} - 3T^{h}\]

as discussed in the Program Description section.
Therefore, rearranging and linearizing, equation (20) becomes

\[
\begin{align*}
\left[ h_j + \left( \frac{4\sigma T_i^{3}}{\frac{1}{e_j} + \frac{1}{e_{j+1}} - 1} \right) \right] T_{i-1,j} - h_j + \left( \frac{4\sigma T_i^{3}}{\frac{1}{e_j} + \frac{1}{e_{j+1}} - 1} \right) T_{i,j} + & \\
\frac{\Delta X_{j+1}}{2k_i, j+1} + \frac{\Delta X_{j+1}}{2k_{i+1}, j+1} & + \frac{\rho_i, j+1 c_p_i, j+1}{2 \Delta \theta} \frac{\Delta X_{j+1}}{T_{i,j+1}} \\
+ & \left( \frac{1}{\Delta X_{j+1}} \right) T_{i, j+1} - T_{i, j+1}
\end{align*}
\]

\[ (20a) \]

(4) Last node of an interior material with an air gap between materials:

\[
\begin{align*}
\left( \frac{T_{i-1,j} - T_{i,j}}{\Delta X_j} \right) + & \\
\frac{\Delta X_j}{2k_{i-1}, j} + \frac{\Delta X_j}{2k_{i}, j} & - h_j \left( T_{i,j} - T_{i,j+1} \right)
\end{align*}
\]

\[
- \left( \frac{1}{e_j} + \frac{1}{e_{j+1}} - 1 \right) \left( T_{i,j} - T_{i,j+1} \right) = \frac{\rho_i, j c_p_i, j + \Delta X_j}{2 \Delta \theta} \left( T_{i,j} - T_{i,j} \right)
\]

\[ (21) \]
Rearranging and linearizing, equation (21) becomes

\[
\left( \frac{1}{\Delta \theta_{i-1,j}} + \frac{\Delta X_j}{2k_{i-1,j} + 2k_{i,j}} \right) T'_{i-1,j} - \left[ \begin{array}{c}
\sum_{j} h_j + \frac{1}{\Delta \theta_{i-1,j}} + \frac{\Delta X_j}{2k_{i-1,j} + 2k_{i,j}} + \left( \frac{4 \sigma T^3_{i,j}}{1 - \frac{1}{\epsilon_j} - \frac{1}{\epsilon_{j+1}} - 1} \right) \\
+ \frac{\rho_{i,j} \cdot c_{p_i,j} \cdot \Delta X_j}{2 \Delta \theta} \end{array} \right] T'_{i,j} + \left[ \begin{array}{c}
h_j + \left( \frac{4 \sigma T^3_{i,j+1}}{1 - \frac{1}{\epsilon_j} - \frac{1}{\epsilon_{j+1}} - 1} \right) T'_{i,j+1} \\
\end{array} \right]
\]

\[
= - \frac{\rho_{i,j} \cdot c_{p_i,j} \cdot \Delta X_j}{2 \Delta \theta} T'_{i,j} + \left( \frac{3 \sigma}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1 \right) \left( T'_{i,j+1} - T'_{i,j} \right)
\]

(21a)

(5) Final node in backup structure:

(a) Adiabatic surface –

\[
\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j} = \frac{\rho_{i,j} \cdot c_{p_i,j} \cdot \Delta X_j}{2 \Delta \theta} \left( T'_{i,j} - T'_{i,j} \right) \]

(22)

Rearranging, equation (22) becomes

\[
\left( \frac{1}{\Delta \theta_{i-1,j}} + \frac{\Delta X_j}{2k_{i-1,j} + 2k_{i,j}} \right) T'_{i-1,j} - \left( \frac{1}{\Delta \theta_{i-1,j}} + \frac{\Delta X_j}{2k_{i-1,j} + 2k_{i,j}} \right) T'_{i,j} + \frac{\rho_{i,j} \cdot c_{p_i,j} \cdot \Delta X_j}{2 \Delta \theta} T'_{i,j} = - \frac{\rho_{i,j} \cdot c_{p_i,j} \cdot \Delta X_j}{2 \Delta \theta} T_{i,j}
\]

(22a)
(b) Radiation and/or convection loss to cabin environment –

\[
\left(\frac{T_{i-1,j} - T_{i,j}}{\Delta X_j} + \frac{T_{i,j} - T_{env}}{\Delta X_j} \right) = h_{env} \left( T_{i,j} - T_{env} \right)
\]

\[
-F_{env} \sigma \left( T_{i,j} - T_{env} \right) = \frac{\rho_{i-j} c_{i-j} \Delta X_j}{2 \Delta \theta} \left( T_{i,j} - T_{i,j} \right)
\]

Rearranging, equation (23) becomes

\[
\left(\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}\right)T_{i-1,j} = \left( h_{env} + \frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}} + F_{env} c_{i-j} \right) T_{i,j} - \frac{\rho_{i-j} c_{i-j} \Delta X_j}{2 \Delta \theta} T_{i,j}
\]

\[
- h_{env} T_{env} - F_{env} \sigma \left( T_{i,j}^l + T_{env}^l \right)
\]

Discussion of Assumptions

A brief discussion of several assumptions and approximations made in deriving the heat balance equations is now presented.

As shown in the Derivation of Equations section, transient heat conduction, thermal degradation, and the flow of the gaseous products from the reaction zone are the internal thermal transport phenomena of interest. Several methods are available in the treatment of the thermal decomposition process, and they differ primarily in whether the chemical decomposition occurs in a single plane at a fixed temperature or whether a spacially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric test data for the particular material being investigated. Figure 5 is a thermogravimetric curve for typical charring ablation material. From this curve, the rate of pyrolysis \( \dot{m}_g \) is calculated by knowing the
temperature change of a particular node with time, that is, 

\[ \dot{\rho}_1 = \frac{\rho'_1 - \rho_1}{\Delta \theta} \quad (24) \]

and 

\[ \dot{m}_g_1 = \sum_{i} \dot{p}_i \Delta X_i \quad (25) \]

This method of computing the gas-generation rates and local instantaneous density may be subject to error since the thermogravimetric curve of a material is influenced by temperature rise rate (deg/sec), and the reaction zone may shift up and down the temperature scale. This error can be eliminated by the use of an Arrhenius expression of the form

\[ \frac{d\rho}{d\theta} = -A (\rho - \rho_c)^n e^{-\frac{E}{RT}} \quad (26) \]

The method now being used in STAB II (equation (25)) to calculate the pyrolysis rate is being investigated to determine its validity. The final formulation of the pyrolysis rate law must rest heavily on the experimental rate data for the material under investigation. The use of simple expressions such as equations (24) and (25) may be entirely adequate, depending upon activation energy for the decomposition process and order of reaction.

The aerodynamic heating input in the analysis consists of convective and radiative components treated separately. This distinction is necessary since the convective heating can be significantly reduced as a result of the injection of the ablation gases into the boundary layer, with generally no effect on radiant heating. Reduction in the convective heating rate can be approximated by the following expression (ref. 6):

\[ \dot{q}_{\text{block}} = \eta m_g (H_T - H_w) \quad (27) \]

Therefore,

\[ \dot{q}_{c, \text{b}, \text{low}} = \dot{q}_{cw} \left( \frac{H_T - H_w}{H_T - H_w^{200}} \right) - \dot{q}_{\text{block}} \quad (28) \]
However, equation (28) is unsatisfactory for high blowing rates, since \( q_{\text{block}} \) can become greater than \( q_{cw} \). An experimental curve of blocking effectiveness \( \psi = \frac{q_{c, \text{blow}}}{q_{cw}} \) as a function of the mass transfer parameter \( \frac{\dot{m}_H T}{q_{cw}} \) can be employed to determine the heating reduction at high blowing rates. Both methods have been employed in the STAB II analysis. Equation (28) is presently in use. However, no satisfactory method for accurately predicting the convective heat blockage has been determined.

Another source of heating is the combustion of the ablation products in the boundary layer. Reference 7 presents an analysis of the oxidation of a carbon surface and the resulting combustive heating. The heating due to combustion as derived in reference 7 is

\[
q_{\text{comb}} = \dot{m}_c \Delta H_c
\]  

(29)

where \( \Delta H_c \) is the heat of combustion per unit weight of char.

The thermal properties of the ablation material are both temperature and state dependent (fully or partially charred). Figure 4 is an illustration of the variation of these properties with temperature and state. The thermal properties are assumed to vary as follows:

1. Char zone \( (T_i \geq T_{\text{char}}) \)
   
   \[
   k_c = f(\text{temp}) \\
   c_p = f(\text{temp}) \\
   \rho_c = \text{constant}
   \]

2. Reaction zone \( (T_{\text{abl}} \leq T_i < T_{\text{char}}) \)
   
   \[
   \rho = f(\text{temp}) = \rho_v + (\rho_v - \rho_c) \left( \frac{T_i - T_{\text{abl}}}{T_{\text{abl}} - T_{\text{char}}} \right) \\
   k = f(\rho) = k_c + (k_v - k_c) \left( \frac{\rho_v - \rho_c}{\rho_v} \right) \\
   c_p = f(\rho) = c_p_c + (c_{p_v} - c_{p_c}) \left( \frac{\rho_v - \rho_c}{\rho_v} \right)
   \]
The calculation of char removal, due to chemical, thermal, or mechanical mechanism or a combination of these mechanisms, has been examined by a multitude of investigators and numerous correlations exist, depending on the specific material involved.

To provide a maximum degree of flexibility for analyzing both ground and flight test data and synthesizing trajectories, the following provisions for char removal (surface movement) are provided:

1. Removal of char as a function of surface temperature.
2. Removal of char at a rate which is a function of time.

As the char is removed, the surface moves with respect to a coordinate fixed in the material. The distance between the initial surface location and the char surface is

\[ s = \int_{0}^{\theta} \dot{s} \, d\theta \]

**ANALYSIS VERIFICATION**

As discussed in the previous sections, approximations and assumptions were made in the analytical model to afford a quick and accurate solution in predicting the thermal response of a charring heat shield. These simplifying assumptions and approximations are expected to introduce only minor errors; however, the validity of the analyses and resultant accuracy can be judged only by a comparison with exact theoretical solutions and experimental data. Three examples have been selected, and a comparison of the STAB II results with the theoretical and test data is discussed in the following paragraphs.

An elementary transient heating example was chosen to demonstrate the accuracy and numerical stability of the STAB II program. A steel slab 6 inches thick was selected and assumed to be at uniform initial temperature of \(460^\circ R\) (\(0^\circ F\)). The thermal properties were considered constant. The
front surface was subjected to a heating rate of 72 Btu/ft\(^2\)-sec, and an adiabatic back surface was assumed. Figure 5 shows a comparison of the STAB II calculated in-depth temperatures as a function of time with the exact solution taken from reference 8.

To demonstrate the STAB II solution with a moving boundary, a slab with constant properties, uniform initial temperature, front surface moving with a constant velocity, and constant surface temperature was chosen. The exact solution for a semi-infinite slab with these boundary and initial conditions is presented in reference 9. Figure 6 presents a comparison of the STAB II temperature response with the exact solutions. As can be seen from this figure, the two solutions are not in agreement for approximately the first 50 to 60 seconds of the transient. This disagreement is the result of the quasi-steady state assumption made in the exact solution analysis.

\[
\left[ \frac{\partial T}{\partial \theta} \right]_{\xi=0} = 0; \quad k \frac{\partial T}{\partial x} \bigg|_{x=0} = \dot{S} \rho c_p \Delta T
\]

A calculation was made to estimate the induction time (time at which \( \frac{\partial T}{\partial \theta} = 0 \) is a good assumption) and found to be approximately 60 seconds, which is in agreement with the STAB II results.

Finally, to verify the fully charring ablation model, an example of a typical charring material was chosen. (See the sample problem in appendix A.) The charring ablation material is initially 1.6 inches thick with an adiabatic back surface and a constant heat flux of 95 Btu/ft\(^2\)-sec applied to the front surface. The surface is assumed to recede at a constant velocity of \( 3.05 \times 10^{-3} \) in./sec. Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located at a depth of 1.0 inch. The disagreement could be attributed to several possible errors: thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, et cetera) is presently being investigated.

Tables I and II present the input and output data used for this example. Figures 8, 9, and 10 are the resulting plot routine output.

The comparisons between the computer results and the exact solutions and test results are considered satisfactory.
CONCLUDING REMARKS

An analysis and a computer program for predicting the transient thermal response of a charring ablation thermal protection system has been described. The numerical formulation of the equations is such that an implicit solution is obtained. This method of solution affords both a rapid and accurate solution for both ablating and nonablating type problems.

Provision is made in the program for a number of surface boundary conditions. These provisions allow efficient use of the program for analyzing both ground and flight test data and trajectory synthesis.

The computer program has been checked out with both exact solutions and actual ablation test data. The numerical results are in good agreement with the exact solutions and test data. However, the analysis depends upon using good property values, and some effort must be expended in obtaining the best possible thermal properties.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, November 1, 1965
REFERENCES

1. Israel, Martin H.; and Nardo, S. V.: An Annotated Bibliography on Ablation and Related Topics. PIBAL rep. no. 686, Polytechnic Institute of Brooklyn, May 1964.


APPENDIX A

SAMPLE PROBLEM

The following sample problem is shown to indicate the form of the data input and the program output. A typical charring material subjected to a constant heating rate as experienced in an arc tunnel is presented. The following is a sketch of the model:

![Sketch of the model]

The various material properties and dimensions are shown in the program output of Table II. The insulation is assumed to be ablation material for this problem. The problem coding sheet and subsequent data card listing are shown in Table I. The initial temperature of the structure was assumed uniform and equal to 530° R (70° F). Figures 8, 9, and 10 are the output data obtained from the plot routines.
APPENDIX B

PROGRAM USAGE INSTRUCTIONS

IBM 7094/40 program F021, standard ablation program, designated STAB II, is designed to evaluate the transient thermal performance of a charring ablation heat protection system. The program considers one ablating material and up to 12 different materials in the supporting backup structure. A maximum of 50 nodes may be considered in the ablation material, and a maximum of 10 nodes per material is allowed for each backup structure material. Air gaps can be considered between successive materials in the backup, thus allowing for both radiative and/or convective heat transfer between materials. The heat loss to the cabin environment from the backup structure can be accomplished by both radiation and/or convection, or an adiabatic backface surface may be prescribed.

Unless otherwise specified, the input problem data are in "floating point" form (E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. It is suggested that each floating point number have a sign, a two-digit exponent, and a decimal point. For example, the number 145.23 can be written as +1.4523 +02, +145.23 +00, or +.14523 +03.

Input Nomenclature

The nomenclature used in the problem data input is as follows:

NCASE number of problems to be run successively
HEAD any 72 alphabetical and/or numerical characters
TITLE control card for reading in new input for successive problems
   1. blank card - new data will be read in
   2. Six asterisks in columns 1 to 6. Skip to next read statement
TLIM time limit of problem, sec
TINT starting time of problem, sec
NPTT number of points in time-step table (the minimum value of NPTT is 2)

NPLT output plot control
   =1 plot routine will be used
   =0 plot routine will be ignored
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTABLE</td>
<td>time in time-step table, sec</td>
</tr>
<tr>
<td>DELTT</td>
<td>time step to be used for each calculation - starting at time TTABLE, sec</td>
</tr>
<tr>
<td>IPRC</td>
<td>variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals</td>
</tr>
<tr>
<td>FCNV</td>
<td>factor to correct convective heating rate for various body locations</td>
</tr>
<tr>
<td>FRAD</td>
<td>factor to correct radiative heating for various body locations</td>
</tr>
<tr>
<td>TABL</td>
<td>temperature at which ablation starts, °R</td>
</tr>
<tr>
<td>TCHAR</td>
<td>temperature at which ablation stops, °R</td>
</tr>
<tr>
<td>TREC</td>
<td>surface temperature, °R, or time at which char removal is to start, sec</td>
</tr>
<tr>
<td>RHV</td>
<td>density of virgin ablation material, lb/ft³</td>
</tr>
<tr>
<td>RHOC</td>
<td>density of mature char material, lb/ft³</td>
</tr>
<tr>
<td>FBLW</td>
<td>blowing efficiency of ablation gases in reducing convective heating</td>
</tr>
<tr>
<td>EMV</td>
<td>emissivity of virgin ablation material</td>
</tr>
<tr>
<td>EMC</td>
<td>emissivity of charred ablation material</td>
</tr>
<tr>
<td>H300</td>
<td>enthalpy of air at 300° K, 129.06 Btu/lbm</td>
</tr>
<tr>
<td>VL</td>
<td>initial thickness of virgin ablation material, in.</td>
</tr>
<tr>
<td>HV</td>
<td>heat of degradation of virgin material, Btu/lbm</td>
</tr>
<tr>
<td>VPT</td>
<td>test to determine if the reaction zone and char zone thermal properties are irreversible with temperature</td>
</tr>
<tr>
<td>=0</td>
<td>properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT)</td>
</tr>
<tr>
<td>=1</td>
<td>properties are reversible</td>
</tr>
<tr>
<td>FV</td>
<td>view factor for external environment</td>
</tr>
<tr>
<td>TV</td>
<td>sink temperature of external environment, °R</td>
</tr>
</tbody>
</table>
CHARK  thermal conductivity of material at $T_{CHAR}$, Btu/ft-hr$^0$R

CHARC  specific heat of material at $T_{CHAR}$, Btu/lbm$^0$R

ABLK  thermal conductivity of material at $T_{ABL}$, Btu/ft-hr$^0$R

ABLC  specific heat of material at $T_{ABL}$, Btu/lbm$^0$R

NF  number of node points in ablation material

NKC  number of points in char thermal conductivity - temperature table

NCPC  number of points in char specific heat - temperature table

NKV  number of points in virgin thermal conductivity - temperature table

NCPV  number of points in virgin specific heat - temperature table

NREC  number of points in surface recession - temperature or time table

TKC  temperature values in char thermal conductivity - temperature table, $^0$R

XKC  thermal conductivity values in char thermal conductivity - temperature table, Btu/ft-hr$^0$R

TCPC  temperature values in char specific heat - temperature table, $^0$R

CPC  specific heat values in char specific heat - temperature table, Btu/lbm$^0$R

TKV  temperature values in virgin thermal conductivity - temperature table, $^0$R

XKV  thermal conductivity values in virgin thermal conductivity - temperature table, Btu/ft-hr$^0$R

TCPV  temperature values in virgin specific heat - temperature table, $^0$R

CPV  specific heat values in virgin specific heat temperature table, Btu/lbm$^0$R

TS  temperature, $^0$R, or time, sec, values in the surface recession table
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>Surface recession values in the surface recession - temperature or time table, in./sec</td>
</tr>
<tr>
<td>NTRAPT</td>
<td>Number of time points in the trajectory input table</td>
</tr>
<tr>
<td>TIME</td>
<td>The array of (NTRAPT) trajectory time values, sec</td>
</tr>
<tr>
<td>QCøN</td>
<td>The corresponding array of cold wall convective heating rates, Btu/ft² - sec</td>
</tr>
<tr>
<td>QRAD</td>
<td>The corresponding array of radiative heating rates, Btu/ft² - sec</td>
</tr>
<tr>
<td>VEL</td>
<td>The corresponding array of flight velocity, ft/sec</td>
</tr>
<tr>
<td>NMB</td>
<td>Number of materials in backup structure</td>
</tr>
<tr>
<td>NPBS</td>
<td>Total number of node points in backup structure</td>
</tr>
<tr>
<td>BL</td>
<td>Total thickness of backup structure, in.</td>
</tr>
<tr>
<td>XNPM</td>
<td>Number of nodes in each individual material in backup structure</td>
</tr>
<tr>
<td>NKPB</td>
<td>Number of points in each individual backup structure material thermal conductivity - temperature table</td>
</tr>
<tr>
<td>NCPB</td>
<td>Number of points in each individual backup structure material specific heat - temperature table</td>
</tr>
<tr>
<td>XIDNT</td>
<td>Any 72 alphanumeric characters used to describe each individual material in the backup structure</td>
</tr>
<tr>
<td>TXK</td>
<td>Temperature values in backup material thermal conductivity - temperature table, °R</td>
</tr>
<tr>
<td>XK</td>
<td>Thermal conductivity values in backup material thermal conductivity - temperature table, Btu/ft-hr-°R</td>
</tr>
<tr>
<td>TCP</td>
<td>Temperature values in backup material specific heat - temperature tables, °R</td>
</tr>
<tr>
<td>CFX</td>
<td>Specific heat values in backup material specific heat - temperature tables, Btu/lbm-°R</td>
</tr>
<tr>
<td>RHøBX</td>
<td>Density of individual materials in backup, lb/ft³</td>
</tr>
<tr>
<td>XBM</td>
<td>Thickness of individual materials in backup, in.</td>
</tr>
<tr>
<td>EMFB</td>
<td>Emissivity of front surface of each material in backup</td>
</tr>
</tbody>
</table>
EMBB  emissivity of back surface of each material in backup
H  film coefficient between adjacent materials in backup, Btu/ft\(^2\)-hr-\(^\circ\)R
GAPX  width of gap between adjacent materials in backup, in.
FTEST, BTEST  tests to determine the mode of heat transfer between materials for the front and backface of each material respectively
  =0  conduction only between materials
  =+1  convective heat transfer only
  =-1  radiation only or radiation and convection heat transfer
TENV  temperature of interior cabin environment, \(^\circ\)R
HENV  film coefficient to interior cabin environment, Btu/ft\(^2\)-hr-\(^\circ\)R
FENV  view factor and emissivity product for radiative heat transfer to cabin interior
QLSS  boundary condition between last node of the backup structure and cabin environment
  =0  adiabatic surfaces
  =+1  radiation and/or convective loss
TEST2  determines the proper heat shield initial temperature distribution
  =0  constant, uniform initial temperature distribution
  =-1  arbitrary initial temperature distribution
  =+1  linear temperature distribution
Tempi  temperature to be used when constant temperature distribution option is used, \(^\circ\)R
TX\(\theta\)  initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, \(^\circ\)R
TEMDF  arbitrary temperature distribution values, to be used only if TEST2 is negative, \(^\circ\)R
The input data are given in the following order. Each number in the following listing refers to a separate record and must begin on a new data card. The input data have been grouped, where possible, into various sections dealing with a particular part of the input, that is, ablation material properties, trajectory data, backup structure, et cetera. This grouping permits the use of a minimum number of input cards for running successive problems. The title card as described in the input nomenclature controls the input for successive problems.

1. The first data card contains the value of NCASE. NCASE is an integer (I5 format) and must end in column 5. This card tells how many problems are to be run and is entered only once at the start of the data deck.

2. Columns 1 to 72 of the second data card contain any title or identification information desired; any alphanumeric character may be used. This card is printed at the top of the first page of the output. This card must be included in all successive problems to be run.

(a) Problem time section

3. TITLE card - if blank, cards 4 and 5 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 6.

4. This record contains, in the following order, TLIM, TINT, NPTT, and NPLT. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPLT are integers entered with an I5 format and must end in column 30 and 35.

5. Start entering the values of TTABLE, DELTT, IPRC. TTABLE and DELTT are floating-point numbers and must end in columns 12 and 24. IPRC is entered as integer with an I5 format and must end in column 30. Use as many cards as required to enter NPTT values.

(b) Heating rate factors section

6. TITLE card - if blank, card 7 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 8.
7. Enter the FCNV and FRAD. These numbers are entered as floating-point numbers and must end in columns 12 and 24.

(c) Ablation material section

8. TITLE card – if blank, cards 9 to 18 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 19.

9. HEADNG card – any alphanumeric characters in columns 1 to 72. Records 9 to 18 contain input data for the ablation material.

10. Enter TABL, TCHARGE, TRECH, RHV, RHVC, and FBLW. These numbers are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72.

11. Enter EMV, EMC, H300, VL, HV, and VPT. Use the same format as card 10.

12. Enter FV, TV, CARK, CHARC, ABLK, and ABLC. Use the same format as card 10.

13. This card contains, in the following order, NP, NKC, NCPC, NKV, NCPV, and NREC. These numbers are fixed-point integers and must end in columns 5, 10, 15, 20, 25, and 30. An I5 format is used to read in these numbers.

14. Start entering the curve of TKC versus XKC, with the values of TKC ending in columns 12, 36, and 60. The corresponding values of XKC must end in columns 24, 48, and 72; for example, three TKC-XKC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter NKC points on the curve.

15. Start entering the curve of TCPC versus CPC with the values of TCPC, ending in columns 12, 36, and 60. The corresponding values of CPC must end in columns 24, 48, and 72; for example, three TCPC-CPC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter the NCPC points on the curve.

16. Start entering the curve of TKV versus XKV with the values of TKV ending in columns 12, 36, and 60. The corresponding values of XKV must end in columns 24, 48, and 72; for example, three TKV-XKV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter the NKV points on the curve.

17. Start entering the curve of TCPV versus CPV with the values of TCPV, ending in columns 12, 36, and 60. The corresponding values of CPV must end in columns 24, 48, and 72; for example, three TCPV-CPV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPV points on the curve.

18. Start entering the curve of TS versus SR with the values of TX, ending in columns 12, 36, and 60. The corresponding values of SR must end in columns
24, 48, and 72; for example, three TS-SR points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NREC points on the curve.

(d) Trajectory data section

19. TITLE card - if blank, cards 20 to 22 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 23.

20. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 21 and 22 contain trajectory input data.

21. Enter NTRAPT. This number is an integer and must end in column 5. An I5 format is used to read in this number.

22. Start entering the trajectory data in the following order: TIME, QCØN, QRAD, VEL. These values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48. There are four trajectory data points on one card. Use as many cards as required to enter NTRAPT points in the trajectory.

(e) Backup structure section

23. TITLE card - if blank, cards 24 to 31 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 32.

24. Enter NMB, NPBS, and BL. These three values must end in columns 5, 10, and 24. NMB and NPBS are integers and are read in under an I5 format. BL is a floating-point number.

25. Enter the values of XNPM. XNPM is in floating-point form and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

26. Enter the values of NKPB and NCPB. These numbers are integers and NKPB must end in columns 5, 15, 25, 35, and 45; and the corresponding values of NCPB must end in columns 10, 20, 30, 40, and 50. An I5 format is used to read these values. Five NKPB-NCPB values are contained on one card. Use as many cards as are required to enter NMB points.

27. XIDNT card - any alphanumeric characters in columns 1 to 72. This card contains a description of each backup material.

28. Start entering the curve of TXK versus XK with the values of TXK, ending in columns 12, 36, and 60. The corresponding values of XK must end in columns 24, 48, and 72; for example, three TXK-XK points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NKPB points on the curve.
29. Start entering the curve of TCP versus CPX with the values of TCP, ending in columns 12, 36, and 60. The corresponding values of CPX must end in columns 24, 48, and 72; for example, three TCP-CPX points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPB points on the curve. Repeat records 27, 28, and 29 until the properties for NMB materials have been entered. The maximum number for NMB is 12.

30. Start entering the following values in order: RHØEX, XBM, EMFB, and EMBB. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

31. Start entering the following values in order: H, GAPX, FTEST, and BTEST. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

(f) Interior environment section

32. TITLE card – if blank, cards 33 and 34 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 35.

33. HEADNG card – any alphanumeric characters in columns 1 to 72. Record 35 contains properties of environment.

34. Enter the following: TENV, HENV, FENV, and QLØSS. The values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48.

(g) Initial temperature section

35. TITLE card – if blank, records 36 and 37 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record 39.

36. HEADNG card – any alphanumeric characters in columns 1 to 72. Records 37 and 38 contain initial temperature distribution input.

37. Enter TEST2, TEMPI, and TXØ. These values are entered as floating-point numbers and must end in columns 12, 24, and 36.

NOTE: If TEST2 is a negative number, record 38 must be submitted; otherwise, skip to record 39.

38. Enter the arbitrary temperature distribution values, TEMDI. These values are entered as floating points with a 6E12.8 format. Use as many cards as required to enter NP plus NPBS node points.

(h) Enthalpy - temperature section
39. TITLE card - if blank, records 40 and 41 must be submitted; if six asterisks are punched in columns 1 to 6, this is the last data card in the problem input.

40. Enter NHP. This value is an integer and must end in column 5. An I5 format is used to read in this number.

41. Start entering the curve of HX versus TW with the value of HX ending in columns 12, 36, and 60. The corresponding values of TW must end in columns 24, 48, and 72; for example, three HX-TW points are contained on one card. The numbers are entered as floating points. Use as many cards as required to enter NHP points on the curve. Record 41 consists of the last data cards required as input for a problem.

As many successive problems as desired may be run at one time by proper input preparation. STAB II has been designed to save all input information until it is changed by new input data. Therefore, the use of the TITLE control card is very important when running more than one problem and using the input data of previous problems. As shown, each input section starts with a TITLE control card for determining whether new input data are to be used. If any data are changed within a section, then all data cards required for that section must be submitted.

STAB II can also be used for solving one-dimensional transient heat-conduction problems of nonablating materials. The following input parameters must be adhered to:

1. TABL must be greater than the maximum temperature expected during the calculation. Also, TABL > TChar > TRec.

2. The ablation material must be considered to be the first material in the structure for calculation purposes.

3. The virgin and char properties must be inputed as described above but can have the same values; that is, XKV = XKC, CPC = CPV, RH@J = RH@!, et cetera.

The following dimensional statements and program limitations should not be violated when preparing the input described above for ablating and non-ablating structure:

1. All property tables can have a maximum of 20 points (i.e., a temperature and specific heat value constitute one point).

2. The surface recession table can have a maximum of 50 points (TS and SR constitute one point).

3. The trajectory table can have a maximum of 300 points (TIME, QCN, QRAD, and VEL constitute one point).
4. The ablation material can be broken into a maximum of 50 nodes. The backup structure can consist of up to 12 different materials with a maximum of 10 nodes per material.

5. A minimum of three nodes per material (ablation or backup) must be specified.

6. A minimum of two materials must be specified (ablation material and one backup structure material).

7. Pure conduction only is allowed between the ablation material and the first material in the backup.

8. If any data input is changed in the Ablation Material Section on successive problems, the Ablation Material Section data cards plus the Initial Temperature Section data cards must be submitted.

Program Output Information

The computed results are available in two forms of output: tabular and plot outputs. The tabular output presents the computed results in block type form for each computation step as controlled by the print count control number. As discussed in the preparation of input data, both the computational time step and print control can be varied throughout the running of a problem. Therefore, excessive printed output is avoided, and there is a considerable savings in actual machine computation time. The plot outputs are printed and plotted only when the entire set of problems to be run are completed.

Tabular output. – The program prints a listing of the data input parameters for identification of the problem and ease in identifying any input mistakes. For stacked problems, the program prints only that input information that is changed from the previous problem. The following calculated problem output is printed:

1. Time, sec
2. Cold wall convective heating rate without blowing, Btu/ft\(^2\)-sec
3. Radiative heating rate, Btu/ft\(^2\)-sec
4. Velocity, ft/sec
5. Gas ablation rate, lbm/ft\(^2\)-hr
6. Char ablation rate, lbm/ft\(^2\)-hr
7. Total ablation rate, lbm/ft\(^2\)-hr
8. Surface recession depth from original surface, in.
9. Hot wall convective heating rate without blowing, Btu/ft²-sec
10. Temperature distribution in ablation material, °R
11. Temperature distribution in backup structure, °R

The temperatures printed for the ablation material are for fixed distances from the original surface. These distances are calculated from the initial ablation material thickness and number of nodes in ablation material. For example

let

\[ VL = 1.0 \text{ in.} \]
\[ NP = 11 \]

then

\[ \Delta X = \frac{VL}{NP - 1} = 0.1 \]

The temperatures will be printed for X distances of 0, 0.1, 0.2, 0.3, et cetera, from the original surface until the surface has receded beyond these fixed distances at which time the node no longer exists and is dropped from the printout. This is illustrated in the following way: let surface recession = 0.26 inch. The first temperature printed then is the surface temperature of the material, located 0.26 inch from the original material surface. The following printed ablation material temperatures are for X distances of 0.3, 0.4, 0.5, ..., 1.0 inch.

The format for the temperature distribution printout is E16.5 with six temperatures printed per line.

Plot output. — The plot output gives the following ablative material performance parameters as a function of time:

1. Surface depth, in.

2. Bondline temperature between ablator and backup structure, °R

3. Two selected isotherm depths

These values are also printed in tabular form for ease in checking and replotting of the results. The plotted curves contain all maximum and minimum values of the parameters.
APPENDIX C

PROGRAM IN FORTRAN STATEMENTS
DIMENSION ESAVE1(3), DSAVE2(3), DSAVE3(3)
DIMENSION TITLE(12), HFPADNR(12), XINT NT(12, 12), TKC(20), XCC(20),
         TCPC(20), TKV(20), XKV(20), TCPV(20), CPV(20), TIME(30), GCON(300),
         R2RAD(300), VEL(300), XNPM(12), NKPR(12), NCPR(12), TKX(20, 12),
         XK(20, 12), 3, TCP(20, 12), CPX(20, 12), RHOBX(12), XBM(12),
         FMB(12), EMBR(12), HX(12), 4, GAPPX(12), FTEST(12), RTEST(12),
         FMD1(200), TXI(200), TX2(200),
         5TX2(10, 12), TUL1(200), TUL2(200), HX(50), Tw(50), IR(50),
         1R1(50), 6IR2(50), TUL5(50), IFM(50), TY(200), A(200), R(200),
         C(200), N(300), 7N(50), RHO(50), CP(50), XKR(10, 12),
         CPB(10, 12), XMDG(50),
         8YK(50), AB(10, 12), RB(10, 12), CR(10, 12), DB(10, 12), SR(10, 12),
         9RP(10, 12), RB2(10, 12), H(12), S(50), NPM(12),
DIMENSION TUL5(50), RHOY1(50), RHOY2(50), DHO(50), TCPC(20),
DIMENSION TS(50), SR(50),
DIMENSION TTALE(20), NELTT(20), IPPC(20),
DIMENSION ASAVE1(3), ASAVE2(3), ASAVE3(3), BSAVE1(3), BSAVE2(3),
1HASAVE(3), CSAVE1(3), CSAVE2(3), CSAVE3(3), HFPAD(12),
1NASAVE(3), DSAVE2(3), DSAVE3(3),
DIMENSION XRA(30), YAI(30),
COMMON TKC, XKC, TCP, TCPC, TKV, XKV, TCPV, CPV, XNPM, RHOX, XRM, EMBR,
         IFMP, NKPR, NCPR, TXK, XKP, TCP, CPV, NPM, GAPX, FTEST, RTEST,
         HMD1, TXI,
         2TX2, TX2T, TUL, TUL1, TUL2, TR, IR1, IR2, A, B, C, D, S, R, AR,
         RB, CR, DB, SR,
         3RP1, RR2, TY, RHOY1, RHOY2, XMDG, RHO, CPY, XKR, CPB, DX, DT,
         XLOST,
         4TABL, TCHAR, TRFC, RHO, RHOX, FLDOW, FMV, EMC, H300, NKC, NCPC,
         NKV, NCPV, 5NP, NMR, NPRS, NFTEST, FMD1, TXO, TFNV, HENU, FFNV,
         GLOSS, TLM, TINT,
         COMMON I1, I2, I3, I4, I5, I6, IN, INT, DX, XMT, TL, VL, BL, DMP,
         FR1, ERR2,
         1FR3, FR4, HV, VPT, CHAK, CHARC, ABLK, ARLK, XMDC, H,
         3000 FORMAT(12A6), 3001 FORMAT(1X, 12A6), 3002 FORMAT(6E12.8),
         3003 FORMAT(6I5), 3004 FORMAT(115), 3005 FORMAT(2I5),
         3007 FORMAT(2I5, 1E14.8), 3008 FORMAT(//I1X, 12A6),
         3009 FORMAT(1H1, 1X, 12A6), 3010 FORMAT(2E12.8),
         3011 FORMAT(2E12.8, 16),
       DATA PRVOS/0454545454545454/
       READN 11
       STOP=9999,
       READ(5, 3003) NCASE
       LPL0T=0
       JCNT=0
50 NK=1
11=2
I2=2
I3=2
I4=2
I5=2
I6=2
I17=2
INT=1
XLOST=0.0
XMT=0.0
XMDT=0.0
FRR1=0.0
FRR2=0.0
FRR3=0.0
FRR4=0.0
ICT=0
CONT=0
XMDC=0.0
NKP=1
XLSTV=0.0
NRS=2
FRR5=0.0
TPI=0
TCT=0
TLOT=1
NXA=1
NXB=1
NXC=1
NXD=1
SAVEY3=-100.
SAVEY4=100.
XO=0.0
XTOT=0.0
C
C GENERAL TITLE OF PROBLEM
100 READ(5,3000) (HEAD(K),K=1,12)
WRITE(6,3009) (HEAD(K),K=1,12)
LLOT=LLOT+1
WRITE (11)(HEAD(I),I=1,12)
WRITE(6,110)
110 FORMAT(/1X,11HINPUT DATA,//)
READ(5,3000) (TITLE(L),L=1,12)
TITITLE(1),FO,PRVOS,GO TO 150
READ(5,3011)TLIM,TINT,NPTT,NPLT,DTMP,TMP
READ(5,3012) (TTARLE(I),DFLT(I),IPRC(I),I=1,NPTT)
T=TINT
NTS=DFLT(1)
DOM=DFLT(1)/3600.0
WRITE(6,120) TLIM,TINT,NPTT
120 FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X,5
1HNPPTT=,1X)
WRITE(6,122)
122 FORMAT(/1X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL)
WRITE(6,124) (TTARLE(I),DFLT(I),IPRC(I),I=1,NPTT)
124 FORMAT(5X,1PE10.4,6X,1PE10.4,9X,14)
C LOCATION FACTORS FOR CONVECTIVE AND RADIATIVE HEATING

150 READ(5,3000) (TITLE(L),L=1,12)
IF(TITLE(1),EQ.,'PROVIOUS') GO TO 200
READ(5,3002) FCONV+FRAD
WRITE(6,155) FCONV+FRAD

155 FORMAT(1X,10H1H0+,1H6H,13HFCONV=,1PE12,5,4X5HFRAD=,1PF12,5/)

C PROPERTIES OF ABLATION MATERIAL

200 READ(5,3000) (TITLE(L),L=1,12)
IF(TITLE(1),EQ.,'PROVIOUS') GO TO 300
READ(5,3000) (HEADNG(K),K=1,12)
READ(S#3000) (TKE(K),K=1,12)
READ(S#3001) (TKC(K),XKC(K),K=1,NKC)
READ(S#3002) (TCPM(M),CPM(M),M=1,NCPC)
READ(S#3002) (TKV(L),XKV(L),L=1,NKV)
READ(S#3002) (TCPN(N),CPN(N),N=1,NCPV)
READ(5,3002) (TS(I),SR(J),I=1,NRFC)
WRITE(6,1000) (HEADNG(K),K=1,12)

1000 FORMAT(1X,22HPROPERTIES OF ABLATION MATERIAL/1X,THERMAL,4X,SPF/CIF/3X,TEMPERATURE,4X,CONDUCTIVITY,19X,TEMPERATURE/7X,HEAT)
KLLL=MINO(NKC,NCPC)
WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPC(L),L=1,KLLL)
WRITE(6,222) (TCPM(M),CPM(M),M=1,NCPC)
IF(NKC-NCPC) ?30r23Sr?3?
KLLL=KLLL+I
WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
GO TO 227

227 WRITE(6,226) (TKC(L),XKC(L),TCP(C(L)),CPC(L),L=1,KLLL)
WRITE(6,222) (TKC(L),XKC(L),TCP(C(L)),CPC(L),L=1,KLLL)
IF(NKC=NCPC) ?30r235r?3?
KLLL=KLLL+I
WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
GO TO 225

225 WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
GO TO 225

226 WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
GO TO 225

227 WRITE(6,224) (TCPV(L),CPC(L),L=KLLL,NCPC)
GO TO 225

48
232 KILL = KLL + 1
WRITE (6, 240)
235 FORMAT ((TKC(L), XKC(I), L = KLL, NKC)
WRITE (6, 245) (TS(I), SR(I), I = 1, NRFC)
240 FORMAT ((24X, 1PF12.5, 7X, 1PF12.5)
245 FORMAT (1H10.2H NO. OF TRAJECTORY POINTS = I4)
WRITE (6, 320)
320 FORMAT (1 H30X, 1H PROPERTIES OF TRAJECTORY)
WRITE (6, 330) (TIME(K), QCON(K), QRAD(K), VFL(K), K = 1, NTRAP)
WRITE (6, 340) (TIME(K), QCON(K), QRAD(K), VFL(K), K = 1, NTRAP)
330 FORMAT (1H4-16, 5)
C
C PROPERTIES OF BACKUP STRUCTURE
C
400 HFAD(5, 3) = TITLE(L), L = 1, 12
IF (PUE(L), 1, 1, NPROV) GO TO 500
WRITE (6, 410)
410 FORMAT ((10X, 1H PROPERTIES OF BACKUP STRUCTURE/))
HFAD(5, 3) = NMP, NMP = 1
HFAD(5, 4) = (XNM(K), K = 1, NMP)
HFAD(5, 4) = (NCPH(I), NCPH(I), I = 1, NMP)
415 FORMAT (1H5)
420 CONTINUE
WRITE (6, 420) NMP, NMP = 1
425 FORMAT (1H4X, 1H NO. OF MATERIALS IN BACKUP SHIELD = I4)
WRITE (6, 430) 1, 114/4X, 40HTOTAI
430 FORMAT (1H7)
WRITE (6, 440) 2, SHIELD, 1, 1PE12, 5/
WRITE (6, 450) 1, 12
440 FORMAT (1H7)
WRITE (6, 460) 1, 11
WRITE (6, 470) 1, CP
450 FORMAT (1H7)
WRITE (6, 480) 1, CP
460 CONTINUE
470 IF (LK = LCP) 435, 440, 437
480 CONTINUE
432 FORMAT (1H6)
WRITE (6, 440) 1, 432
435 FORMAT (1H4)
WRITE (6, 440) 1, 435
DO 436 N=KLLLI,LC
WRITE(6,224) (TCP(N,1),CXY(N,1))
436 CONTINUE
GO TO 440
437 ALLLL=KLLLI+1
DO 439 N=KLLLI,LL
WRITE(6,228) (TXK(N,1),XY(N,1))
439 CONTINUE
440 CONTINUE
READ(5,3002) (RHORX(L),XRM(L),EMFR(L),EMRR(L),L=1,NMR)
READ(5,3002) (H(J),GAPX(J),FTEST(J),BTST(J),J=1,NMR)
WRITE(6,450)
450 FORMAT(/S5X,10H0MISTIVITY///XAMATERIAL,5X,7HDFNSITY,7X,9HTHICKM
1F5.7X,9HFRONT,9X,4HHACK,7X,4HNODES/MATERIAL/)
DO 461 LL=1,NMR
WRITE(6,455) (LL,RHORX(LL),XRM(LL),EMFR(LL),FMRB(LLJ),FMRD(LLJ),XNPM(LLJ)
465 FORMAT(11X,I11,8X,1PF10.4,4X,1PF10.4,4X,1PE10.4,6X,1PF1
10.4)
460 CONTINUE
WRITE(6,445)
465 FORMAT(/4X,5AHADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP
1STRUCTURE///XAMATERIAL,5X,16HFLM COEFFICIENT,5X,13HRAP THICKN
2F5.8X,5HTEST,13X,5HTEST/)
DO 481 J=1,NMR
WRITE(6,470) J, H(J),GAPX(J),FTEST(J),BTST(J)
470 FORMAT(I13X,13X,12X,1PF10.4,9X,1PF10.4,7X,1PF11.4,7X,1PE11.4)
480 CONTINUE
C
C PROPERTIES OF ENVIRONMENT
500 READ(5,3000) (TITLE(I),I=1,12)
500 READ(5,3000) (TITLE(I),I=1,12)
500 READ(5,3000) (TITLE(I),I=1,12)
READ(5,3000) (HEADNG(L),L=1,12)
READ(5,3002) TENV,HFUV,FFNV,Q105C
WRITE(6,3008) (HEADNG(L),L=1,12)
WRITE(6,3000) TENV,HFUV,FFNV,Q105C
520 FORMAT(/4X,12HTEMPERATURE,F10.5,4X,17HFLM COEFFICIENT=1PF10.5
1X,4X,12HVIEWS FACTOR=1PE12.5,4X,7HO LOST=1PE12.5)
C
C INITIAL TEMPERATURE DISTRIBUTION
600 READ(5,3000) (TITLE(I),I=1,12)
600 READ(5,3000) (TITLE(I),I=1,12)
600 READ(5,3000) (TITLE(I),I=1,12)
READ(5,3000) (HEADNG(L),L=1,12)
NPF=NPF+NPS
TL=VL+BL
XNP=NPF
DX=VL/(XNP-1,0)
DX=DX
READ(5,3002) TEST2,TFMPI,TX0
READ(5,3002) TEST2,TFMPI,TX0
IF(T2ST) 610,620,620
610 READ(5,3002) (TEMPDI(K),K=1,NPF)
610 READ(5,3002) (TEMPDI(K),K=1,NPF)
DO 615 K=1,NPF
DO 615 K=1,NPF
615 READ(5,3000) TX1(K),TX2(K),TX1(K)
READ(5,3000) TX1(K),TX2(K),TX1(K)
TUL2(K)=TX1(K)
TUL2(K)=TX1(K)
CONTINUE
CONTINUE
END
DO 619 I=1,NMR
IN=NMR(I)
DO 617 J=1,LN
TX2T(J,I)=TFMDI(L)
I=I+1
617 CONTINUE
619 CONTINUE
GO TO 625
620 CALL TEMI-N
625 WRITE(6,3008) (HEADING(L),L=1,12)
IF(TEST2) 630,635,640
630 WRITE(6,632)
632 FORMAT(4X,'52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBITRARY/1')
WRITE(6,633) (TFMDI(K),K=1,NPF)
633 FORMAT(1PE12.5)
GO TO 645
635 WRITE(6,637) TEMPI
637 FORMAT(//4X,'4HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM1 AND EQUAL TO ,1PE10.4/)  
GO TO 645
640 WRITE(6,641)
641 FORMAT(4X,'54HTEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIELD1')
WRITE(6,642) (TEMPI(L),L=1,NPF)
642 IF(DMP) 700,700,646
646 WRITE(6,647)
647 FORMAT(//)
648 WRITE(6,649) (TX1(L),TX2(I),L=1,NPF)
649 FORMAT(2X,'1PF12.5,4X,1PF12.5')
WRITE(6,650)
650 FORMAT(//)
C
C ENTHALPY AS A FUNCTION OF TEMPERATURE
700 WRITE(5,3002) (TITLE(L),L=1,12)
IF(TITLE(1),EQ,'WATER') GO TO 725
WRITE(5,3003) NHP
WRITE(5,3004) (HX(K),TW(K),K=1,NHP)
725 NO 728 I=1,NP
1P(I)=0
1P1(I)=0
1P2(I)=0
1FM(I)=0
YMDF(I)=0
728 CONTINUE
WRITE(6,730)
730 FORMAT(1H1,12HOUTPUT DATA,
X(I)=0,0
NO 740 I=2,NP
X(I)=X(I)-X(I-1)+DX
740 CONTINUE
750 IF(T=TIME(NK)) 765,770,760
760 NK=NK+1
IF(NK=NTKAPT) 750,750,762
762 WRITE(6,763) NK
763 FORMAT(1H1,33H THE VALUE OF NK IS IN ERROR, NK=114)
GO TO 905

765 IF(NK-2) 762,766,766
766 QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(I-TIMF(NK-1))
QONX=FCOWN*QCONX
GRADX=GRAD(NK-1)+((GRAD(NK)-GRAD(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(I-TIMF(NK-1))
GRADX=FRAD*GRADX
VFLEX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(I-TIMF(NK-1))
GO TO 775
770 QCONX=FCOWN*QCON(NK)
GRADX=FRAN*GRAD(NK)
VFLEX=VEL(NK)
C COMPUTE HFAT, PLOCKAGE AT FRONT SURFACE
775 IF(I17=1) 777,778,779
776 IF(I17=NHP) 777,778,779
777 IF(TXP(INT)-TW(I17)) 782,784,786
778 IF(T(XP INT)-779) TX2(INT)
779 FORMAT((INT)=NH,THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS
1*XCEED UNDER A TEMPERATURE OF,1E10,4)
GO TO 905
780 I17=I17+1
GO TO 775
782 IF(TXP(INT)-TW(I17-1)) 784,786,788
784 I17=I17-1
GO TO 775
786 HWX(HX(I17)+HX(I17-1))/(TW(I17)-TW(I17-1))
1*(TX2(INT)-TW(I17-1))
GO TO 789
788 HWX(HX(I17)
789 HTX=HDO+((VFX**2)/3600,5)
0FLOCK=(F(ALOW*XMODG(INT)*(HTX-HW))/3600,8
C COMPUTE HFAT, PLOCKAGE DUE TO SURFACE COMBUSTION
xMOD=XMOD,
CALC OXIXAT(XMOD,XXINT)
C COMPUTE Q=HOT WALL
790 IF(TMP,E0,0.) GO TO 4001
791 IF(T,0,E,TMP) DMP=1,n
4001 Z=(HTX-HW)/(HTX-HF00)
793 IF(Z<1,0) 790,792,793
790 IF(Z) 791,791,793
791 OHW=0,0
GO TO 1790
792 OHW=QCONX
GO TO 1790
793 OHW=Z+QCONX
1790 IF(Z((OHW-OBLK)1/OHW
1792 IF(Z<0,2) 1790,1790,179A
179A QBLK=O,A*OHW
C COMPUTE HFAT INTO FRONT SURFACE
1794 IF(TMP(INT)) 795,795,797
795 IF(TX2(INT)-TCHAR) 795,795,797
796 FMX=EMV
GO TO 798
797 IFM(INT)=1
FMX=EMC
798 ATNGRADX+QHW*QOXID=QRLOCK-(4,833E-13)*FMX*FV*(I($X2$INT)*4)-
1(TV*4))
IF(DMP) A048$B48$A00
800 WRITE(6,B01)
801 FORMAT(/0/)
WRITE(6,B02) ACONX,GRADX,VELX,HTX,HW,QRLOCK,QHW,QOXID,QIN
802 FORMAT(1X,H5=CONX=1PF12,5,2,6=GRADX=1PF12,5,2=VELX=1PF12,5,
1X,H5=HTX=1PF12,5,2=HW=1PF12,5,1X,H5=QRLOCK=1P
2F12,5,2=QHW=1PF12,5,2=QOXID=1PF12,5,2=QIN=1PF12,5,7)
804 ATINGIN*3600,0
C
C CHECK FOR FRONT SURFACE RECESSION (CHAR LAYER REMOVAL)
CALL RECLSS(XMDG,XLOST,TRFC,DT,PHOC,TS,SJ,TX2(1),NREC,NRS,ERRS,SY)
1,SDOT,DM)
IF(ERR5) A050,8050,905
8050 VLV=VLV*X10ST
X1STV=XLS7TV+X10ST
X1ST=T*XLS7TV*12,0
NXY=VLV/(XNP-1,0)
XV(1)=0,0
DO 17A0 I=2,NP
XV(I)=XV(I-1)+DXV
17A0 CONTINUE
NXY=DXV
IF(ERR4) A068,A069,A05
805 GO TO 905
806 CALL COFF(NPF,SDT)
IF(DMP) A069,A069,A061
8061 WRITE(6,B062)
8062 FORMAT(1X,3H COEFFICIENTS FOR S(WUFT/)
1X,5H=I=1,NPFT
WRITE(6,B064) A(I),A(I),C(I),D(I),I
8064 FORMAT(1H0,H5=I=1,PF12,5,2,H5=I=1,PF12,5,2,H5=H(I)=1,PE12,5,2,
1X,5H=I=1,PF12,5,2,H=13)
8066 CONTINUE
8069 IF(ERR2) A078,A078,A05
807 IF(ERR3) A107,A107,A0A
808 WRITE(6,B09) T0K
809 FORMAT(1H0,1H THF VALUE OF IKK=14)
GO TO 905
810 CALL SWUTF(A,R,C,D,Ty,NPFT,DM)
827 DO A2R I=1,NP
TX1(I)=TX2(I)
TX2(I)=TY(I)
828 CONTINUE
CALL ND2(XLOST,TV,TX2,XP,XC,TX2,DXV,KKX,XLS7TV,NN)
830 CALL ABLATE
XMDT=YMDG(INT)+XMDC
LT=NP+1
DO 1815 I=1,NMB
LTL=NPM(I)
IF(I,F0,1) GO TO 1812
IF(GAPX(I-1),F0,0) GO TO 1812
KKT=1
2.5X1.9xCHAR APLATION RATE=1PF12.5,2X,20HTOTAL ABLATION RATE=1P 3PF12.5/1X,16HFCESSION DFPTH=1PF12.5,2X,10HATOM WALL=1PE12.5)

840 T=T+DTS
841 IF(NPLOT,NE,1) GO TO 842
CALL SAVE(ASAVE1,ASAVF2,ASAVF3,USEA,XFA,XMLT1,DTS,TLIM,T,VALFA)
CALL ISOTHM(XV1,XX2,1060.,NP,Y3)
CALL SAVE(CSAVE1,CSAVF2,CSAVF3,CUSEC,XNC,Y3,DT,TLIM,T,VALEC)
CALL ISOTHM(XV1,XX2,1460.,NP,Y4)
CALL SAVE(DSAVE1,DSAVF2,DSAVF3,DUSED,XND,Y4,DT,TLIM,T,VALUEN)
IF(USFA,NE,0,0)GO TO 9842
IF(USFB,NE,0,0)GO TO 9842
IF(UFC,NE,0,0)GO TO 9842
IF(USFD,NE,0,0)GO TO 9842
GO TO 9843
9842 XPL0T=T-DTS
YPL0T1=VALUEA
IF(USFA,NE,0,0)YPL0T1=USFA
YPL0T2=VALUEP
IF(USFB,NE,0,0)YPL0T2=USFP
YPL0T3=VALUEC
IF(UFC,NE,0,0)YPL0T3=USFC
YPL0T4=VALUED
IF(USFD,NE,0,0)YPL0T4=USFD
WRITE (1)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4
9843 IF(ICTP,NE,0) GO TO 842
ICTP=1
XPL0T=T
YPL0T1=XMLST1
YPL0T2=TX2(NP)
CALL ISOTHM(XV1,XX2,1060.,NP,Y1)
CALL ISOTHM(XV1,XX2,1460.,NP,Y2)
WRITE (1)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4
846 IF(IPRCT=ICTP) 845,845,900
845 WRITE(6,850) T1
ICTP=ICTP+1
IF(IPRCT,EQ,2)ICTP=0
IF(IPRCT,EQ,0)ICTP=0
850 FORMAT(1X,49HTEMPERATURF DISTRIBUTION IN HEAL SHIEFL AT THE FIFD 0
IF THE TEMPE STFP, T=1PE12.5,1X,10HFCOND)
860 FORMAT(1X,49HTEMPERATURF DISTRIBUTION IN THE ABLATING MATERIAL//)
882 FORMAT(1X,49HTEMPERATURF DISTRIBUTION IN THE PACK-UP STRUCTURF//)
ICTP=0
CONTINUE
IF(T-TLIM) 75n,750,9n5
905 IF(NPLOT,NE,1) GO TO 809
XNY3=SAY3=SAY3/12.
XAVY4X=SAYV4X-SAVY1X/12.
TF(SAVYX.EQ.XPLOT)GO TO 9005
WRITE(11)SAVY,SAYV1X,SAYV2X,SAYV3X,SAVY4X
WRITE(11)SAVY,SAV4I=SAVY4X*12.
9005 TF(SAVEXX.EQ.XPLOT)GO TO 9006
SAV4I=SAVY4X*12.
9006 SAV3I=SAVY3X*12.
WRITE(11)SAVY4X,SAVY1X,SAVY2X,SAVY3X,SAVY4X
WRITE(11)SAVY4I
929 FORMAT(1H0,23HMAXIMUM 1040 ISOThFRM =EL7.A,2X23HMAXIMUM 1460 ISOTh
FRM =EF16.A)
WRITE (11)STOP,STOP,STOP,STOP,STOP
909 TF(LPLOT.NE.NCASE)GO TO 911
WRITE(11)FND,FND,END,FND,FND,FND,END,FND,FND
QUIT=FND
WRITE (11)QUIT,QUIT,QUIT,QUIT
FND FILE 11
RFWIN 11
911 TF(TEST2) 910,930,93n
910 DO 920 JJK=1,NPF
TX1(JJK)=TEMP(JJK)
TX2(JJK)=TX1(JJK)
TIL1(K)=TX1(K)
TIL2(K)=TX1(K)
920 CONTINUE
II=II+1
DO 924 I=1,NMR
II=NPM(I)
DO 924 J=1,ILN
TX2(I,J)=TEM(I,IL)
II=II+1
924 CONTINUE
926 CONTINUE
GO TO 940
930 CALL TEMP
940 T=TINT
NX=DX
NT=DFLT(1)
NT=DELT(1)/3600.0
VL=VL
GO TO 50
END
$18FC COEF

C THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX

SUBROUTINE COEFF(NPFT, SDOT)

C

DIMENSION TITLE(12), HEADNG(12), XIDNT(12,12), TKC(20), XK(20)
1PC(20), TKV(20), XKV(20), TCPV(20), CPV(20), TIME(300), QCON(300)
2GAP(300), VEL(300), XNPM(12), NKPB(12), NCPB(12), TXK(20,12), XK(20,12)
3*TCP(20,12), CPX(20,12), RHOBX(12), XM(12), EMFB(12), EMGB(12), HXX(12)
4*GAPX(12), FTEST(12), BTEST(12), TEMDI(200), TX1(200), TX2(200)
5*TK2T(10,12), TUL1(200), TUL2(200), HX(50), TW(50), IR(50), IR1(50)
6*IR2(50), TUL(50), IE(50), TY(200), A(200), B(200), C(200), D(200)
7*R(50), RH0(50), CP(50), DBX(12), XKB(10,12), CPB(10,12), XMDG(50)
8*YK(50), AB(10,12), BB(10,12), CB(10,12), DB(10,12), SB(10,12)
9*RBB1(10,12), RBB2(10,12), H(12), S(50), NPM(12)
10
DIMENSION TTUL(50), RH0Y1(50), RH0Y2(50), ORHO(50), TPCC(50)

C

COMMON TKC, XK, TCP, CPX, CPV, CPV, CPV, XNPM, RHOBX, XMB, EMBM
1EMFB, NKPB, NCPB, TXK, TCP, CPX, XNPM, GAPX, FTEST, BTEST, TEMDI, TX1
2TX2, TX2T, TUL, TUL1, TUL2, IR, IR1, IR2, AB, CB, DB, SB
3RB1, RB2, TY, RH0Y1, RH0Y2, XMDG, RH0, CP, YK, XKB, CPB, DBX, DT, XロST
4TCHAR, TREC, RH0F, RBL0W, EMW, EMW, EMW, H300, TKC, NP, NCPB, NKB, XCPV,
5SNP, NMBP, NPFT, TEST, TEMDI, TX1, TENV, HENV, FENV, GLOSS, TLIM, INT

COMMON N1, N2, N3, N4, N5, N6, GIN, INTDX, XM, TL, XMB, DMP, ERR1, ERR2,
6ERR3, ERR4, HV, VPT, CH, CHAR, ABLK, ABL, XMDG, H

CALL PROP

YN=NP

S(INT)=(RH0(INT)*DX*CP(INT))/(2.0*DT)

R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT))+(1.0/YK(INT+1))))

A(INT)=0.0

B(INT)=(-((XMDG(INT)+XMDG)*CP(INT)+S(INT)+R(INT)-RH0(INT)*CP(INT))

1/(SDOT(2.0*(YN-1.0))))

C(INT)=XMDG(INT+1)*CP(INT+1)+R(INT)+RH0(INT+1)*CP(INT+1)*SDOT

1/(YN-1.5)/(YN-1.0))

D(INT)=(-GIN+S(INT)*TX2(INT))+(XMDG(INT)-XMDG(INT+1)*HV

NPP=1

JNT=INT+1

DO 10 I=JNT,NPP

XI=I

S(I)=(RH0(I)*DX*CP(I))/DT

R(I)=(1.0)/((DX/2.0*YK(I))+(DX/2.0*YK(I+1)))

A(I)=R(I-1)

B(I)=((-XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+RH0(I)*CP(I)*SDOT*(YN-XI)

1/0.5)/(YN-1.0))

C(I)=XMDG(I+1)*CP(I+1)+R(I)+RH0(I+1)*CP(I+1)*SDOT*(YN-XI-0.5)

1/(YN-1.0))

D(I)=(-S(I)+TX2(I))+(XMDG(I)-XMDG(I+1))*HV

10 CONTINUE

R(NP)=1.0/((DXB(1)/(2.0*XKB(1.1)))+(DXB(1)/(2.0*XKB(1)))

S(NP)=(RH0(NP)*DX*CP(NP)+RHOBX(1)*CPB(1,1)*DXB(1))/(2.0*DT)

A(NP)=R(NP-1)

B(NP)=((-XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP))

C(NP)=R(NP)

D(NP)=(-S(NP)*TX2(NP))+(XMDG(NP)*HV

DO 20 I=1,NMB

IF(I-1)=20,20,30

20 AB(I)=A(NP)

BB(I)=B(NP)

CB(I)=C(NP)

DB(I)=D(NP)
GO TO 65
30 L=NPM(I-1)
   IF(BTEST(I)) 45=40*45
40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DBX(I)+RHOBX(I-1)*CPB(L,I-1)*DBX(I-1))/
   (1.2+0*DT)
   RBL(1,I)=(1.0)/(DBX(I-1)/(2.0*XKB(L,I-1))+(DBX(I-1)/(2.0*XKB(L-1,
   1,I-1))))
   RBL(1,I)=(1.0)/(DBX(I)/(2.0*XKB(1,I))+(DBX(I)/(2.0*XKB(2,I))))
   AB(1,I)=RBL(1,I)
   BB(1,I)=(-RBL(1,I)+RBL(1,I)+SB(1,I))
   CB(1,I)=RBL(1,I)
   DB(1,I)=(-SB(1,I)*TX2T(1,I)))
   GO TO 65
45 IF(BTEST(I)) 50=40*55
50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I-1)+0)
   GO TO 60
55 G=0.0
60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DBX(I))/(2.0*DT)
   RBL(1,I)=(1.0)/(DBX(I)/(2.0*XKB(1,I))+(DBX(I)/(2.0*XKB(2,I))))
   AB(1,I)=(H(I-1)+4.0*G*(TX2T(L,I-1))**3)+RBL(1,I)+SB(1,I))
   CB(1,I)=RBL(1,I)
   DB(1,I)=(3.0*G*(TX2T(L,I-1))**4)-(TX2T(1,I)**4)-SB(1,I)*TX2T(1,I)
   LF=NPM(I-1)
   DO 100 J=2,LF
   SB(J,I)=(RHOBX(I)*CPB(J,I)*DBX(I))/DT
   RBL(J,I)=(1.0)/(DBX(I)/(2.0*XKB(J-1,I)))(DBX(I)/(2.0*XKB(J,I))))
   RBL(J,I)=(1.0)/(DBX(I)/(2.0*XKB(J-1,I)))(DBX(I)/(2.0*XKB(J,I))))
   AB(J,I)=RBL(J,I)
   BB(J,I)=(-RBL(J,I)+BB(J,I)+SB(J,I))
   CB(J,I)=RBL(J,I)
   DB(J,I)=(-SB(J,I)*TX2T(J,I)))
100 CONTINUE
   IF(I=NMB) 110=250*250
110 LNF=NPM(I)
   IF(BTEST(I)) 120=15*120
115 LNF=I)=[(RHOBX(I)*CPB(LNF,I)*DBX(I)+RHOBX(I+1)*CPB(1,I+1)*DBX(I+1))/
   (1.2+0*DT)
   RBL(LNF,I)=(1.0)/(DBX(I)/(2.0*XKB(LNF-1,I)))(DBX(I)/(2.0*XKB(LNF,
   1,I)))
   RBL(LNF,I)=(1.0)/(DBX(I+1)/(2.0*XKB(1,I+1)))(DBX(I+1)/
   (1.2+0*XKB(2 I+1))))
   AB(LNF,I)=RBL(LNF,N)
   BB(LNF,I)=(-RBL(LNF,N)+BB(LNF,N)+SB(LNF,N))
   CB(LNF,I)=RBL(LNF,N)
   DB(LNF,I)=(-SB(LNF,N)*TX2T(LNF,N)))
   GO TO 200
120 IF(BTEST(I)) 125=15*127
125 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I-1)+0)
   GO TO 130
127 G=0.0
130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DBX(I))/(2.0*DT)
   RBL(LNF,I)=(1.0)/(DBX(I)/(2.0*XKB(LNF-1,I)))(DBX(I)/(2.0*XKB(LNF,
   1,I)))
   AB(LNF,I)=RBL(LNF,N)
   BB(LNF,I)=(-RBL(LNF,N)+H(I)+SB(LNF,N)+(X2T(LNF,N)**3))
   CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I)**3)
   DB(LNF,I)=3.0*G*(TX2T(1,I)**4)-(TX2T(LNF,N)**4)-SB(LNF,N)*TX2T,
   100 CONTINUE
250 MN=NPM(NMB)
260 IF(QLoss) 270, 260, 270
       RB1(MN*NMB)=(1.0)/((DXB(NMB)/(2.0*XK(N+1*NMB)))+(DXB(NMB)/(2.0*XK
1B(MN*NMB))))
       AB(NN*NMB)=RB1(MN*NMB)
       BB(NN*NMB)=(-((KB1(MN*NMB)+SB(MN*NMB))))
       CB(NN*NMB)=0.0
       DB(MN*NMB)=((-SB(MN*NMB)*TX2T(MN*NMB)))
60 TO 280
270 SB(MN*NMB)=(RHOBX(NMB)*CPB(MN*NMB)*DXB(NMB))/(2.0*DT)
       KB1(MN*NMB)=(1.0)/((DXB(NMB)/(2.0*XK(MN-1*NMB)))+(DXB(NMB)/(2.0*XK
1B(MN*NMB))))
       AB(NN*NMB)=RB1(MN*NMB)
       BB(NN*NMB)=(-((KB1(MN*NMB)+HENV+1.73E-09)*FENV*4.0*(TX2T(MN,NMB)**
13)+SB(MN,NMB)))
       CB(NN*NMB)=0.0
       DB(MN,NMB)=((-HENV*FENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM
1B)**4)))*SB(MN,NMB))*TX2T(MN,NMB))
280 L=NPF+1
       DO 300 I=1:NMB
       K=NPM(I)
       IF(I.EQ.1) GO TO 282
       IF(GAPX(I-1).EQ.0.) GO TO 282
       KT=1
       GO TO 285
282 KT=2
285 DO 290 J=KT*K
       A(L)=AB(J,I)
       B(L)=BB(J,I)
       C(L)=CB(J,I)
       D(L)=DB(J,I)
       IF(JMP) 289, 289, 286
286 WRITE(6,287) AB(J,I), BB(J,I), CB(J,I), DB(J,I), J, I, A(L), B(L), C(L), D(1L), L
287 FORMAT(1H0, 8HAB(J,I)=1PE12.5, 2X, 8HBB(J,I)=1PE12.5, 2X, 8HCBB(J,I)=, 1PE12.5, 2X, 8HDBC(J,I)=, 1PE12.5, 2X, 8HD(J,I)=, 1PE12.5, 2X, 8HDJ(J,I)=, 1PE12.5, 2X, 8HDL(J,I)=, 1PE12.5, 2X, 2
JHL=13)
289 L=L+1
290 CONTINUE
300 CONTINUE
       NPFT=L-1
       RETURN
       END
**SUBROUTINE PROP**

**THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE**

**HEAT SHIELD STRUCTURE**

**DIMENSION** TII(12), HFAANG(12), XINTT(12,12), TKC(20), XKC(20),
1CPC(20), TKV(20), XKV(20), TRPV(20), CPV(20), TIME(30), OCONN(300),
20RAD(300), VEL(300), XNPM(12), NKPR(12), NCPC(12), TKX(20,12), XK(20,12),
3, TCP(20,12), CPCX(20,12), RHOBX(12), XBM(12), FMFR(12), EMAB(12), HXX(12),
4, GAPX(12), FTFST(12), ATFTST(12), TEMD1(200), TX1(200), TX2(200),
5, TX2T(10,12), TUL1(200), TUL2(200), HX(50), TX(50), IR(50), IR1(50),
6, TPRZ(50), TUL(50), IEINT(50), TY(200), A(200), R(200), C(200), R(200),
7, TK(50), RH(50), CP(50), XNP(12), XKP(10,12), CPB(10,12), XMKG(50),
RYK(50), A(10,12), RB(10,12), C(10,12), DB(10,12), SR(10,12),
9, WII(10,12), XIA(10,12), H(12), S(50,5), NP(12),
DIMENSION** TII(50), RH0Y(50), RH0Y2(50), DRO(50), DCP(20),

**COMMON** TKC, XKC, TP, XCP, XKV, TCP, CPV, XNPM, RH0X, CHM, FMBR,
1FRK, NKPD, NCPC, XK, TCP, CPN, GAPA, FTFST, ATFTST, TEMD1, TX1,
2TX2T, TUL, TUL1, TUL2, IR, IR1, IR2, A, B, C, N, R, AR, RB, CR, D, SR,
3KPI, AR, 5B, HROY1, RHOY2, RMSD, RH0, CP, Y, XKP, CPB, DXR, DT, XLOST,
4ATBL, TCHR, TRMF, RH0V, PHOC, FLOW, FMV, EME, HOO, CHPD, NCPC, XCPV,
5NP, NMR, IFPS, 1PF, TFST, TEMPI, TXO, TFEN, HENV, FENV, GLOSS, TLT, TINT,
**COMMON** II, TT, IJ, JT, IN, IJ1, IJ2, IJ3, IJ4, IJ5, IJ6, NP, NP1, NP2, NP3,
1FRA, FRB, 1FRC, 1FRD, 1FRS, 1FRS2, 1FRS3, 1FRS4, 1FRS5, 1FRS6,

**KINT=INT**

10 IF(IH(1)) 12, 12, 100
12 TUL(I)=AMAX1(TX1(I), TX2(I))
19 IF(TUL(I)=L, E, TAL) GOTO 20
18 IF(I1)=1
17 GOTO 100
20 IF(I1=1 25, 2, 21
21 IF(I1-NK) 55, 55, 30
22 IF(TX2(I)-TKV(12)) 30, 35, 30
25 WRITE(6*26) TX2(I)
26 FORMAT(14H8.4) THE RANGE OF ONE OF THE RATION PROPERTY CURVE FIT
IC WAS EXCEEDED AT A TEMPERATURE OF 1PE12, 5)

**FRR2=1.0**

54 GOTO 36
55 II=II+1
56 GOTO 21
35 IF(12-I) TKV(I1-1)) 40, 55, 50
40 II=II-1
41 GOTO 20
50 YK(I)=XK(I1-1)+(XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1))
1*(TX2(I)-TKV(I1-1))
51 GOTO 60
65 YK(I)=XK(I1)
60 IF(I2=1) 60, 60, 61
60 IF(I2=NCV) 60, 62, 25
62 IF(TX2(I)-TCPV(I2)) 70, 85, 65
65 T2=I2+1
66 GOTO 61
70 IF(TX2(I)-TCPV(I2)) 75, 85, 80
75 T2=12-1
GO TO 60
80 CP(I)=CP(V(I2-1)+(CP(V(I2)-CP(V(I2-1)))/(TCP(V(I2)-TCP(V(I2-1))))
GO TO 90
1*(TX2(I)=TCP(V(I2-1))
GO TO 170
90 RHO(I)=RHOV
GO TO 170
100 TUL(I)=AMAX1(TUL(I),TX2(I))
IF(TUL(I)-TCHAR)=110,110,115
110 RHO(I)=RHOV+(RHOV-RHOC)*(TUL(I)-TABLE)/(TABLE-TCHAR)
IF(C(I)=CHARK+(ABL-C(HARK)*((RHO(I)-RHOC)/(RHOV-RHOC)))
CP(I)=CHARK+(ABL-C(HARK)*((RHO(I)-RHOC)/(RHOV-RHOC)))
GO TO 170
115 IF(VPT) 116,116,117
116 TTUL(I)=TUL(I)
GO TO 120
117 TTUL(I)=T2(I)
120 IF(I3-1) 25,25,121
121 IF(I3-NKC) 122,122,25
122 IF(TTUL(I)=TKC(I3)) 124,135,123
123 I3=I3+1
GO TO 121
124 IF(TTUL(I)=TKC(I3-1)) 125,135,130
125 I3=I3-1
GO TO 120
130 IF(VPT) 131,131,135
131 CP(I)=CP(I4)
GO TO 140
135 V(I)=XKC(I3-1)+(XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1))
1*(TTUL(I)=TKC(I3-1))
136 IF(I5-1) 203,203,201
137 IF(I5-NKP) 204,204,203
138 CP(I)=CP(I4)
139 RHO(I)=RHOC
140 CONTINUE

C

DETERMINATION OF PROPER RACK-UP SHIELD MATERIAL PROPERTY

NO 300 I=1,NMA
NXR(I)=XBM(I)*((XNPM(I)-1.0)*12.0)
LKP=NKPB(I)
LCP=NCPB(I)
NN=NPM(I)
NO 260 J=1,NN
200 IF(I5-1) 203,203,201
201 IF(I5-NKP) 204,204,203
202 IF(TX2T(J,I)=TXK(I5,J)) 206,220,205
203 WRITE(6,204) I,TX2T(J,I)
204 FORMAT(1HO,39H THE RANGE OF ONE OF THE NUMBERS, I2,71H BACKUP STRUC
THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE AERATING NODES.

*DIMENSION TITLE(12),HFADNG(12),XI1NT(12,12),TKC(20),XKC(20),*

1PC(20),V(20),XXV(20),TCPV(21),CPUV(21),TIME(30n),GCON(300),
2OPAD(300),VEL(300),XNPM(12),NKPR(12),NCP(12),TXK(20,12),XK(20,12),
3TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBR(12),HXX(12),
46APX(12),TFST(12),RETS(12),TEM(200),TXV(200),TXV(200),
57XPT(10,12),TUL1(200),TUL2(200),HXX(50),TW(50),IR(50),IR(50),
62P(50),TUL(50),IFM(50),TV(200),A(200),B(200),C(200),D(200),
75(A50),RHO(50),CP(50),NPX(12),XK(10,12),CPB(10,12),XMG(50),
8AYX(50),A550,10,12,RB(10,12),CR(10,12),NB(10,12),SR(10,12),
9981(10,12),RH2(10,12),H(10),S(50),R(50),

*DIMENSION TTUL(50),RHOY(50),RHOY(50),RHOY(50),RHOY(50),

1TUL(50),RHOY(50),RHOY(50),RHOY(50),RHOY(50),TCP(20),

COMMON TKC,XXV,TCPC,CPC,TKV,XXV,TCPV,CPV,XNPM,RHBA,XBM,EMFB,
1MKPB,NKPR,NCP(12),TXK,XXV,TCPC,CPV,XNPM,RHBA,XBM,EMFB,,
2XXV,TCPV,CPV,XNPM,RHBA,XBM,EMFB,TFST,RETS,TEM(200),
32P,TUL1,TUL2,TUL1,TUL2,TP,IR1,IR2,AR,AB,CP,DR,SR,
4351,RB,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,
5A,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,ATR0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,
6TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,
7TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,
8TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,
9TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,TRH0Y,

COMMON I1,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,
1028,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,

$IFTXK(1) 1010,20,10,20
1020,10
2010,20,10
3010,20,10
4010,20,10
5010,20,10
6010,20,10
7010,20,10
8010,20,10
9010,20,10

C

XMT=0.0
1N=INT
1K=NP
1F(DMP) N=8,3
3WRITE(6,N)
5FORMAT (X10, *),
8*NO NO K I=INT, N P
1F(I1(I)) I1=I1+1
11IF (TX1(K) = TABLE) GO TO 9
12TUL1(K) = MAXI 1 (TUL1(K), TX1(K))
1P1(I1)=1
1G0 TO 20
9 IF(TX1(K) = TABLE) 10,10,20
10WHY1(K) = RHOY
1G0 TO 50
20IF(TUL1(K) = TABLE) 40,30,30
30WHY1(K) = RHOY
1G0 TO 50
40WHY1(K) = RHOY + (RHOY - RHO) * (TUL1(K) - TAU1) / (TAR1 - TAU1)
50IF(I1(K)) 50,52,52
52IF (TX2(K) = TABLE) GO TO 56
54TUL2(K) = MAXI (TUL2(K), TX2(K))
1P2(K)=1
1G0 TO 70
1F (TX2(K) = TABLE) 60,60,70
60WHY2(K) = RHOY
1G0 TO 95
70IF(TUL2(K) = TABLE) 90,80,90
80WHY2(K) = RHOY
1G0 TO 95
90WHY2(K) = RHOY + (RHOY - RHO) * (TUL2(K) - TABLE) / (TABLE - TAU1)
95 DH0(KI) = (RH0Y(KI) - RH0Y2(KI))/N*DX
96 IF(KI-NP) 97, 96, 96
97 GO TO 98
98 IF(DH0(KI)) 110, 120, 120
110 DH0(KI) = 0
120 XMT = XMT + DH0(KI)
125 XMDG(KI) = XMT
130 IF(DMP) 190, 190, 150
150 WRITE(6, 160) XMDG(KI), DRHO(KI), RH0Y2(KI), RH0Y1(KI)
160 FORMAT(1X, 5HXMDSG =, 1PE12.5, 2X, 5HDRHO =, 1PF12.5, 2X, 6HRH0Y2 =, 1PE12.5)
190 KI = KI - 1
200 CONTINUE
250 RETURN
260 END
THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION.
IT IS ASSUMED THAT OXYGEN AND CARBON REACT TO FORM CO ONLY.

SUBROUTINE OXIDAT(XMDO,GOXID)
GOXID=XMDO*4000.0/3600.0
GOXID=GOXID*0.0
RETURN
END
SIBFTC SWUFT
C THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES
C BY SOLVING THE TRI-DIAGONAL MATRIX
SUBROUTINE SWUFT(A,B,C,D,N,NP,NMP)
DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),NP(200)
CP(1)=C(1)/B(1)
NP(1)=D(1)/B(1)
DO 100 I=2,N
CP(I)=C(I)/(B(I)-A(I)*CP(I-1))
NP(I)=(D(I)-A(I)*NP(I-1))/(B(I)-A(I)*CP(I-1))
100 CONTINUE
N=N-1
T(N)=NP(N)
N1=N-1
DO 200 J=N1,N-1
I=N-J
T(I)=NP(I)-CP(I)*T(I+1)
200 CONTINUE
IF(DMP) 300,330,250
WRITE(6,260)
260 FORMAT(1X,'COEFFICIENTS CALCULATED BY SUBROUTINE SWUFT/')
WRITE(6,270)
270 FORMAT(6X,5HCP(I),10X,5HNP(I),10X,4HT(I)/)
WRITE(6,275) (CP(I),NP(I),T(I),I=1,N)
275 FORMAT(2X,1PE12.5,2X,1PF19.5,6X)
SUBFTC REC
C THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR Masse
C
C SUBROUTINE RECESS(XMDC, xLOST, TRFC, DT, RHOC, TS, SR, TX2, NREC, NRS, FRPS,
1<XS, 5000, 000010, 0
1 IF(TX2-TRFC) 10, 20, 20
10 XMDC=0.0
XLOST=0.0
COT=0.0
GO TO 60
20 IF(NRS-1) 25, 25, 25
21 IF(NRS=NHF(C) 22, 22, 25
22 IF(X2-TS(NRS)) 32, 40, 30
25 WRITE(6, 26) TX2
26 FORMAT(1H0, 7FH THE RANGE OF THE SURFACE RECESSION TABLE WAS EXCEEDED
1FD AT A TEMPERATURE OF ,1PE12, 5
FRR5=1.0
GO TO 60
30 NRS=NRS+1
GO TO 21
32 IF(TX2-TS(NRS-1)) 34, 40, 36
34 NRS=NRS-1
GO TO 20
36 SX=SR(NRS-1)+(SR(NRS)-SR(NRS-1))/(TS(NRS)-TS(NRS-1))
1*(TX2-TS(NRS-1))
GO TO 50
40 SX=SR(NRS)
50 XLOST=300.0*SY*DT
XMDC=(XLOST*RHOC)/DT
COT= SX*300.0
1F(DMP) 60, 60, 52
52 WRITE(6, 54) SX, XLOST, XMDC
54 FORMAT(1H0, 3H0, 1PE12.5, 1X, 6H0, 1PE12.5, 3X, 5HMDC, 1PE12.5)
60 RETURN
FEND
**SIBFTC**

**TEMP**

**C**

THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION IN THE HEAT SHIELD STRUCTURE

**SUBROUTINE TEMPD**

**C**

**DIMENSION** T(T(12)),HEADD(12),X1DNT(12,12),TKC(20),XKC(20),
1CP(20),TVK(20),XKV(20),TCPV(20),CPV(20),TIME(30),QCON(300),
2RAD(300),VEL(300),XNPM(12),NKP(12),NCP(12),TXK(20,12),XK(20,12),
3,TC(20,12),CPC(20,12),RHO(12),XXM(12),EM(12),ERMF(12),XMM(12),
4,GAPX(12),FTEST(12),RETEST(12),TFMDI(200),TXI(200),TX2(200),
5TX2(10,12),TULL(200),TULI(200),H(50),TX(50),IR(50),IR1(50),
6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
7,R(50),RHO(50),C(50),DXR(12),XK(10,12),XK(10,12),XM(50),
8Y(50),AB(10,12),BB(10,12),CR(10,12),DB(10,12),SR(10,12),
9RP(10,12),RRP(10,12),H(12),T(50),NPM(12),
0NIMENSION TUTL(50),RHY1(50),RHY2(50),RHR(50),TCPV(20)
1C

**COMMON** Tc,XXC,XXP,XXR,XXV,CPC,CPC,CPV,CPV,XNPM,RHOX,RX,RX,RX,
1EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,EMF,
2TX2,TVX2,TUXI,TVUXI,IRI,IR2,IR2,IR2,IR2,IR2,IR2,IR2,IR2,IR2,IR2,IR2,
3R1,R2,TY,RHY1,RHY2,RHY2,RHY2,RHY2,RHY2,RHY2,RHY2,RHY2,RHY2,RHY2,
4TAB,TCHAP,TRFC,RHOV,RHOC,FLOW,FMV,EMC,H300,NK,NCPC,NKVNCP,
5NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,NPM,
6COMMON 11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30
7COMMON 11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30
8COMMON 11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30

**C**

**=0.0**

**TF(TFTEST) = 30,10n,20**

**100**

**NO** 150 L=1,NP

**TX1(L)=TEMP**

**TX2(L)=TEMP**

**TUXI(L)=TX1(L)**

**TUXI(L)=TX2(L)**

**TFMDI(L)=TMD**

**150**

**CONTINUE**

**NO** 160 I=1,NMR

**N=NPM(1)**

**NO** 155 M=1,JN

**TUXI(W)=TMD**

**155**

**CONTINUE**

**160**

**CONTINUE**

**GO TO 320**

**200**

**NO** 220 L=1,NP

**TFMDI(L)=TX0+(TENV-TX0)/TL)**

**TX1(L)=TMDI(L)**

**TX2(L)=TX1(L)**

**TUXI(L)=TX1(L)**

**TUXI(L)=TX2(L)**

**X=X+DX**

**220**

**CONTINUE**

**LENP+1**

**NO** 270 I=1,NMR

**KJ=NPM(I)**

**NO** 250 J=1,KJ

**TFMDI(L)=TX0+(TENV-TX0)/TL)**

**TX1(L)=TMDI(L)**

**TX2(L)=TMDI(L)**
I

TX2I(J+I)=TEMNI(L)

Y=X+DXB(I)

L=L+1

250 CONTINUE

X=X+(GAPX(I)/12.0)

270 CONTINUE

GO TO 320

C AN ARBITRARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT

C DATA IF TEST* IS A NEGATIVE NUMBER

300 WRITE(6,310)

310 FORMAT(1H0,7G4) THE VALUE OF TEST* WAS NEGATIVE, SUBROUTINE TEMPD S

1OULD NOT HAVE BEEN CALLED.

320 RETURN

END
SUBRUTINE DON2
C THIS SUBROUTINE DETERMINES THE TEMPERATURE OF POINTS A FIXED
C DISTANCE FROM A REFERENCE PLANE FROM THE TEMPERATURES CALCULATED
C IN A VARYING THICKNESS
C
SUBRUTINE DON2(xLOST, XARRAY, TARRAY, NA, XNODE, TEMP, XNODEV, KK, XLSTV, 1DX)
C
DIMENSION XARRAY(50), TARRAY(50), XNODE(50), TEMP(50), XNODEV(50)
C
K = 0
NXT = 0.0
DO 10 I = 1, NA
IF (XLSTV.LE.DX) GO TO 150
K = K + 1
100 NXT = NXT + UX
150 K = NA - K
XK = XK
XNODEV(I) = XLSTV
TFPM(I) = TARRAY(I)
DO 200 I = 1, KK
XNODE(I) = XK + DX
CALL DISCT3(XNODE(I), XARRAY, TARRAY, NA, TEMP(I+1))
XNODEV(I+1) = XK + DX
200 UX = XK + 1.0
RETURN
END
**SUBTFC UINTRP**

SUBROUTINE UINTRP(X,XTBL,Y,YTPL,N,J)

DIMENSION XTRL(50),YTPL(50)

J=J

IF(I.GT.N.OR.I.LT.2) I=2

10 IF(XTRL(I-1).LE.X.AND.X.LT.XTRL(I)) GO TO 40

IF(X.GT.XTRL(I)) GO TO 30

20 I=I-1

IF(I.LT.2) GO TO 10

I=2

GO TO 40

30 I=I+1

IF(I.LE.N) GO TO 10

I=N

40 FRACT=(X-XTRL(I-1))/(XTPL(I)-XTPL(I-1))

Y=YTPL(I-1)+(YTPL(I)-YTPL(I-1))*FRACT

RETURN

END
$1BFTC 150T
$1BROUTINF 150THM(DEPTH,TFMP,ROND,N,ANS)
DIMENSION DEPTH(1),TFMP(1)
ANS=1.
K2N=1
NO 100 I=1,K
IF(TFMP(I)-BOND)2,1,3
1  ANS=DFPTH(I)
   GO TO 100
  2 IF(TFMP(I+1)=ROND)100,100,4
  4 ANS=DFPTH(I+1)-(TFMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TFMP(I+1)-1TFMP(I))
   GO TO 100
  3 IF(TFMP(I+1)-ROND)5,100,100
  5 ANS=(TEMP(I)-ROND)*(DFPTH(I+1)-DFPTH(I))/(TFMP(I)-TEMP(I+1))+DEPTH(I)
100 CONTINUE
IF(ROND.EQ.TFMP(N))ANS=DFPTH(N)
RETURN
END
SIBFTC SAVE
SUBROUTINE SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,DT,TFINAL,TIMF,
1THING)
DIMENSION SAVE1(1),SAVE2(1),SAVE3(1)
USE=0,0
SAVE1(NX1)=VALUE
NX2=NX1+1
IF(NX2.EQ.0)NX2=3
SAVE2(NX2)=VALUE
NX3=NX2+1
IF(NX3.EQ.0)NX3=3
SAVE3(NX3)=VALUE
IF((TIME.GT.(2.*DT)).OR.(TIME.GF.(TFINAL-3.*DT)))GO TO 4
GO TO (1,2,3),NX1
1 IF(ABS(SAVE2(1)-SAVE2(2)).LE..001).OR.(ABS(SAVE2(2)-SAVE2(3))
1.LE..001)GO TO 5
IF(SAVE2(1).LT.SAVE2(2)).AND.(SAVE2(2).GT.SAVE2(3))).OR.(SAVE2(1)
11,SAVE2(2)).AND.(SAVE2(2).LT.SAVE2(3)))USE=SAVE2(2)
5 THING=SAVE2(2)
GO TO 4
2 IF(ABS(SAVE3(1)-SAVE3(2)).LE..001).OR.(ABS(SAVE3(2)-SAVE3(3))
2.LE..001)GO TO 6
IF(SAVE3(1).LT.SAVE3(2)).AND.(SAVE3(2).GT.SAVE3(3))).OR.(SAVE3(1)
11,SAVE3(2)).AND.(SAVE3(2).LT.SAVE3(3)))USE=SAVE3(2)
6 THING=SAVE3(2)
GO TO 4
3 IF(ABS(SAVE1(1)-SAVEF1(2)).LE..001).OR.(ABS(SAVE1(2)-SAVE1(3))
3.LE..001)GO TO 6
IF(SAVE1(1).LT.SAVE1(2)).AND.(SAVE1(2).GT.SAVE1(3))).OR.(SAVE1(1)
11,SAVE1(2)).AND.(SAVE1(2).LT.SAVE1(3)))USE=SAVE1(2)
7 THING=SAVE1(2)
GO TO 4
4 NX1=NX1+1
RETURN
END
SUBROUTINE DISCT3(XA,TABX,TARY,NY,ANS)
DIMENSION TABX(1),TARY(1)
CALL DISSFR(XA,TARX,1,NY,D,NN)
NNN=3
CALL LAGHFAN(XA,TARX(NN),TABY(NN),NNN,ANS)
RETURN
END
SUBROUTINE DISSER (XA, TAB, I, NX, ID, NPX)
DIMENSION TAB(2000)
C DIMENSION TAB(2000)
NPT = ID + 1
NPB = NPT / 2
NPU = NPT - NPB
IF (NX - NPT) 10, 5, 10
5 NPX = I
RETURN
10 NLOW = I + NPB
NUPP = I + NX - (NPU + 1)
DO 15 II = NLOW, NUPP
NLOC = II
IF (TAB(II) - XA) 15, 20, 20
15 CONTINUE
NPX = NUPP - NPB + 1
RETURN
20 NL = NLOC - NPB
NU = NL + ID
DO 25 JJ = NL, NU
NDIS = JJ
IF (TAB(JJ) - TAB(JJ + 1)) 25, 30, 25
25 CONTINUE
NPX = NL
RETURN
30 IF (TAB(NDIS) - XA) 40, 35, 35
35 NPX = NDIS - ID
RETURN
40 NPX = NDIS + 1
RETURN
END
SUBROUTINE LAGRAN (XA, X, Y, N, ANS)
C     DIMENSION X(200), Y(200)

SUM=0.0
DO 3 I=1,N
    PROD=Y(I)
    DO 2 J=1,N
        A=X(I)-X(J)
        IF (A) 1,2,1
        1 B=(X(I)-X(J))/A
        PROD=PROD*B
        2 CONTINUE
    3 SUM=SUM+PROD
    ANS=SUM
RETURN
END
$IBFTC MORE
RFIND 11
RFAD(11) (TITLE(I),I=1,12)
RFAD(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
Y3(I)=Y3(I)*12.+Y1(I)
Y4(I)=Y4(I)*12.+Y1(I)
I=2
30 RFAD(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
IF(X(I)-500<10,20,20)
10 Y3(I)=Y3(I)*12.+Y1(I)
Y4(I)=Y4(I)*12.+Y1(I)
I=I+1
GO TO 30
20 NPLLOT=I+1
YM1=Y1(I)
YM2=Y2(I)
YM3=Y3(I)
YM4=Y4(I)
NO 40 K = 2 , NPLLOT
IF(Y1(K),GT,YM1) YM1 = Y1(K)
IF(Y2(K),GT,YM2) YM2 = Y2(K)
IF(Y3(K),GT,YM3) YM3 = Y3(K)
IF(Y4(K),GT,YM4) YM4 = Y4(K)
40 CONTINUE
1000 FORMAT(1H1,(1?A6))
CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLLOT)
XMAX=X(NPLLOT)
CALL APLLOT(X,Y1,XMAX,YM1,TITLE,NPLLOT)
CALL RPLLOT(X,Y2,XMAX,YM2,TITLE)
CALL CPLLOT(X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)
WRITE(6,1000) (TITLE(I),I=1,12)
WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLLOT)
1001 FORMAT(5E20,A)
WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLLOT
1002 FORMAT(/6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
1YM4=F10.4,2X,NPLLOT=Iu)
RFAD(11) (TITLE (I),I = 1,12)
RFAD(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
I=2
IF(X(I)-500<10,30,50)
50 WRITE(6,1003) (TITLE(I),I=1,12)
1003 FORMAT(/12A6)
RFRETURN
END
SUBROUTINE ACCEND(X, Y, A, B, C, N)
DIMENSION X(1:N), Y(1:N), A(1:N), B(1:N), C(1:N)
K = 1

101 SMALL = X(K)
   DO 100 I = K + 1, N
      DUMMY = X(I)
      SMALL = MIN(SMALL, DUMMY)
      IF (SMALL .EQ. X(I)) INDEX = I
   100 CONTINUE
   X(INDEX) = X(K)
   X(K) = SMALL
   SAVE = Y(K)
   Y(K) = Y(INDEX)
   Y(INDEX) = SAVE
   SAVEA = A(K)
   A(K) = A(INDEX)
   A(INDEX) = SAVEA
   SAVEB = B(K)
   B(K) = B(INDEX)
   B(INDEX) = SAVEB
   SAVEC = C(K)
   C(K) = C(INDEX)
   C(INDEX) = SAVEC
   K = K + 1
   IF (K .EQ. N) RETURN
   GO TO 101
END
$I B F C A P L O T 
SUBROUTINE A P L O T ( X, Y, X L I M, Y L I M, T I T L E, I P L O T )
DIMENSION X ( 1 0 0 ), Y T I T L E ( 1 0 0 ), X T I T L E ( 1 0 0 )
DIMENSION T I T L E ( 1 2 ) , Y ( 3 0 0 ) , A L O N G Y ( 7 )
COMMON / A R C / A L O N G X ( 7 ), N P L O T , Z E R O , X M A X , T I F Y
DATA ( X T I T L E ( i ) ) , i = 1 , 1 0 ) / 3 8 H
DATA ( Y T I T L E ( i ) ) , i = 1 , 1 0 ) / 3 8 H
S U R F A C E R E C T I O N ( I N )
Z E R O = 0 , 0
A L O N G ( 1 ) = 5 0 , 0
A L O N G ( 2 ) = 1 0 0 , 0
A L O N G ( 3 ) = 2 5 0 , 0
A L O N G ( 4 ) = 5 0 0 , 0
A L O N G ( 5 ) = 1 0 0 0 , 0
A L O N G ( 6 ) = 2 5 0 0 , 0
A L O N G ( 7 ) = 5 0 0 0 , 0
N P L O T = 1 P L O T
D O 1 0 I = 1 , 7
1 0 I = I + 1
IF ( X L I M = = A L O N G ( I ) ) G O T O 2 0 , 1 0
1 0 CONTINUE
3 0 W R I T E ( 6 , 1 0 0 0 ) X L I M , Y L I M
1 0 0 0 F O R M A T ( / / 7 7 H ) A P L O T C A N N O T B E D O N E B E C A U S E F I T H E R X L I M E X C E E D E D E N
1 0 0 , O R Y L I M E X C E E D E D E N . / / 6 H X L I M = F 1 2 , 5 , 5 X , 6 H Y L I M = E 1 2 , 5 // 1 0 H W F
2 0 N O W G O T O V B L O T // //
W T U R N
2 0 X M A X = A L O N G ( I )
I F ( X M A X = = A L O N G ( I ) ) G O T O 2 5 , 0 0
I F ( Y M A X = = A L O N G ( I ) ) G O T O 2 5 , 0 0
4 0 CONTINUE
6 0 T O 3 0
5 0 Y M A X = A L O N G ( I ) / 1 0 0 ,
C A L L P R I N T ( 1 2 3 , 1 0 2 3 , 2 4 , 2 4 , 1 8 , 1 8 , 5 , 5 )
C A L L P L O T ( 1 , 1 , Z E R O , X M A X , Z E R O , Y M A X , X , Y , N P L O T , 1 , 1 4 )
A L O N G X ( 1 ) = 0 , U
A L O N G Y ( 1 ) = 0 , U
D O 6 0 I = 1 , 6
C A L L L A R E ( X ( A L O N G X ( I ) ) )
C A L L L A R E ( Y ( A L O N G Y ( I ) ) )
A L O N G X ( I + 1 ) = 8 A L O N G X ( I ) + * X M A X
A L O N G Y ( I + 1 ) = 8 A L O N G Y ( I ) + * Y M A X
C A L L P R I N T ( 2 0 0 , 9 7 5 , 1 2 , 0 , 3 8 , X T I T L E )
C A L L P R I N T ( 4 7 , 2 0 0 , 1 2 , 3 8 , Y T I T L E )
C A L L P R I N T ( 1 2 3 , 1 0 0 0 , 1 2 , 0 , 7 2 , T I T L E )
C A L L N M P L O T
W T U R N
F N D
7 9
$IBFIC PLOT
SUBROUTINE PLLOT (X,Y,XLIM,YLIM,TITLE)
DIMENSION X(300),Y(300),YTITLE(10),ALONGY(7),XTITLE(10)
DIMENSION TITLE(12)
COMMON /ARC / ALLOW(7),ALONGX(7),NPLLOT,ZERO,XMAX,TFIX
DATA (XTITLE(I),I=1,10)/TIME (SEC.)
DATA (YTITLE(I),I=1,10)/LONGLINE TEMPERATURE (R)
ALONGY(I)=0.,0.
DO 10 I=1,7
10 CONTINUE
IF (YLIM .NE. ALLOW(I)) 20,20,10
100 CONTINUE
WRITE (6,1000) YLIM
100 FORMAT(/// 37H PLOT WILL NOT BE DONE BECAUSE YLIM = E12.5 ///)
RETURN
20 YMAX = ALLOW(I)
CALL RSTERM
CALL ORIGIN(123,1027,24,924,18,1,5,5 )
CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,Y, NPLLOT,1,1H/ )
DO 30 I=1,6
CALL LAP1X (ALONGX(I),1)
CALL LAP1Y (ALONGY(I),1)
30 ALONGY(I+1) = ALONGY(I) + .2*YMAX
CALL PRINT (200,975,12,0,3A,XTITLE)
CALL PRINT (47,200,0,12,3A,YTITLE)
CALL PRINT (123,1000,12,0,72,TITLE)
CALL NMPLOT
RETURN
END
$IBFTC  CPLOT
CHEIRG/INP  CPLOT (X,Y1,Y2,XLIM,Y1,IM1,YLIMP,TITLE, Y)
DIMENSION X(N),Y1(N),Y2(N),YTITLE(Y0),YY(YM),YY(TITLE(10)),
DIMENSION TITLE(J),Y(3N),ALONG(7)
DIMENSION CURVE(I),VRUG(4),HRTG(7)
COMMON /ARC/ ALLOW(7),ALANGX(7),NPLT,PPP0,XMAX,TFIX
DATA (VRUG(I),I=1,4) /100.0,60.0,20.0,10.0 /
DATA (HRTG(I),I=1,7) /1.0,2.0,5.0,10.0,20.0,50.0,100.0 /
DATA (XTITLE(I),I=1,10)/9AH
DATA (XTITLE(I),I=1,10)/9AH
DATA (YY(1:4),YY(1:10)/IN,
DATA WONE/W1H0F0 /TWO/4H1660 /
DATA WONE/W1H1M1 /*TOO/142 /
C *** FOUR (4) CHARACTERPS ARE ALLOWED FOR CURVE(I)
C
CURVE(I)=ONE
HFACTR=HRUG(4)
SYMPOL=VRUG
YRUG=MAX (Y1,IM1,YLIMP )
NCURVE =1
NO 1=I,NPLT
1 YY(I)= Y1(I)
NO 7=I+4
T=I
1F (YY(I)=100.=-ALLOW(I)K,I,7
7 CONTINUE
WRITE (6,T)YY,I,NPLT
1000 ENDMAT ( /// 34H (1) NOT IF DONE BECAUSE Y1,IM1=F12.5,1AH OR
1Y1,IM2= F12.5 /// )
WHITE
6 YMAX =ALLOW (I/100.
VFACR=HRUG(4)
CALL PSTRM
CALL ARTICON (123,1024,24,024,18,18,5,5)
J=I
70 ON 18 I=I,NPLT
II=I
I=I =I-1
1F (YY(I)=YY(I) )20,18,18
10 CONTINUE
NPLT=NPLT-J+1
II=J+NPLT
TVLOC=(YMAX-YY(LL))*1A+VFACR*.5+.4
IMLOC= XX(LL)*18. /VFACR + 123. + 48,
CALL PRINT(III,OC,IVLOC, R,0.4,CURVE)
CALL PLOT(II1,1,7,0,1,0,0,YMAX,X(J),YY(J),NPLT, 1,SYMPOL )
IF (NCURVE=1 )90,85,90
A5 NO RA I=1,NPLT
A6 YY(I)=YY(I)
SVHEVE(I)=TWO
SYMPOL=VRUG
NCURVE =2
J=1
GO TO 70
20 NPLT=1-I
J=J + NPLT
IVLOC=(YMAX-YY(LL))*1A+VFACR*.5+.4
IMLOC= X(LL)*18. /VFACR + 123. + 48,
CALL PRINT(III,OC,IVLOC, R,0.4,CURVE)
CALL PLO1I(1,1,ZERO,XMAG,ZERO,YMAG,X(J),YY(J),NPT,1,SYMPL)
50 50 JJ=II, NPLT
50 JJ, JJ
TF(YY(J)-YY(J))=50,40,40
50 CONTINUE
IF(NCHREV=1) 90,95,90
40 JJ=JJ
GO TO 70
90 AI=ONGY(I)=0.0
DO 100 I=1,6
CALL LAPIX(AI,ONGX(I),1)
CALL LAPLX(AI,ONGY(I),1)
100 AI=ONGY(I+1)=AI+ONGY(I)+2*YMAG
CALL PRINT(200,975,12,0,3A,XTT1NF)
CALL PRINT(47,200,0,12,3A,YT1NF)
CALL PRINT(12,1000,12,0,72,T1NF)
CALL OMPIU1F
FTU1N
F00
## APPENDIX D

## PROGRAM TERMINOLOGY

<table>
<thead>
<tr>
<th>FORTRAN</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&quot;A&quot; coefficient in matrix, single subscript</td>
</tr>
<tr>
<td>AB</td>
<td>&quot;A&quot; coefficient in matrix, double subscript</td>
</tr>
<tr>
<td>ABLC</td>
<td>specific heat of material at TABL</td>
</tr>
<tr>
<td>ABLK</td>
<td>thermal conductivity of material at TABL</td>
</tr>
<tr>
<td>B</td>
<td>&quot;B&quot; coefficient in matrix, single subscript</td>
</tr>
<tr>
<td>BB</td>
<td>&quot;B&quot; coefficient in matrix, double subscript</td>
</tr>
<tr>
<td>BL</td>
<td>Total thickness of backup structure</td>
</tr>
<tr>
<td>BLTEM</td>
<td>value of 1460 isotherm depth from previous time step</td>
</tr>
<tr>
<td>BTEST</td>
<td>test to determine mode of heat transfer out of back surface of backup materials</td>
</tr>
<tr>
<td>C</td>
<td>&quot;C&quot; coefficient in matrix, single subscript</td>
</tr>
<tr>
<td>CB</td>
<td>&quot;C&quot; coefficient in matrix, double subscript</td>
</tr>
<tr>
<td>CHARC</td>
<td>specific heat of material at TCHAR</td>
</tr>
<tr>
<td>CHARK</td>
<td>thermal conductivity of material at TCHAR</td>
</tr>
<tr>
<td>CP</td>
<td>specific heat of a node in ablation material</td>
</tr>
<tr>
<td>CPB</td>
<td>specific heat of backup material node</td>
</tr>
<tr>
<td>CPC</td>
<td>specific heat values in char specific heat table</td>
</tr>
<tr>
<td>CPV</td>
<td>specific heat values in virgin specific heat table</td>
</tr>
<tr>
<td>CPX</td>
<td>specific heat values in backup material specific heat tables</td>
</tr>
<tr>
<td>D</td>
<td>&quot;D&quot; coefficient in matrix, single subscript</td>
</tr>
<tr>
<td>DB</td>
<td>&quot;D&quot; coefficient in matrix, double subscript</td>
</tr>
<tr>
<td>DELTT</td>
<td>time step in the time step table</td>
</tr>
<tr>
<td>FORTRAN</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>DMP</td>
<td>test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping)</td>
</tr>
<tr>
<td>DRHΦ</td>
<td>local mass flow rate of ablation gas</td>
</tr>
<tr>
<td>DT</td>
<td>time step from the time step table in hours</td>
</tr>
<tr>
<td>DTS</td>
<td>time step from time step table in seconds</td>
</tr>
<tr>
<td>DX</td>
<td>thickness of a node in the ablation material</td>
</tr>
<tr>
<td>DXB</td>
<td>thickness of a node in a backup structure material</td>
</tr>
<tr>
<td>DXV</td>
<td>variable ablation node thickness (= \frac{VLV}{NP - 1})</td>
</tr>
<tr>
<td>DXX</td>
<td>fixed ablation material node thickness (= \frac{VLI}{NP - 1})</td>
</tr>
<tr>
<td>EMBB</td>
<td>emissivity of back surface of each material in backup</td>
</tr>
<tr>
<td>EMC</td>
<td>char material emissivity</td>
</tr>
<tr>
<td>EMFB</td>
<td>emissivity of front surface of each material in backup</td>
</tr>
<tr>
<td>EMV</td>
<td>virgin material emissivity</td>
</tr>
<tr>
<td>EMX</td>
<td>emissivity of front surface of ablation material</td>
</tr>
<tr>
<td>END</td>
<td>code word for plot routine</td>
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<tr>
<td>ERR1</td>
<td>Control numbers for printing error statements when an input or calculational mistake is made</td>
</tr>
<tr>
<td>ERR2</td>
<td></td>
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<tr>
<td>ERR3</td>
<td></td>
</tr>
<tr>
<td>ERR4</td>
<td></td>
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<tr>
<td>FBLΦW</td>
<td>blowing efficiency in reducing convective heating</td>
</tr>
<tr>
<td>FCΦNV</td>
<td>factor to correct convective heating rate for various body locations</td>
</tr>
<tr>
<td>FENV</td>
<td>emissivity - view factor product to cabin interior</td>
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<tr>
<td>FRAD</td>
<td>factor to correct radiative heating rate for various body locations</td>
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<tr>
<td>PTEST</td>
<td>test to determine mode of heat transfer into front surface of backup materials</td>
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<tr>
<td>FORTRAN</td>
<td>Description</td>
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<tr>
<td>FV</td>
<td>view factor for external environment</td>
</tr>
<tr>
<td>G</td>
<td>defined by FORTRAN statement</td>
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<tr>
<td>GAPX</td>
<td>gap width between backup materials</td>
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<tr>
<td>H</td>
<td>film coefficient between backup materials</td>
</tr>
<tr>
<td>H300</td>
<td>enthalpy of air at 300° K</td>
</tr>
<tr>
<td>HEAD</td>
<td>any 72 alphanumeric characters used to identify problems being run - printed at top of first page of output</td>
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<tr>
<td>HEADNG</td>
<td>any 72 alphanumeric characters used to identify each input section</td>
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<tr>
<td>HENV</td>
<td>film coefficient to cabin environment</td>
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<tr>
<td>HTX</td>
<td>total enthalpy</td>
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<tr>
<td>HV</td>
<td>heat of degradation of virgin material</td>
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<tr>
<td>HW</td>
<td>wall enthalpy computed from enthalpy - temperature table</td>
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<tr>
<td>HX</td>
<td>enthalpy values in enthalpy table</td>
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<tr>
<td>IEM</td>
<td>test used to determine if front surface is virgin or char for using proper emissivity</td>
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<tr>
<td>IPRC</td>
<td>variable print frequency in time-step table</td>
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<td>present print control number</td>
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<tr>
<td>IR</td>
<td>test to determine if node temperature is greater than TABL</td>
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<tr>
<td>IRL</td>
<td>test used in determining node density at TX1 temperature</td>
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<tr>
<td>IR2</td>
<td>test used in determining node density at TX2 temperature</td>
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<tr>
<td>NCASE</td>
<td>number of problems to be run</td>
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<tr>
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<td>number of points in each backup material specific heat table</td>
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<td>NCPC</td>
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<td>NCPV</td>
<td>number of points in virgin specific heat temperature table</td>
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<td>NKC</td>
<td>number of points in char thermal conductivity - temperature table</td>
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<td>FORTRAN</td>
<td>Description</td>
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<tr>
<td>NKPB</td>
<td>number of points in each backup material thermal conductivity table</td>
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<tr>
<td>NKV</td>
<td>number of points in virgin thermal conductivity temperature table</td>
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<tr>
<td>NMB</td>
<td>number of materials in backup structure</td>
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<td>NP</td>
<td>number of node points in ablation material</td>
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<td>NPBS</td>
<td>total number of node points in backup structure</td>
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<td>NPF</td>
<td>total number of points in heat shield structure (NP + NPBS)</td>
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<td>number of nodes per material in backup</td>
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<td>number of points in enthalpy–temperature table</td>
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<td>NPTT</td>
<td>number of points in time-step table</td>
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<td>NREC</td>
<td>number of points in surface recession–temperature or time table</td>
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<td>number of points in trajectory input table</td>
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<td>NXC</td>
<td>dummy indices for subroutine SAVE</td>
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<td>NXD</td>
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<td>NXE</td>
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<tr>
<td>QBLOCK</td>
<td>amount of convective heat blocked due to mass injection into boundary layer</td>
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<tr>
<td>QC(N)</td>
<td>trajectory table convective heating rates</td>
</tr>
<tr>
<td>QC(\text{ONX})</td>
<td>cold wall convective heat rate at present time step</td>
</tr>
<tr>
<td>QHW</td>
<td>hot wall convective heat rate without blowing</td>
</tr>
<tr>
<td>QIN</td>
<td>net heat flux into front surface</td>
</tr>
<tr>
<td>QLOSS</td>
<td>boundary condition for heat transfer to cabin interior</td>
</tr>
<tr>
<td>QXID</td>
<td>heating rate due to combustion</td>
</tr>
<tr>
<td><strong>FORTRAN</strong></td>
<td><strong>Description</strong></td>
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<tr>
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<td>trajectory table radiative heating rates</td>
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<td>radiative heat flux at present time step</td>
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<tr>
<td>QUIT</td>
<td>code word for plot routine</td>
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<tr>
<td>R</td>
<td>thermal resistance due to conductivity between nodes in the ablation material</td>
</tr>
<tr>
<td>RB1</td>
<td>thermal resistance due to conductivity between past and present node in backup material</td>
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<tr>
<td>RHφV</td>
<td>virgin ablation material density</td>
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<td>density of node at past time step</td>
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<td>time corresponding to maximum depth of 1460 isotherm</td>
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<tr>
<td>SAVX</td>
<td>time corresponding to maximum depth of 1060 isotherm</td>
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<td>TCPV</td>
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<tr>
<td>TKV</td>
<td>temperature values in virgin thermal conductivity table</td>
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<td>surface temperature or time at which char removal is to start</td>
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<td>TS</td>
<td>temperature or time values in surface recession table</td>
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<td>equals TUL if VPT = 0 or equals TX2 if VPT = 1 - used in computing char properties</td>
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<td>maximum value of TX1 and TX2</td>
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<td>TULL</td>
<td>maximum TX1 values - used in computing gas ablation rate</td>
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<tr>
<td>TUL2</td>
<td>maximum TX2 values - used in computing gas ablation rate</td>
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<td>temperature of nodes at present time step</td>
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<td>TX2C</td>
<td>temperature at fixed locations in ablation material as defined by XC</td>
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<td>temporary storage of TX2 temperatures for computing thermal properties</td>
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<td>XLSTV</td>
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<td>ZZZ</td>
<td>ratio to determine when the limiting value of heat blockage has been reached</td>
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APPENDIX E

GENERAL FLOW CHART

Start

Rewind 11
Read NCASE

Initialize
program constants

Read and write
input data and
setup initial conditions

Transfer to subroutine
TEMPD
determines initial
temperature distribution

Calculate surface
heating conditions

Transfer to subroutine
RECESS
calculates surface recession
depth and char ablation rate

Transfer to subroutine
CJEFF
calculates tri-diagonal
matrix coefficients

Transfer to subroutine
SWUFT
solves tri-diagonal matrix
for temperature distribution

Continue
Transfer to subroutine DYN2
  calculates fixed location temperatures

Transfer to subroutine ABLATE
  calculates gas ablation rate

Transfer to subroutine SAVE
  determines maximum and minimum values for plot program

Setup temperature distribution for printing
  Perform isotherm depth calculations

Write output tape
  NPLF = 1

If time is less than TLIM, loop back to surface heating calculations

Check for time limit of problem

Check NCASE
  LPLF = NCASE
  Rewind 11

Reinitialize program to initial input conditions

Go to initialization of program constants to start next problem

Transfer to subroutine ISOTHERM
  calculates 1060° R and 1450° R isotherm depths

Setup data for plot program

End File 11

Continue
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**FORTRAN STATEMENT**

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**TYPICAL CHARRING ABLATION - TEST CASE - 4/6/65 - DONALD M. CURRY**

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**TYPICAL CHARRING ABLATION MATERIAL PROPERTIES**

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**NO TRAJECTORY - 0.95 BTU/SEC - SQFT**

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*NOTE: WRITE NUMBERS 10, LETTERS U, G, Z, C, SYMBOLS */
### TABLE I. - SAMPLE PROBLEM INPUT - Continued

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**Note:** Write numbers 10, letters 10, UGZC, symbols / -
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NOTE: WRITE NUMBERS 10, LETTERS PGZC, SYMBOLS */+.
TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

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**Typical Charring Ablation Material Properties**

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**No Trajectory**

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**Backup Material**

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<td></td>
</tr>
</tbody>
</table>

**Heat Transfer to Capin Furnish**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>+500.0 +un +0.0 +un +0.0 +un +0.0 +un</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

**Initial Temperature Is Constant**

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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>+500.0 +un +1400.0 +un +342.9 +un +1400.0 +un</td>
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<td></td>
</tr>
<tr>
<td>+711.0 +un +4100.0 +un +711.0 +un +4100.0 +un</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>+1113.0 +un +6000.0 +un +1200.0 +un +4240.0 +un</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1400.0 +un +999.0 +un +1500.0 +un +4936.0 +un</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1710.0 +un +299.0 +un +1800.0 +un +5654.0 +un</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>+2000.0 +un +5728.0 +un +2100.0 +un +5519.0 +un</td>
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</tr>
<tr>
<td>+2400.0 +un +8778.0 +un +2400.0 +un +6186.0 +un</td>
<td></td>
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<tr>
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<tr>
<td>+4200.0 +un +6999.0 +un +3000.0 +un +6999.0 +un</td>
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<td></td>
</tr>
</tbody>
</table>
(b) Fortran data card listing

<table>
<thead>
<tr>
<th>Card Number</th>
<th>Data Card Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>+32000</td>
<td>+00007175.0</td>
</tr>
<tr>
<td>+35000</td>
<td>+00007800.0</td>
</tr>
<tr>
<td>+38000</td>
<td>+00008300.0</td>
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<td>+41000</td>
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<tr>
<td>+44000</td>
<td>+00009300.0</td>
</tr>
<tr>
<td>+47000</td>
<td>+00009800.0</td>
</tr>
<tr>
<td>+50000</td>
<td>+00010300.0</td>
</tr>
</tbody>
</table>

TABLE I - SAMPLE PROBLEM INPUT - Concluded
**TABLE II. - SAMPLE PROBLEM OUTPUT**

**TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY**

**INPUT DATA.**

TIME LIMIT = 6.0000E 02 INITIAL TIME = 0.0

<table>
<thead>
<tr>
<th>TIME</th>
<th>TIME STEP</th>
<th>POINT CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.0000E-01</td>
<td>100</td>
</tr>
<tr>
<td>6.00</td>
<td>1.0000E-01</td>
<td>100</td>
</tr>
</tbody>
</table>

FCNV = 1.0000E 03 FRAN = 1.0000E 00

**TYPICAL CHARRING ABLATION MATERIAL PROPERTIES**

<table>
<thead>
<tr>
<th>TABLE</th>
<th>TCMA=</th>
<th>TREC=</th>
<th>RHOC=</th>
<th>RHOC=</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBLD=</td>
<td>0.00</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>MV=</td>
<td>2.5000E-02</td>
<td>0.</td>
<td>1.1000E 00</td>
<td>0.</td>
</tr>
<tr>
<td>CMRA=</td>
<td>4.3000E-01</td>
<td>1.0000E-02</td>
<td>0.</td>
<td>0.</td>
</tr>
</tbody>
</table>

NP= 31 NKC= 2 NCPC= 9 NV= 9 NCPV= 2 NREC= 2

**VIRGIN MATERIAL**

**TEMPERATURE**

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>CONDUCTIVITY</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6000E 02</td>
<td>6.5000E-02</td>
<td>1.1000E 00</td>
</tr>
<tr>
<td>5.6000E 02</td>
<td>6.5000E-02</td>
<td>1.1000E 00</td>
</tr>
<tr>
<td>7.6000E 02</td>
<td>6.5000E-02</td>
<td>1.1000E 00</td>
</tr>
<tr>
<td>8.0000E 02</td>
<td>6.5000E-02</td>
<td>1.1000E 00</td>
</tr>
<tr>
<td>9.0000E 02</td>
<td>6.5000E-02</td>
<td>1.1000E 00</td>
</tr>
<tr>
<td>1.0000E 03</td>
<td>7.0000E-02</td>
<td>1.1000E 00</td>
</tr>
</tbody>
</table>

**CHAR MATERIAL**

**TEMPERATURE**

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>CONDUCTIVITY</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4600E 04</td>
<td>1.2000E-01</td>
<td>1.4600E 03</td>
</tr>
<tr>
<td>1.0000E 04</td>
<td>1.2000E-01</td>
<td>1.0000E 04</td>
</tr>
</tbody>
</table>

**SURFACE RECESSSION TABLE**

<table>
<thead>
<tr>
<th>TIME</th>
<th>SM = 1/IN/SEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>9.00000E-04</td>
</tr>
<tr>
<td>6.00</td>
<td>9.00000E-04</td>
</tr>
</tbody>
</table>

**NO TRAJECTORY = 0=95 BTU/SEC-SOFT**

**NO. OF TRAJECTORY POINTS = ?**
TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

<table>
<thead>
<tr>
<th>TIME</th>
<th>Q CONVECTIVE</th>
<th>Q RADIATIVE</th>
<th>VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>7.99990E 01</td>
<td>0.</td>
<td>2.92500E 04</td>
</tr>
<tr>
<td>6.00000E 02</td>
<td>9.60000E 01</td>
<td>0.</td>
<td>2.92500E 04</td>
</tr>
</tbody>
</table>

PROPERTIES OF BACKUP STRUCTURE

NO. OF MATERIALS IN BACK-UP SHIELD= 1
TOTAL NUMBER OF NODES IN BACK-UP SHIELD= 3
THICKNESS OF BACK-UP SHIELD= 1.00000E-01

BACKUP MATERIAL 0.1 INCHES THICK

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>CONDUCTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.60000E 02</td>
<td>6.90000E-02</td>
</tr>
<tr>
<td>4.60000E 02</td>
<td>6.50000E-02</td>
</tr>
<tr>
<td>5.60000E 02</td>
<td>6.10000E-02</td>
</tr>
<tr>
<td>6.60000E 02</td>
<td>6.70000E-02</td>
</tr>
<tr>
<td>7.60000E 02</td>
<td>7.30000E-02</td>
</tr>
<tr>
<td>8.60000E 02</td>
<td>7.90000E-02</td>
</tr>
<tr>
<td>9.60000E 02</td>
<td>8.50000E-02</td>
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<tr>
<td>1.06000E 02</td>
<td>9.10000E-02</td>
</tr>
<tr>
<td>1.16000E 03</td>
<td>9.70000E-02</td>
</tr>
</tbody>
</table>

EMISSIVITY

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DENSITY</th>
<th>THICKNESS</th>
<th>EMIS SIVITY</th>
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<tbody>
<tr>
<td>1</td>
<td>3.40000E 01</td>
<td>1.00000E-01</td>
<td>9.00000E-01</td>
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<tr>
<td></td>
<td>9.00000E 01</td>
<td>9.00000E 01</td>
<td>3.40000E 00</td>
</tr>
</tbody>
</table>

ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>FILM COEFFICIENT</th>
<th>GAP THICKNESS</th>
<th>FRONT</th>
<th>BACK</th>
<th>NODES/MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
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</tbody>
</table>

HEAT TRANSFER TO GAIN ENVIRONMENT - HENV=0.0

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>FILM COEFFICIENT</th>
<th>VIEW FACTOR</th>
<th>Q LOST</th>
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<tbody>
<tr>
<td>3.60000E 02</td>
<td>0.</td>
<td>0.</td>
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</table>

INITIAL TEMPERATURE IS CONSTANT

TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.30000E 02
TABLE II. SAMPLE PROBLEM OUTPUT - Concluded

OUTPUT DATA.

TIME= 9.79000E 00 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0, VELOCITY= 2.92500E 04
GAS ABLATION RATE= 0, CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 5.40000E 00
RECESSION DEPTH= 9.00000E-03 OHot WALL= 8.99282E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 1.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

<table>
<thead>
<tr>
<th>Temperature</th>
<th>3.79022E 03</th>
<th>5.30000E 02</th>
<th>2.33046E 03</th>
<th>1.06300E 03</th>
<th>6.38075E 02</th>
<th>5.47600E 02</th>
<th>5.32434E 02</th>
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</thead>
<tbody>
<tr>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
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<td>5.30000E 02</td>
<td>5.30000E 02</td>
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<td>5.30000E 02</td>
<td>5.30000E 02</td>
</tr>
<tr>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
</tr>
</tbody>
</table>

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

| Temperature | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |

TIME= 9.79000E 00 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0, VELOCITY= 2.92500E 04
GAS ABLATION RATE= 2.57200E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 3.44720E 01
RECESSION DEPTH= 1.80000E-02 OHot WALL= 8.99173E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 2.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

<table>
<thead>
<tr>
<th>Temperature</th>
<th>3.80935E 03</th>
<th>5.30254E 02</th>
<th>2.87678E 03</th>
<th>1.64576E 03</th>
<th>9.77202E 02</th>
<th>6.72698E 02</th>
<th>5.66204E 02</th>
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</thead>
<tbody>
<tr>
<td>5.38578E 02</td>
<td>5.31499E 02</td>
<td>5.30254E 02</td>
<td>5.30254E 02</td>
<td>5.30254E 02</td>
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<tr>
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<td>5.29999E 02</td>
<td>5.29999E 02</td>
</tr>
</tbody>
</table>

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

| Temperature | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |

TIME= 9.79000E 00 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0, VELOCITY= 2.92500E 04
GAS ABLATION RATE= 1.25330E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 1.79330E 01
RECESSION DEPTH= 2.70000E-02 OHot WALL= 8.98427E 01
Figure 1. - Radiation temperature approximation error.
Figure 2. - Schematic diagram of charring ablator thermal protection system.
Figure 3. - Thermogravimetric data for typical charring ablation material.
Figure 4. - Charring material property variation used as input to STAB II.
Figure 5. - Comparison of temperature histories for nonablating steel slab (pure conduction)
Figure 6. - Comparison of temperature histories for moving boundary model.
Figure 7. - Comparison of temperature histories for typical charring ablator.
Figure 8. - Plot program surface recession curve from typical charring ablactor test case.
Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.
Figure 10. - Plot program 1060°R and 1460°R isotherm curves from typical charring ablator test case.
"The aeronautical and space activities of the United States shall be conducted to as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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