AN ANALYSIS OF
A CHARRING ABLATION
THERMAL PROTECTION SYSTEM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D.C.
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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

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

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

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

\( \dot{q}_{\text{cw}} \)  
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 (\( \theta' - \theta \))

\( \varepsilon \)  
emissivity of material

\( \eta \)  
transpiration cooling efficiency

\( \theta \)  
initial time

\( \theta' \)  
final time

\( \xi \)  
transform for the ablation material
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 nonablating homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is

$$\frac{\partial}{\partial X} \left( k \frac{\partial T}{\partial X} \right) = \rho c_p \frac{\partial T}{\partial \theta}$$

(1)

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

$$\frac{T_i - T_{i-1}}{\Delta X} + \frac{T_{i+1} - T_i}{2k_i} = \rho c_p \frac{\Delta X (T'_i - T_i)}{\Delta \theta}$$

(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:

$$\frac{\rho c_p (\Delta X)^2}{k \Delta \theta} \geq 2$$
which places an upper limit on the time step \( \Delta \theta \) 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:

\[
\frac{(T_i' - T_{i-1}')}{\Delta X} + \frac{\Delta X}{2k_i} \left( T_i' - T_{i-1}' \right) = \rho c_p \frac{\Delta X}{\Delta \theta} \left( T_i' - T_i \right)
\]

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 \( T_i' \), 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

\[
\left( \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} \right) T_i' = \left( \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} \right) T_{i-1}' + \left( \frac{1}{\Delta X} + \frac{\Delta X}{2k_{i+1}} \right) T_{i+1}' - \left( \frac{\rho c_p \Delta X}{\Delta \theta} \right) T_i
\]

Equation (4) is of the form

\[ A T_i'_{i-1} + B T_i' + C T_i'_{i+1} = D \]  

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:

\[ q_{rad} = F \sigma \left( T_i' - T_{\infty}' \right) \]
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:

\[
\left( T_f' \right)^4 = \left( T_f + \Delta T \right)^4 = T_f^4 \left( 1 + \frac{\Delta T}{T_f} \right)^4 \quad (7)
\]

where

\[
\Delta T = T_f' - T_f
\]

let

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

and rewrite equation (7) as

\[
\left( T_f' \right)^4 = \left( T_f \right)^4 (1 + Z)^4 \quad (8)
\]

If $Z$ has an absolute value near zero, the following is true

\[
(1 + Z)^4 \approx 1 + 4Z \quad (9)
\]

Now substituting equation (9) into equation (8)

\[
\left( T_f' \right)^4 \approx \left( T_f \right)^4 (1 + 4Z) = \left( T_f \right)^4 \left( 1 + 4 \frac{\Delta T}{T_f} \right)
\]

\[
\approx 4T_f \frac{3T_f' - 3T_f}{T_f} \quad (10)
\]

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 $\Delta T/T_f$ 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 $\Delta T/T_f$ can easily be controlled to values of less than $\pm 0.1$.

Therefore, equation (6) can now be written

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

\[
\begin{align*}
B_1 T_{11} + C_1 T_{21} &= D_1 \\
A_2 T_{11} + B_2 T_{21} + C_2 T_{22} &= D_2 \\
A_3 T_{21} + B_3 T_{22} + C_3 T_{23} &= D_3 \\
&\vdots \\
A_{N-1} T_{N-2} + B_{N-1} T_{N-1} + C_{N-1} T_{N-1} &= D_{N-1} \\
A_N T_{N-1} + B_N T_N &= D_N
\end{align*}
\]

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

$$\frac{d}{d\theta} \left( \frac{1}{2} \Delta X \rho_1 c_p T_1 \right) = \frac{1}{2} \Delta X \rho_1 c_p T_1 \frac{dT_1}{d\theta} + \frac{1}{2} \rho_1 c_p T_1 \frac{d(\Delta X)}{d\theta}$$

$$= Q_{in} + \dot{m}_2 c_p T_{2'} + \rho_2 \dot{s}_2 c_p T_{2'} - \dot{m}_1 c_p T_{1'} - \rho_1 c_p \dot{s}_1 T_{1'} - k_{1-2} \left( \frac{\Delta T}{\Delta X} \right)$$

(12)

where

$$Q_{in} = \dot{q}_c, \text{ blow} + \dot{q}_{\text{rad}} + \dot{q}_{\text{comb}} - \rho \sigma \left( T_1^4 - T_\infty^4 \right)$$

and

$$\frac{d(\Delta X)}{d\theta} = \frac{d}{d\theta} \left( \frac{VL - S}{NP - 1} \right) = - \frac{\dot{S}}{NP - 1}$$

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

\[ Q_{in} + \dot{m}_g c_{p_2} T_2^\prime - \dot{m}_g c_{p_1} T_1^\prime - \dot{S}_0 c_{p_1} T_1^\prime - \frac{(T_1^\prime - T_2^\prime)}{\Delta X + \frac{\Delta X}{2k_1}} \]

\[ + \rho_2 c_{p_2} \frac{(NP - 1.5)}{NP - 1.0} T_2^\prime = \rho_1 c_{p_1} \frac{\Delta X}{2} \left( \frac{T_1^\prime - T_1}{\Delta \theta} \right) \]

\[ - \frac{1}{2} \frac{\rho_1 c_{p_1} T_1^\prime}{NP - 1} \]

(12a)

Then, rearranging and collecting terms yield

\[ \begin{bmatrix} \dot{m}_g c_{p_1} + \dot{S}_0 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta \theta} + \frac{1}{\Delta X + \frac{\Delta X}{2k_1}} - \frac{\rho_1 c_{p_1}}{2} \left( \frac{\dot{S}}{NP - 1} \right) \end{bmatrix} T_1^\prime \]

\[ + \begin{bmatrix} \dot{m}_g c_{p_2} + \frac{1}{\Delta X + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \frac{(NP - 1.5)}{NP - 1.0} \end{bmatrix} T_2^\prime \]

\[ = -\rho_1 c_{p_1} \frac{\Delta X}{2\Delta \theta} T_1 - Q_{in}. \]

(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

\[
\frac{d}{d\theta} \left( \Delta X \rho_i c_{p_i} T_i \right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i \left( \frac{\dot{S}}{NP - 1} \right) \\
= \dot{m}_{i+1} c_{p_{i+1}} T_{i+1} + k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1} \\
- k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_{i} c_{p_i} T_i - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_i 
\] (13)
Putting equation (13) in an implicit finite difference form yields

\[
\left( \frac{1}{\Delta x} + \frac{1}{\Delta x} \right) T_{i-1} = \left[ \begin{array}{c} \dot{m}_{i} c_{p_{i}} + \rho_{i} c_{p_{i}} \frac{\dot{S}}{(NP - 1 + \frac{1}{2})} + \frac{1}{\Delta x} \rho_{i} c_{p_{i}} \frac{\Delta \theta}{\Delta \theta} - \rho_{i} c_{p_{i}} \left( \frac{\dot{S}}{NP - 1} \right) \\
\frac{\dot{m}_{i+1} c_{p_{i+1}}}{\Delta x} + \frac{\Delta \theta}{\Delta \theta} + \rho_{i+1} c_{p_{i+1}} \left( \frac{\dot{S}}{NP - 1 + \frac{1}{2}} \right) \end{array} \right] T_{i} + \left[ \begin{array}{c} \frac{\Delta x}{2k_{i-1}} + \frac{\Delta x}{2k_{i+1}} \\
\frac{\Delta x}{2k_{i}} \end{array} \right] \left( NP - 1 \right) T_{i+1}^{'}
\]

\[= -\rho_{i} c_{p_{i}} \frac{\Delta \theta}{\Delta \theta} T_{i}^{'} \]

(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

\[
\frac{d}{d\theta} \left( \Delta x \rho_{i} c_{p_{i}} T_{i} \right) = \Delta x \rho_{i} c_{p_{i}} \frac{dT_{i}}{d\theta} - \rho_{i} c_{p_{i}} T_{i} \left( \frac{\dot{S}}{NP - 1} \right) - (\dot{m}_{i} - \dot{m}_{i+1}) \frac{H_{d}}{\Delta \theta}
\]

\[= \dot{m}_{i+1} c_{p_{i+1}} T_{i+1}^{'} + k_{i-1,i} \left( \frac{dT_{i}}{dx} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T_{i+1}^{'}
\]

\[- k_{i,i+1} \left( \frac{dT_{i}}{dx} \right) - \dot{m}_{i} c_{p_{i}} T_{i} - \rho_{i} c_{p_{i}} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_{i}^{'} \]

(14)
Rearranging,

\[
\left(\frac{1}{\Delta x} + \frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}\right)T_{i-1}^' = \left[\dot{m}_{g_i} c_i p_i + \rho_i c_i p_i \left(\frac{\Delta X}{NP - 1}\right)\right] + \frac{1}{\Delta x} \frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i} + \\
\frac{1}{\Delta x} \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_i c_i p_i \frac{\Delta X}{\Delta \theta} - \rho_i c_i p_i \left[\frac{\Delta X}{NP - 1}\right] T_i + \left[\dot{m}_{g_{i+1}} c_{p_{i+1}}\right] + \\
\frac{1}{\Delta x} \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}} + \rho_{i+1} c_{p_{i+1}} \frac{\Delta X}{\Delta \theta} - \rho_{i+1} c_{p_{i+1}} \left[\frac{\Delta X}{NP - 1}\right] T_{i+1}^' + \\
-\rho_i c_i \frac{\Delta X}{\Delta \theta} T_i - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d (14a)
\]

The physical model for the interface between the reaction zone and virgin material is illustrated as follows:

\[
\begin{array}{c}
\dot{S}_{i-1,1} \rho_i c_i T_i \\
\dot{S}_{i-1,1} \rho_i c_i T_i \\
k_{i-1,1} \left(\frac{\Delta T}{\Delta X}\right)
\end{array}
\]

\[
\begin{array}{c}
\dot{S}_{i,1} \rho_{i+1} c_{p_{i+1}} T_i \\
k_{i,1} \left(\frac{\Delta T}{\Delta X}\right)
\end{array}
\]

\[
\dot{S}_{i,1} = \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)
\]

\[
\dot{S}_{i-1,1} = \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right)
\]
The heat balance equation for this node is

\[
\frac{d}{d\theta} \left( \Delta X \rho c_{p_1} T_1 \right) = \Delta X \rho c_{p_1} \frac{dT_1}{d\theta} - \rho c_{p_1} T_1 \left( \frac{\dot{S}}{NP - 1} \right) - \dot{m}_{g_1} H_d
\]

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

\[
- k_{i,1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_1} c_{p_1} T_1 - \rho c_{p_1} S \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T_1^1
\]

(15)

Rearranging yields

\[
\left( \frac{1}{2k_{i-1,i}} + \frac{\Delta X}{2k_{i,i+1}} \right) T_{i-1}^1 = \left[ \dot{m}_{g_1} c_{p_1} + \frac{1}{2k_{i-1,i}} + \frac{1}{2k_i} + \frac{1}{2k_{i+1,i}} \right] \frac{\Delta X}{2k_{i-1,i}} + \frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1,i}}
\]

\[
+ \rho c_{p_1} S \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho c_{p_1} \frac{\Delta X}{\Delta \theta} - \rho c_{p_1} \left( \frac{\dot{S}}{NP - 1} \right) T_{i-1}^1
\]

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

\[
= -\rho c_{p_1} \frac{\Delta X}{\Delta \theta} T_1^1 - \dot{m}_{g_1} H_d
\]

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

\[ \dot{S}_{i-1,i} \rho_i c_p^i \left( \frac{\Delta T}{\Delta x} \right) = \dot{S}_{i,i+1} \rho_{i+1} c_p^{i+1} \left( \frac{\Delta T}{\Delta x} \right) + k_{i,i+1} \left( \frac{\Delta T}{\Delta x} \right) \]

The heat balance for this nonablating node is

\[
\frac{d}{ds} \left( \Delta x \rho_i c_p^i T_i \right) = \Delta x \rho_i c_p^i \frac{dT_i}{ds} - \frac{\dot{S}_i c_p^i T_i}{\Delta T} \left( \frac{\Delta T}{\Delta x} \right) \\
= k_{i-1,i} \left( \frac{\Delta T}{\Delta x} \right) + \rho_{i+1} c_p^{i+1} \frac{\Delta T}{\Delta x} T_{i+1} - k_{i,i+1} \left( \frac{\Delta T}{\Delta x} \right) - \rho_i c_p^i \frac{\Delta T}{\Delta x} T_i
\]

(16)
Rearranging,

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

\[+ \rho p_i c_p \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho p_i c_p \frac{\Delta X}{\Delta \theta} - \rho p_i c_p \left( \frac{\dot{S}}{NP - 1} \right) \left[ T'_{i} \right]
\]

\[+ \left[ \frac{1}{\Delta X} + \frac{\Delta X}{2k_i} \right] + \rho p_i+1 c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \left[ T'_{i+1} = -\rho p_i c_p \frac{\Delta X}{\Delta \theta} T'_{i} \right]
\]

(16a)

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

\[
\frac{\Delta X_j}{2} \quad \frac{\Delta X_{j+1}}{2}
\]

\[\dot{S}_{i-1,1,1}^T, i, p_i, c_{p_{i,j}}, T^T_{i,j,1}\]

\[k_{i-1,1,1}^T, i, p_i, c_{p_{i,j}}, T^T_{i,j,1}\]

\[\dot{S}_{i-1,1,1} = \dot{S} \left( \frac{\Delta T}{\Delta X} \right)
\]

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

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

\( (17) \)

Rearranging yields

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

\( (17a) \)

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:

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

Rearranging, equation (18) becomes

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

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

(18a)

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

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

\[
= \left( \frac{\rho_{i,j} C_{p_{i,j}} \Delta X_j + \rho_{i,j+1} C_{p_{i,j+1}} \Delta X_j}{2 \Delta \theta} \right) \left( T'_{i,j} - T_{i,j} \right)
\]

(19)

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

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

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

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

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

Equation (20) may be linearized by using the approximation

\[
T'_{i,j} \approx 4T''_{i,j} - 3T''_{i,j}
\]

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

\[
\begin{align*}
\left[ h_j + \left( \frac{\frac{4\sigma T_{i-1,j}}{z_i} + \frac{1}{e_j} + \frac{1}{e_{j+1}} - 1}{z_i} \right) \right] T_{i-1,j} & - \left[ h_j + \left( \frac{\frac{4\sigma T_{i,j+1}}{z_i} + \frac{1}{e_j} + \frac{1}{e_{j+1}} - 1}{z_i} \right) \right] T_{i,j+1} \\
+ \frac{\Delta X_{j+1}}{2k_i,j+1} + \frac{\Delta X_{j+1}}{2k_i+1,j+1} & + \frac{\Delta X_{j+1}}{2k_i+1,j+1} \\
+ \left( \frac{1}{\Delta X_{j+1}} \right) T_{i+1,j+1} & = - \frac{\rho_i,j}{} \frac{\Delta X_{j+1}}{2 \Delta \theta} T_{i,j+1} \\
- \left( \frac{3\sigma}{\Delta X_j} \right) & \left( T_{i,j+1} - T_{i-1,j} \right) \\
(20a)
\end{align*}
\]

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

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

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

(21)
Rearranging and linearizing, equation (21) becomes

\[
\left( \frac{1}{\Delta x_j} + \frac{\Delta x_j}{2k_{i-1,j} + 2k_{i,j}} \right) T'_{i-1,j} - \left[ \begin{array}{c}
h_j + \frac{1}{\Delta x_j} \cdot \frac{1}{2k_{i-1,j} + 2k_{i,j}} + \left( \frac{4\sigma T^3_{T_{i,j}}}{\varepsilon_j + \varepsilon_{j+1} - 1} \right) \\
\rho_{i,j} c p_{i,j} \frac{\Delta x_j}{2 \Delta \theta} \end{array} \right] T'_{i,j} + \left[ \begin{array}{c}
h_j + \left( \frac{4\sigma T^3_{T_{i,j+1}}}{\varepsilon_j + \varepsilon_{j+1} - 1} \right) \\
\rho_{i,j} c p_{i,j} \frac{\Delta x_j}{2 \Delta \theta} \end{array} \right] T'_{i,j+1}
\]

\[
= - \frac{\rho_{i,j} c p_{i,j} \Delta x_j}{2 \Delta \theta} T_{i,j} + \left( \frac{3\sigma}{\varepsilon_j + \varepsilon_{j+1} - 1} \right) \left( T'_{i,j+1} - T'_{i,j} \right)
\]

(21a)

(5) Final node in backup structure:

(a) Adiabatic surface

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

(22)

Rearranging, equation (22) becomes

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

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

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

\[ - F_{\text{env}} \sigma \left( T_{i,j}^h - T_{\text{env}}^h \right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} (T_{i,j} - T_{i,j}) \quad (23) \]

Rearranging, equation (23) becomes

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

\[ - h_{env} T_{\text{env}} - F_{\text{env}} \sigma \left( 3T_{i,j}^h + T_{\text{env}}^h \right) \quad (23a) \]

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 spatially 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 3 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,

\[ \dot{\rho}_i = \frac{\rho_i' - \rho_i}{\Delta t} \]  \hspace{1cm} (24)

and

\[ \dot{m}_{g_i} = \sum_{i} \rho_i \Delta X_i \]  \hspace{1cm} (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

\[ \frac{d\rho}{\Delta t} = -A (\rho - \rho_c)^n e^{-\frac{E}{RT}} \]  \hspace{1cm} (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):

\[ \dot{q}_{\text{block}} = \eta \dot{m}_g (H_T - H_w) \]  \hspace{1cm} (27)

Therefore,

\[ \dot{q}_{c,\text{blow}} = \dot{q}_{c,w} \left( \frac{H_T - H_w}{H_T - H_{200}} \right) - \dot{q}_{\text{block}} \]  \hspace{1cm} (28)
However, equation (28) is unsatisfactory for high blowing rates, since $\dot{q}_{\text{block}}$ can become greater than $\dot{q}_{cw}$. An experimental curve of blocking effectiveness $\psi = \frac{\dot{q}_{c,\text{blow}}}{\dot{q}_{cw}}$ as a function of the mass transfer parameter $\frac{\dot{m} H T}{\dot{q}_{cw}}$ 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

$$\dot{q}_{\text{comb}} = \dot{m}_c \Delta H_c$$

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 ($T_{\text{abl}} \leq T_i < T_{\text{char}}$)
   
   $$\rho = f(\text{temp}) = \rho_v + (\rho_v - \rho_c) \left( \frac{T_i - T_{\text{abl}}}{T_{\text{abl}} - T_{\text{char}}} \right)$$
   $$k = f(\rho) = k_c + (k_v - k_c) \left( \frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$
   $$c_p = f(\rho) = c_{p_c} + (c_{p_v} - c_{p_c}) \left( \frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$
(3) Virgin zone \( T_i < T_{abl} \)

\[
\begin{align*}
\rho_v &= \text{constant} \\
K_v &= f(\text{temp}) \\
C_p_v &= f(\text{temp})
\end{align*}
\]

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° R (0° 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.

\[
\left[ \left( \frac{\partial T}{\partial \theta} \right)_{x=0} = 0; \ k \left( \frac{\partial T}{\partial x} \right)_{x=0} = \dot{S}c_p \Delta T \right]
\]

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.
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:

\[
\begin{align*}
\text{ABLATION MATERIAL} & \\
\text{Insulation} & \\
\text{Adiabatic} & \quad \dot{q}_{cw} = 95 \text{ Btu/ft}^2\text{-sec} \\
& \quad 1.5 \text{ in.} \\
& \quad 0.1 \text{ in.}
\end{align*}
\]

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 E02, +145.23 E00, or +.14523 E03.

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)

NPLOT output plot control

  =1 plot routine will be used

  =0 plot routine will be ignored
<table>
<thead>
<tr>
<th>Symbol</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>FCONV</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>RHVC</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 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></td>
<td>=0 properties are irreversible</td>
</tr>
<tr>
<td></td>
<td>=1 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>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>CHARK</td>
<td>thermal conductivity of material at TCHAR, Btu/ft-hr°R</td>
</tr>
<tr>
<td>CHARC</td>
<td>specific heat of material at TCHAR, Btu/lbm°R</td>
</tr>
<tr>
<td>ABLK</td>
<td>thermal conductivity of material at TABL, Btu/ft-hr°R</td>
</tr>
<tr>
<td>ABLC</td>
<td>specific heat of material at TABL, Btu/lbm°R</td>
</tr>
<tr>
<td>NF</td>
<td>number of node points in ablation material</td>
</tr>
<tr>
<td>NKC</td>
<td>number of points in char thermal conductivity - temperature table</td>
</tr>
<tr>
<td>NCPC</td>
<td>number of points in char specific heat - temperature table</td>
</tr>
<tr>
<td>NKV</td>
<td>number of points in virgin thermal conductivity - temperature table</td>
</tr>
<tr>
<td>NCPV</td>
<td>number of points in virgin specific heat - temperature table</td>
</tr>
<tr>
<td>NREC</td>
<td>number of points in surface recession - temperature or time table</td>
</tr>
<tr>
<td>TKC</td>
<td>temperature values in char thermal conductivity - temperature table, °R</td>
</tr>
<tr>
<td>XKC</td>
<td>thermal conductivity values in char thermal conductivity - temperature table, Btu/ft-hr°R</td>
</tr>
<tr>
<td>TCPC</td>
<td>temperature values in char specific heat - temperature table, °R</td>
</tr>
<tr>
<td>CPC</td>
<td>specific heat values in char specific heat - temperature table, Btu/lbm°R</td>
</tr>
<tr>
<td>TKV</td>
<td>temperature values in virgin thermal conductivity - temperature table, °R</td>
</tr>
<tr>
<td>XKV</td>
<td>thermal conductivity values in virgin thermal conductivity - temperature table, Btu/ft-hr°R</td>
</tr>
<tr>
<td>TCPV</td>
<td>temperature values in virgin specific heat - temperature table, °R</td>
</tr>
<tr>
<td>CPV</td>
<td>specific heat values in virgin specific heat temperature table, Btu/lbm°R</td>
</tr>
<tr>
<td>TS</td>
<td>temperature, °R, or time, sec, values in the surface recession table</td>
</tr>
</tbody>
</table>
SR  surface recession values in the surface recession –
temperature or time table, in./sec
NTRAPT  number of time points in the trajectory input table
TIME  the array of (NTRAPT) trajectory time values, sec
QCØN  the corresponding array of cold wall convective heating
  rates, Btu/ft$^2$-sec
QRAD  the corresponding array of radiative heating rates,
  Btu/ft$^2$-sec
VEL  the corresponding array of flight velocity, ft/sec
NMB  number of materials in backup structure
NPBS  total number of node points in backup structure
BL  total thickness of backup structure, in.
XNPM  number of nodes in each individual material in backup
  structure
NKPB  number of points in each individual backup structure
  material thermal conductivity – temperature table
NCPB  number of points in each individual backup structure
  material specific heat – temperature table
XIDNT  any 72 alphanumeric characters used to describe each
  individual material in the backup structure
TXK  temperature values in backup material thermal conductivity –
temperature table, °R
XX  thermal conductivity values in backup material thermal
  conductivity – temperature table, Btu/ft-hr-°R
TCP  temperature values in backup material specific heat –
temperature tables, °R
CFX  specific heat values in backup material specific heat –
temperature tables, Btu/lbm-°R
RHØBX  density of individual materials in backup, lb/ft$^3$
XBM  thickness of individual materials in backup, in.
EMFB  emissivity of front surface of each material in backup
EMBB  emissivity of back surface of each material in backup

H  film coefficient between adjacent materials in backup, Btu/ft²·hr·°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, °R

HENV  film coefficient to interior cabin environment, Btu/ft²·hr·°R

FENV  view factor and emissivity product for radiative heat transfer to cabin interior

QLLOSS  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, °R

TXθ  initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, °R

TEMDI  arbitrary temperature distribution values, to be used only if TEST2 is negative, °R
NHP  number of points in enthalpy – temperature curve fit
HX   enthalpy values in enthalpy – temperature table, Btu/lbm
TW   corresponding temperature values in enthalpy – temperature table, °R

Input Data Card Preparation

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 NPLNT. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPLNT 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 FC@N and FR@D. 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. HEADING card – any alphanumeric characters in columns 1 to 72. Records 9 to 18 contain input data for the ablation material.

10. Enter TABL, TCHAR, TREC, RH@V, RH@C, and FBL@W. 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, CHARK, 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 the 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: RH$BX, 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. HEADING card – any alphanumeric characters in columns 1 to 72. Record 35 contains properties of environment.

34. Enter the following: TENV, HENV, FENV, and QL$SS. 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. HEADING card – any alphanumeric characters in columns 1 to 72. Records 37 and 38 contain initial temperature distribution input.

37. Enter TEST2, TEMPI, and TX$. 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**, **QC@N**, **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/ft$^2$-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), ESAVE2(3), ESAVE3(3).
DIMENSION TITLE(12), HFADN(12), XTNT(12), TKN(20), XCC(20),
1 CPC(20), TKV(20), XSV(20), CPCV(20), CPV(20), TIME(30), GCON(30),
2 RAD(300), VEL(300), XPM(12), NKPR(12), NCPP(12), TXK(20), XK(20),
3 CPC(20), CPX(20), RHOBX(12), XBM(12), FMFXB(12), EMBR(12), HX(12),
4, GAPX(12), FTST(12), TST(12), TFM(200), TX1(200), TX2(200),
5 TSTX(10), TIL1(200), TIL2(200), HX(50), Tw(50), IR(50), IR1(50),
6 IR2(50), TUL(50), IFM(50), TY(200), A(200), R(200), C(200), P(200),
7 RH(50), CP(50), XN(12), XKR(10), CPB(10), XMDG(50),
8 YK(50), As(10), RB(10), CR(10), DB(10), SR(10),
9 RC(10), PC(10), HR(10), S(50), NPM(12),
DIMENSION TTUL(50), RH(50), RHO(50), XNPS(50), TPC(50),
DIMENSION TS(50), SR(50),
DIMENSION TDTR(20), P(20), IPC(20),
DIMENSION ASAVE1(3), ASAVE2(3), ASAVE3(3), BSSAVE1(3), BSSAVE2(3),
1 BSSAVE3(3), CSAVE1(3), CSAVE2(3), CSAVE3(3), HFAD(12),
1 NSAVE1(3), NSAVE2(3), NSAVE3(3),
DIMENSION XRA(30), YA(30)

COMMON TKC, XCV, CPC, TKV, XSV, CPCV, CPV, XPM, RHORX, XRM, FMFBR,
1 FMFX, NKPR, NCPP, TXK, XN, CPC, XPM, GAPX, FTST, FTST, TFM, TX1,
2 TX2, TX2, TIL1, TULP, IR, IR1, IR2, As, CB, CR, SR, AR, RB, CR, DB, SR,
3 RP1, RR2, TY, RHOB, RHOY, XMDG, RHO, CP, YK, XRA, CPB, DXR, DT, XLOST,
4 TBLA, TBLR, TRFC, RHO, ROHC, FFL, FCM, EMC, H300, NKC, NCPP, NCV, NCPV,
5 NP, NMR, NPPS, TST, TFM, TX0, TNV, HENV, FENV, QLOSS, TLM, TINT,
COMMON II, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD, JD,
1 FRR, FRR, HV, VPT, CHAKC, CHAR, ABL, ABL, ABL, ABL, ABL, ABL, ABL, ABL, ABL,
1 FRF, FRF, HV, VPT, CHAKC, CHAR, ABL, ABL, ABL, ABL, ABL, ABL, ABL, ABL,
1 FRR, FRF, HV, VPT, CHAKC, CHAR, ABL, ABL, ABL, ABL, ABL, ABL, ABL, ABL,
1 FRR, FRF, HV, VPT, CHAKC, CHAR, ABL, ABL, ABL, ABL, ABL, ABL, ABL, ABL,
50  NK=1
     INT=1
     XLOST=0.0
     XMT=0.0
     XMDC=0.0
     NKP=1
     XLSVI=0.0
     NRS=2
     NRC=0.0
     LPC=0
     NPL=1
     NXC=1
     NXD=1
     SAVY3=-100.
     SAVY4=100.
     SXO=0.0
     SNOT=0.0

C GENERAL TITLE OF PROBLEM
100 READ(5,3000) (HEAD(K),K=1,12)
     WRITE(6,3009) (HEAD(K),K=1,12)
     LPILOT=LPILOT+1
     WRITE (11)(HEAD(I),I=1,12)
     WRITE(6,110)
110 FORMAT(/1X,11HINPUT DATA,/)  
     READ(5,3000) (TITLE(L),L=1,12)
     IF(TITLE(1).EQ.PRVOUS) GO TO 150
     READ(5,3011) TLIM,TINT,NPTT,NPLOT,NMP,TMDP
     READ(5,3012) (TTABLE(I),DFLT(T),IPRC(I),I=1,NPTT)
     T=TINT
     NTS=DFLT(T)
     DT=DFLT(T)/3600.0
     WRITE(6,120) TLIM,TINT,NPTT
120 FORMAT(1HINPUT,11HTIME LIMIT=,1PE10.4,4X,13HTLINAL TIME=,1PE10.4)
     1HNPTT=I14)
     WRITE(6,122)
122 FORMAT(/1X,4HTHEME,10X,4HTIME STEP,6X,13HPRINT CONTROL)
     WRITE(6,124) (TTABLE(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

C LOCATION FACTORS FOR CONVCTIVE AND RADIATIVE HEATING

1 TF(TITLE(1),EQ.PREVIOUS) GO TO 200
RFAD(5,3002) FCONVF,FRAD
WRITE(6,155) FCONVF,FRAD

155 FORMAT(1I10,6HFCONV=1PE12.5,4X5HFRAD=1PF12.5/

C PROPERTIES OF ABLATION MATERIAL

200 RFAD(5,3000) (TITLE(L),L=1,12)
TF(TITLE(L),EQ.PREVIOUS) GO TO 300
RFAD(5,3000) (HEADNG(K),K=1,12)
WRITE(6,J000) (HEADNG(K),K=1,12)

VPT,FV,TV,CHARK,CHARC,ABLK,ABLKC
RFA (5,3003) NP,NKC,NCPC,NKV,NCPV,NREC
READ(5,3002) (TKC(K),XKC(K),K=1,NKC)
READ(5,3002) (TCPC(M),CPC(M),M=1,NCPC)
READ(5,3002) (TKV(L),XKV(L),L=1,NKV)
READ(5,3002) (TCPV(N),CPCV(N),N=1,NCPC)
READ(5,3002) (TS(I),SR(J),I=1,NRFC)
WRITE(6,210) (HEADNG(K),K=1,12)

VPT,FV,TV,CHARK,CHARC,ABLK,ABLKC

210 FORMAT(1I10,5HTABL=1PE12.5,5X5HTCHARC=1PE12.5,5X5HTREC=1PE12.5,
13X5HRHOV=1PE12.5,3X5HRIOC=1PE12.5,21X/1X6HFRLOW=1PE12.5,4X4,
2HEMV=1PE12.5,4X4HEMC=1PE12.5,3X5H30=1PE12.5,5X3WV=1PE12.5,
35/4X,3HVL=1PE12.5,4X4HVT=1PE12.5,5X3HV=1PE12.5,5X3HT=1PE12.5,
112.5,2X6HCHARK=1PE12.5,3X6HFRAD=1PE12.5,5X6HABLKC=1PE12.5,5X/

VLI=VL
VL=VL/12.0

WRITE(6,220) MP,NKC,NCPC,NKV,NCPV,NREC

220 FORMAT(1PE12.5,14X4X4HNKC=1PE12.5,14X4X4HNCPC=1PE12.5,
15X4HNCPV=1PE12.5,14X4X5HNR=1PE12.5)
WRITE(6,221)

221 FORMAT(32X,15HHERMAL,MATFRIAL/26X,12HCONDUCTIVITY,19X,11HTEMPERATURE,
4X12HCONDUCTIVITY,19X,11HTEMPERATU)

KLLL=MINO(NKC,NCPC)
WRITE(6,222) (TKV(L),XKV(L),TCPV(L),L=1,KLLL)

222 FORMAT(1PE12.5,4X1PE12.5,18X,1PE12.5,3X3PE12.5)

KLLL=KLLL+1
WRITE(6,224) (TCPV(L),L=KLLL,NCPV)

224 FORMAT(48X,1PE12.5,3X1PE12.5)

GO TO 227

227 KLLL=KLLL+1
WRITE(6,226) (TKV(L),L=KLLL,NKV)

226 FORMAT(1PE12.5,4X1PE12.5)

227 WRITE(6,227)

228 FORMAT(1PE12.5,4X1PE12.5,18X,1PE12.5,3X3PE12.5)

KLLL=MINO(NKC,NCPC)
WRITE(6,228) (TKC(L),XKC(L),TCPC(L),L=1,KLLL)

228 IF(NKC=NCPC) ?30,230,30

KLLL=KLLL+1
WRITE(6,229) (TCPC(L),L=KLLL,NCPV)

229 GO TO 235

230 KLLL=KLLL+1
WRITE(6,230) (TCPC(L),L=KLLL,NCPV)

230
232  KILL = KLL + 1
   WRITE (6, 240) (TKC(L), XKC(I), L = KILL, NKC)
235  WRITE (6, 240)
240  FORMAT (/'SURFACE REFLECTION TABLE/' /5X, 11HTMPERATURE, 7X, 11H
      1SR = IN/SC)
   WRITE (6, 245) (TS(I), SR(I), I = 1, NRFC)
245  FORMAT (24X, 1PF12.5, 7X, 1PF12.5)

C
C PROPERTIES OF TRAJECTORY
C
300  HFA(I, 000) (TITLE(L), L = 1, 12)
   IF (TITLE(1), FO, PREVIOUS) GO TO 400
   HFA(I, 004) NTRAP
   HFA(I, 310) (TIMF(K), QCON(K), QRAD(K), VFL(K), K = 1, NTRAP)
   WRITE (6, 300) (HEADING(L), L = 1, 12)
   WRITE (6, 310) NTRAP
310  FORMAT (1HN, 2N, NO. OF TRAJECTORY POINTS = 1I4)
   WRITE (6, 320)
320  FORMAT (/'NTIMF, AX, 12AD convective, 4X, 11H radiative, 7X, AVELOC
       1ITY/)
   WRITE (6, 330) (TIMF(K), QCON(K), QRAD(K), VFL(K), K = 1, NTRAP)
330  FORMAT (1H4-16E4)

C
C PROPERTIES OF BACK-UP STRUCTURE
C
400  HFA(I, 000) (TITLE(L), L = 1, 12)
   IF (TITLE(1), FO, PREVIOUS) GO TO 500
   WRITE (6, 410)
410  FORMAT (/'10X, 11H PROPERTIES OF BACKUP STRUCTURE/)
   HFA(I, 007) NMR, NPS, BL
   HFA(I, 002) (XNP(M), K = 1, NMR)
   HFA(I, 415) (NKP(I), NCPH(I), T = 1, NMR)
415  FORMAT (1UT5)
   N = 420 K = 1, NMR
   NPM(K) = XNPM(K) + 0.00000002
420  CONTINUE
   WRITE (6, 425) NMR, NPS, BL
425  FORMAT (/'4X, 3H NO. OF MATERIALS IN BACK-UP SHIELD = 1I4/4X, 40HTOT
       1 NUMBER OF NODES IN BACK-UP SHIELD = 1I4/4X, 2RAFTICNESS OF BACK-UP
       2SHIELD = 1PE12.5/)
   RL = AL/12.0
   N = 440 I = 1, NMR
   LK = NKP(I)
   IC = NCPH(I)
   HFA(I, 000) ((XINT(K, I), K = 1, I))
   HFA(I, 002) (TXK(J, I), XM(J, I), J = 1, LK)
   HFA(I, 002) (TCP(J, I), CPX(J, I), J = 1, LCP)
   WRITE (6, 430) (XINT(K, I), K = 1, 12)
430  FORMAT (1H4-16E4)
432  FORMAT (//H12AI)
   WRITE (6, 432)
433  FORMAT (/'XHTMPERATURE, 3X, 11HTMPERATURE, 4X, 12W COND
       1ACTIVITY, 19X, 11HTMPERATURE, 7X, 4HEAT)
   KILL = MINO(LK, 1, CP)
   N = 434 (N + 1, KLL)
   WRITE (6, 422) (TXK(N + 1, I), XM(N + 1, I), TCP(N, I), CPX(N, I))
434  CONTINUE
   IF (LK = LCHR) 435, 440, 437
435  KILL = KLL + 1
   WRITE (6, 435)
DO 436 N=KLL!, LCP
WRITE(6,224) (TCP(N,I),CPY(N,I))
436 CONTINUE
GO TO 440
437 KLLL=KLL+1
DO 438 N=KLLL,LK
WRITE(6,226) (TXK(N,I),XK(N,I))
438 CONTINUE
440 CONTINUE
READ(5,3002) (HRHXR(L),XRX(L),EMFR(L),EMRR(L),L=1,NMR)
READ(5,3002) (H(J),GAPX(J),FTEST(J),BTEST(J),J=1,NMR)
WRITE(6,450)
450 FORMAT(/55X,10HELMISCIVITY/A,1X,AHMATERIAL,5X,7HDENSITY,7X,9HTHICKN
155X,70FRONT,9X,2HTHICK,7X,14HNODES/MATERIAL/
DO 460 LLJ=1,NMR
WRITE(6,445) (LLJ,RHORX(LLJ),XPM(LLJ),FMRX(LLJ),FMRB(LLJ),XNPM(LLJ)
460 CONTINUE
WRITE(6,445)
465 FORMAT(/4X,6ANADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP
14X,70FRONT,9X,2HTHICK,7X,14HNODES/MATERIAL/
DO 480 J=1,NMR
WRITE(6,470) J, H(J),GAPX(J),FTEST(J),BTEST(J)
470 CONTINUE
WRITE(6,470) J, H(J),GAPX(J),FTEST(J),BTEST(J)
480 CONTINUE
C
C PROPERTIES OF ENVIRONMENT
500 READ(5,3000) (TITLE(L),L=1,12)
TF(TITLE(1),FO,PRV0US) GO TO 600
READ(5,3002) (HEADER(L),L=1,12)
READ(5,3002) TENV,HENV,FENV,Q05C
WRITE(6,3008) (HEADER(L),L=1,12)
WRITE(6,520) TENV,HENV,FENV,Q05C
520 FORMAT(/4X,12HTEMPERATURE,F12.5,4X,17HELMISCIVITY,F12.5
14X,2HTHICK,7X,70L,O,L,0ST,F12.5
C
C INITIAL TEMPERATURE DISTRIBUTION
600 READ(5,3002) (TITLE(L),L=1,12)
TF(TITLE(1),FO,PRV0US) GO TO 700
READ(5,3000) (HEADER(L),L=1,12)
NPF=NP+NP
TL=VL+BL
XNP=NP
LX=VL/XP=1,0)
DXX=DX
READ(5,3002) TEST,TMPL,TMPL
TF(TEST) 610,620,620
610 READ(5,3002) (TMDK(K),K=1,NPF)
DO 615 K=1,NPF
TX1(K)=TMDI(K)
TX2(K)=TX1(K)
TUL(K)=TX1(K)
TUL2(K)=TX1(K)
615 CONTINUE
1=NP+1
I=NPM

\( lT(l+1) = \text{TMDI}(l) \quad \text{for} \quad I = 1, L \)

\( lY2T(l,I) = \text{TMTFL}(l) \quad \text{for} \quad I = 1, L \)

\( \text{GO TO 625} \)

\( \text{CONTINUE} \)

\( \text{GO TO 625} \)

\( \text{CALL TEMPI} \)

\( \text{WRITE}(6,3000) \) (\text{HEDING}(L), \text{I}=1,12)

\( \text{IF} \left( \text{TEST2} \right) \text{GO TO 630,635,640} \)

\( \text{WRITE}(6,632) \)

\( \text{FORMAT}(4X,52H\text{TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBITRARY/}) \)

\( \text{WRITE}(6,633) \) (\text{TMDI}(K), \text{K}=1,NPF)

\( \text{FORMAT}(1X,1PE12.5) \)

\( \text{GO TO 645} \)

\( \text{WRITE}(6,637) \)

\( \text{TEMTFL} \)

\( \text{IF(TEMP2) 633,635,640} \)

\( \text{WRITE}(6,648) \) (\text{TMDI}(L), \text{I}=1,NPF)

\( \text{FORMAT}(2X,1PF12.5,4X,1PF12.5) \)

\( \text{WRITE}(6,650) \)

\( \text{FORMAT}//) \)

\( \text{FORMAT}(/4X,52H\text{TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIELD}) \)

\( \text{WRITE}(6,641) \)

\( \text{FORMAT}(4X,54H\text{LINEAR TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIELD}) \)

\( \text{WRITE}(6,639) \) (\text{TMDI}(L), \text{L}=1,NPF)

\( \text{WRITE}(6,649) \)

\( \text{FORMAT}(4,6,647) \)

\( \text{GO TO 645} \)

\( \text{WRITE}(6,646) \)

\( \text{FORMAT}//) \)

\( \text{WRITE}(6,640) \)

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C COMPUTE HFAT PLECTION AT FRONT SURFACE

765 IF(NK-2) 762,766,766
766 GCONX=GCON(NK-1)+((GCON(NK)-GCON(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(T-TMF(NK-1))
GCONX=GCONV*GCONX
GRADX=GRAD(NK-1)+((GRAD(NK)-GRAD(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(T-TMF(NK-1))
GRADX=FRAD*GRADX
VFLX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIMF(NK-1)))
1*(T-TMF(NK-1))
GO TO 775
770 GCONX=GCONV*GCON(NK)
GRADX=FRAD*GRAD(NK)
VFLX=VEL(NK)

C COMPUTE HFAT IN DUE TO SURFACE COMBUSTION

775 IF(I17=1) 777,778,779
776 IF(I17=HWP) 777,777,778
777 IF(TX>(INT)-TW(I17)) 782,788,789
778 WRITE(6,779) TX2(1:INT)
779 FORMAT(I10)
IF THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS
EXCEEDED AT A TEMPERATURE OF 1E10.4
GO TO 905
780 I17=I17+1
GO TO 776
782 IF(TX>(INT)-TW(I17-1)) 784,788,789
784 I17=I17-1
GO TO 775
786 HH=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))
1*(TX2(1:INT)-TW(I17-1))
GO TO 789
788 HH=HX(I17)
789 HTX=HTX+4+(VFLX**2)/40065.5
OPLCK=FRLOW*XMDG(1:INT)*(HTX-HW)/3600
C COMPUTE Q=HOT WALL

4001 IF(DMP=0.1) 4001
401 TF(TMP,E0,0) IF(T.BT,TMP) DMP=1.1
402 IF(HW=800) 794,795,796
790 IF(Z) 791,791,793
791 OHW=0.0
GO TO 1790
792 OHW=OHFW
GO TO 1794
793 OHW=OHFW
GO TO 1798
1790 IF(ZZ=OHW+OBLOCK)/OHW
1791 IF(ZZ=OHW) 1794,1794,1794
1798 OPLCK=OHW
GO TO 1798
C COMPUTE HFAT INTO FRONT SURFACE

1794 IF(I17(1:INT)) 795,795,797
795 IF(TX>(INT)-TCHAR) 796,796,796
796 FMX=EMV

C COMPUTE HFAT DUE TO SURFACE COMBUSTION

C COMPUTE Q=HOT WALL

C COMPUTE HFAT INTO FRONT SURFACE

C COMPUTE Q=HOT WALL

C COMPUTE HFAT INTO FRONT SURFACE
GO TO 798
797 IFM(INT)=1
FMX=EMC
798 QNGQRADX+QH+QOXID-QRLLOCK=(4,8333E-13)*FMX*FV*((TX2(INT)**4)-
1*(TV**4))
IF(DMP) A04,B04+800
800 XRITE(6,B01)
801 FORMAT(///)
WRITE(6,B02) QCONX,QRADX,VELX,HTX,HW,7,QRLLOCK,QH,QOXID,QIN
802 FORMAT(1X,6HACONX=,1PF12,5,2X,6HQRADX=,1PF12,5,2X,5HVFLEX=,1PF12,5,2X,
1X,4HHTX=,1PE12,5,2X,3HHW=,1PF12,5/1X,2H7=,1PF12,5,2X,7HQRLOCK=,1P
2F12,5,2X,4H0HW=,1PE12,5,2X,6H0XID=,1PE12,5,2X,4H0INZ=,1PF12,5/7)
804 QINGQIN=3600.0
A1410
C
C CHECK FOR FRONT SURFACE REFLECTION (CHAR LAYER REMOVAL)
CALL RECLS(XMD,XLOST,TRFC,DT,PHOC,T5,SR,TX2(1),NREC,NRS,ERRS,SV0
1,SDDT,DMP)
IF(ERR5) A050,B050,905
170 CONTINUE
C
XV=XDV
1F(ERR4) A06,B06,A05
805 GO TO 905
806 CALL COFF(NPFT,SNDT)
IF(DMP) A069,A069,A061
8061 XRITE(6,A062)
8062 FORMAT(1X,2H COEFFICIENTS FOR SWUTF/)
NO AN6 1=NPFT
WRITE(6,A064) A(I),A(I),C(I),D(I),X
8064 FORMAT(1H0,5HA(I)=,1PF12,5,2X,5HR(I)=,1PF12,5,2X,5HC(I)=,1PE12,5,2X,
1X,5HD(I)=,1PE12,5,2X,2HI=,13)
8066 CONTINUE
8069 IF(ERR2) A07,A07,A05
87 IF(ERR3) A10,A10,A09
808 WRITE(6,AN9) TKK
809 FORMAT(1H0,1RH THF VALUE OF IKK=,14)
GO TO 905
810 CALL SWUTF(A,R,C,D,TY,NPFT,DMP)
827 NO A28 I=1,NP
TX1(I)=TX2(I)
TX2(I)=TY(I)
828 CONTINUE
CALL NON2(XLOST,TV,TX2,NP,XC,TX2C,XDV,XXV,XLSTV,XX)
830 CALL ABLATE
XMDT=YMDG(INT)+XMDC
LTNP+1
NO 1815 I=1,NUM
LTT=NPM(1)
IF(I,FQ,1) GO TO 1812
IF(SAPXI(I-1),FQ,0) GO TO 1812
KKT=1
A3200
A4100
A4010
A4020
A4030
A4040
A4050
A4060
A4070
A4080
A4090
A4100
A4110
A4120
A4130
A4140
A4150
A4160
A4170
A4180
A4190
A4200
A4210
A4220
A4230
A4240
A4250
A4260
A4270
A4280
A4290
A4300
A4310
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A4530
A4540
A4550
2.5, 19 CHAR ABLATION RATE = 1PF12.5, 5X, 10 HTOTAL ABLATION RATE = 1P  
3PF12.5/1X, 16 HRCHERSION DFPTH = 1PF12.5, 5X, 10 HTOTAL WALL = 1PF12.5

860 T = T + DTS

841 IF (NPLOT .NE. 1) GO TO 942
CALL SAVE (ASAVE1, ASAVE2, ASAVE3, USFAN, NXA, XLSTI, DTS, TLIM, T, VALUF)
CALL 150THM (XV, TX2, 1060, NP, Y3)
CALL SAVE (CSAVE1, CSAVF2, CSAVF3, USFC, NXC, Y3, DTS, TLIM, T, VALUC)
CALL 150THM (XV, TX2, 1460, NP, Y4)
CALL SAVE (DSAVE1, DSAVF2, DSAVF3, USFD, NXD, Y4, DTS, TLIM, T, VALUF)
IF (USFA, NF, 0, 0) GO TO 9842
IF (USFB, NF, 0, 0) GO TO 9842
IF (USFC, NF, 0, 0) GO TO 9842
IF (USFD, NF, 0, 0) GO TO 9842
GO TO 9843

9842 XPLOT = T - DTS
YPLOT1 = VALUEA
IF (USFA, NF, 0, 0) YPLOT1 = USFA
YPLOT2 = VALUEB
IF (USFB, NF, 0, 0) YPLOT2 = USFB
YPLOT3 = VALUEC
IF (USFC, NF, 0, 0) YPLOT3 = USFC
YPLOT4 = VALUED
IF (USFD, NF, 0, 0) YPLOT4 = USFD
WRITE (11) XPLOT, YPLOT1, YPLOT2, YPLOT3, YPLOT4

9843 IF (ICTP, NF, 0) GO TO 942
ICTP = 1
XPLOT = T
YPLOT1 = XLSTI
YPLOT2 = TX2 (NP)
CALL 150THM (XV, TX2, 1060, NP, YPLOT3)
CALL 150THM (XV, TX2, 1460, NP, YPLOT4)
WRITE (11) XPLOT, YPLOT1, YPLOT2, YPLOT3, YPLOT4

862 IF (IPCT = ICTP) 845, 845, 900
845 WRITE (6, 850) T
ICTP = ICTP + 1
IF (ICTP .EQ. 2) ICTP = 0
IF (ICTP .EQ. 0) ICTP = 0
850 FORMAT (1HIW79 HTEmPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END)
IF THE TIME STFP, T = .1PF12.5, 1X, 10HTOCNDS//)
852 WRITE (6, 860)
860 FORMAT (4X, 49 TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL//)
KKV = KKV + 1
WRITE (6, 862) (TX2 (I), I = 1, KKV)
862 FORMAT (4X, 1PF12.5, 1PF16.5)
I = I + 1
WRITE (6, 864)
844 FORMAT (4X, 49 TEMPERATURE DISTRIBUTION IN THE PACK-UP STRUCTURE//)
1
WRITE (6, 862) (TX2 (I), I = 1, NPF)
WRITE (6, 865)
865 FORMAT (/)
ICTP = 0
CONTINUE
IF (T = TLIM) 75N, 750, 905
905 IF (NPLOT .NE. 1) GO TO 909
XVY3 = SAVY3 = SAVY1/12.
XAVY4X = SAVY4X - SAVY1X / 12.

TF(SAVX.EQ.XPLOT) GO TO 9005
WRITE(11) SAVX, SAVY1, SAVY2, SAVY3, SAVY4

9005 TF(SAVEXX.EQ.XPLOT) GO TO 9006
SAVY1 = SAVY4X * 12.

9006 SAVY3 = SAVY3 * 12.
WRITE(11) SAVY1, SAVY2, SAVY3, SAVY4
WRITE(6, 929) SAVY3, SAVY4

929 FORMAT(1H40, 23HMAYMUM 1060 ISOTHFRM = E16.8, 2X23HMAYMUM 1460 ISOTH FRM = E16.8)
WRITE(11) STOP, STOP, STOP, STOP

909 TF(LPLOT.NE.NCASE) GO TO 911
WRITE(11) FND, FND, FND, FND, FND, FND, FND, FND, FND
QUIT
WRITE(11) QUIT, QUIT, QUIT, QUIT, QUIT
FND FILE 11
RFWIN 11

911 TF(TEST2) 910, 930, 93n
910 NN 920 JJK = 1, NPF
TX1(JJK) = TEMD(JJK)
TX2(JJK) = TX1(JJK)
T(1)(K) = TX1(K)
T(2)(K) = TX1(K)
920 CONTINUE
I = NP + 1
NN 926 I = 1, NMR
I = NNM(1)
NN 924 J = 1, ILN
TX2T(J, I) = TEM(J, I)
T(I) = I + 1
924 CONTINUE
926 CONTINUE
GO TO 940
930 CALL TEMPD
940 T = TINT
NX = DX
NTS = DFLTT(1)
NT = DELTT(1) * 3600.0
VL = VVL
GO TO 50
END
SUBRoutines COEFF

THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX

DIMENSION TITLE(12), HEADNG(12), XIDNT(12), TKC(20), XKC(20),
1PC(20), TKV(20), KXV(20), TCP(20), CPV(20), TIME(300), GCON(300),
2GRAD(300), VEL(300), XNPM(12), NKPBL(12), NCPB(12), TK(20), XK(20),
3TCP(20, 12), CPX(20, 12), RHOBX(12), XBM(12), EMFB(12), EMGB(12), HXX(12),
4GAPX(12), FTEST(12), BTEST(12), TEMDI(200), TX(1200), TX2(200),
5TXT(10, 12), TUL(50), TUL(50), IEM(50), TY(200), A(200), B(200), C(200), D(200),
6R(50), RHO(50), CP(50), DBX(12), XKB(10, 12), CPB(10, 12), XDMD(50),
7TK(50), AB(10, 12), BB(10, 12), CB(10, 12), DB(10, 12), SB(10, 12),
8YK(50), 9RBI(10, 12), RBE(10, 12), H(12), S(50), NPM(12),
9DIMENSION TTUL(50), RHOPY1(50), RHOPY2(50), ORHO(50), TCPC(50),
10COMMON TkC, XKC, TCPC, CPC, TKV, XKV, TCPV, CPV, XNPM, RHOBX, XBM, EMBB,
11EMFB, NKPBL, NCPB, TKX, CPX, CPX, NPM, GAPX, FTEST, BTEST, TEMDI, TX1,
12TX2, TX2T, TUL, TUL1, TUL2, IR, IR1, IR2, A, B, C, D, S, R, AB, BB, CB, DB, SB,
13RBI, RB2, TY, RHOY1, RHOY2, XDMD, RHO, CP, YK, XKB, CPB, DBX, DT, XLOST,
14TAB, TCH, TREC, RHOV, RHOC, FBL, EMW, EMC, H, 300, NKC, NCPRC, NKC, NCPY, CPV,
15SNP, NMB, NPS, NPF, TEST2, TEMPI, TX0, TENV, HENV, FENV, FENV, GLOSS, TLM, INT,
16COMMON X1, 12, 13, 14, 15, 16, GIN, INT, DX, XMT, TL, VL, BL, DMP, ERR1, ERR2,
17ERR3, ERR4, HV, VPT, CH, CHAR, ABLK, ABL, XMDH, XMDG, XMDH

CALL PROP

YNP=NP
S(INT)= (RHO*INT*DX*CP/INT))/ (2.0*DT)
R(INT)= (1.0)/ ((DX*2.0*INT)*(1.0/YK*INT))+(1.0/YK*INT+1))
A(INT)=0.0
B(INT)= (XMDG*INT*INT*XMDG*CP*INT+INT)+R(INT)-RHO*INT*CP*INT
1/(SDOT(2.0*INT+1, 0)))
C(INT)=XMDG*INT+1)*CP*INT+1)+R.INT+RHO*INT+1)*CP*INT+1)*SDOT
1/(YNP+1.5)/ (YNP+1.0)
D(INT)= (GIN+S(INT)*TX2(INT))+(XMDG*INT-XMDG*INT+1)*HV
NPP=NP
JNT=INT+1
10 DO 10 I=JNT, NPP
XI=I
S(I)=RHO*I*DX*CP(I)/DT
R(I)= (1.0)/( (DX*2.0*YK(I))+(OX*(2.0*YK(I+1)))
A(I)=R(I-1)
B(I)= (XMDG*INT*CP(I)+R(I-1)+R(I)+S(I)+RHO*INT*CP(I)*SDOT*(YNP-XI)
1/(YNP-I, 0))
C(I)=XMDG*INT+1)*CP(I+1)+R(I)+RHO*INT+1)*CP(I+1)*SDOT*(YNP-XI-0.5)
1/(YNP-I, 0))
I=(S(I+1)+TX2(I))+(XMDG(I)-XMDG(I+1)*HV
10 CONTINUE
R(NP)= (1.0)/( (DX*1, 0)+(2.0*KBX*1.1)+(DXB*2.0*KBX*2.1))
S(NP)= R(NP)*DX*CP+NP*RHOB*INT*CPB*1,1)*DXB*2.0*DT
A(NP)=R(NP)
B(NP)= (XMDG*NP*CP*NP)+R(NP-1)+R(NP)+S(NP)
C(NP)=R(NP)
D(NP)= (S(NP)*TX2(NP)+XMDG*HV
DO 20 1=1,NMB
IF(I=1) 20, 20, 30
20 AB(I, 1)=A(NP)
BB(I, 1)=B(NP)
CB(I, 1)=C(NP)
DB(I, 1)=D(NP)
GO TO 65
30 L=NPM(I-1)
IF( TETH(I)) 45.40.45
40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/
(1.0+DT)
RBI(1,I)=(1.0/((DXB(I-1)/(2.0*XB(L,I-1)))+(DXB(I-1)/(2.0*XK(L-1,
I-1))))
RBI(1,I)=RBI(1,I)
BB(1,I)=(-RBL(1,I)+RBE(1,I)+SB(1,I))
CB(1,I)=RBE(1,I)
DB(1,I)=(-SB(1,I)*TX2T(1,I))
GO TO 65
45 IF(TETH(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)*DXB(I))/(2.0+DT)
RBE(1,I)=(1.0/((DXB(I)/(2.0*XK(J-1,I)))+(DXB(I)/(2.0*XK(J,I))))
AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1))**3
BB(1,I)=(-H(I-1)+4.0*G*(TX2T(L,I-1))**3+RBE(I)+SB(1,I))
CB(1,I)=RBE(1,I)
DB(1,I)=3.0*G*(TX2T(L,I-1)**4)-TX2T(L,I-1)**4)*SB(1,I)*TX2T(I-I)
65 LF=NPM(I-1)
DO 100 J=2,LF
SB(1,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT
RBE(1,J)=(1.0/((DXB(I)/(2.0*XK(B-1,J)))+(DXB(I)/(2.0*XK(B,J)))))
AB(1,J)=RBI(J)
BB(1,J)=(-RBI(J)+RBE(J)+SB(J))
CB(1,J)=RBE(J)
DB(1,J)=(-SB(J)*TX2T(J,I))
100 CONTINUE
90 IF(I-NMB) 110,250,250
110 LNF=NPM(I)
IF(TETH(I)) 120.115,120
115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(I+1,I)*DXB(I+
1,1))/2.0+DT
RBE(LNF,I)=(1.0/((DXB(I)/(2.0*XK(LNF,1,I)))+(DXB(I)/(2.0*XK(LNF,
1,1)))))
RBE(LNF,I)=(1.0/((DXB(I)/(2.0*XK(LNF,1,I)))+(DXB(I)/(2.0*XK(LNF,
1,1)))))
AB(LNF,I)=RBI(LNF,I)
BB(LNF,I)=(-RBI(LNF,I)+RBE(LNF,I)+SB(LNF,I))
CB(LNF,I)=RBE(LNF,I)
DB(LNF,I)=(-SB(LNF,I)*TX2T(LNF,I))
GO TO 200
120 IF(TETH(I)) 125,115,127
125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1.0)
GO TO 130
127 G=0.0
130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0+DT)
RBE(LNF,I)=(1.0/((DXB(I)/(2.0*XK(LNF-1,I)))+(DXB(I)/(2.0*XK(LNF,
1,1))))
AB(LNF,I)=RBI(LNF,I)
BB(LNF,I)=(-RBI(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3))
CB(LNF,I)=H(I)+4.0*G*(TX2T(I+1,I)**3)
DB(LNF,I)=3.0*G*(TX2T(I,1)**4)-(TX2T(LNF,I)**4)*SB(LNF,I)*TX2T
1(LNF,I)
200 CONTINUE
250 MN=NPM(NMB)
260 IF(QLOSS) 270,260,270
   RB1(MN,NMB)=(1.0)/(DXB(NMB)/(2.0*XK*(MN-1,NMB)))+DXB(NMB)/(2.0*XK
   1B(MN,NMB)))
   A8(MN,NMB)=RB1(MN,NMB)
   B8(MN,NMB)=(-((RB1(MN,NMB)+SB(MN,NMB)))
   CB(MN,NMB)=0.0
   DB(MN,NMB)=(-SB(MN,NMB)*TX2T(MN,NMB)))
280 L=NPI+1
290 DO 300 I=1,NMB
300 K=NPM(I)
   IF(I*EQ.1) GO TO 282
   IF(GAPX(I-1),EQ.0.) GO TO 282
   KT=1
   GO TO 285
285 KT=2
290 DO 300 J=KT,K
   A(L)=AB(J,I)
   B(L)=BB(J,I)
   C(L)=CB(J,I)
   D(L)=DB(J,I)
   IF(LMP) 289,289,286
300 WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(L)
297 FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,
   1PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,8HDL(J,L)=,1PE12.5,2X,5HCL(L)=,1PE12.5,2X,
   JH(L)=,13)
299 L=L+1
300 CONTINUE
300 CONTINUE
300 NPFT=L-1
300 RETURN
300 END
$\text{SUBROUTINE PRP}$

$\text{C THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE}$

$\text{HEAT SHIELD STRUCTURE}$

$\text{SUBROUTINE PRP}$

$\text{DIMENSION}$ $\text{TII(12), HFAANG(12), TXDNT(12,12), TKC(20), XKC(20)},$
$\text{1PC(20), TKV(20), XKV(20), TFPV(20), CPV(20), TIME(30), QCON(300),}$
$\text{20RAD(300), VEL(300), XNM(12), NKPR(12), NCPR(12), TKX(20,12), XK(20,12),}$
$\text{3, TCP(20,12), CPX(20,12), RHNX(12), XBM(12), FMFR(12), EMAR(12), HXX(12),}$
$\text{4, GAX(12), FTFT(12), HTST(12), TCMD(200), TX1(200), TX2(200),}$
$\text{5TP2(10,12), TUL1(200), TUL2(200), HX(50), TX(50), IR(50), IR1(50),}$
$\text{6TP2(50), TUL5(50), IEM(40), TY(200), A(200), R(200), C(200), R(200),}$
$\text{7TP(50), RHO(50), CP(50), XP(12), XKP(10,12), CPB(10,12), XMDN(50),}$
$\text{RYK(50), AH(10,12), RB(10,12), CR(10,12), DB(10,12), SR(10,12),}$
$\text{9W(10,12), RA(10,12), H(12), S(50), NPM(12),}$
$\text{DIMENSION}$ $\text{TII(50), RHOYI(50), RHOY2(50), DRHO(50), TCMD(20)}$

$\text{COMMON}$ $\text{TKC,XKC,TCPC,CPX,TKV,XKV,CPV,CPX,NPM,RH0X,RH0Y,RH0Z,}$
$\text{1FMPR,NKPR,NCPR,TKX,XK,CPX,NPM,GAPX,FTFT,ATST,TST,TCMD,TX1,}$
$\text{2TYP,X2T,TUL,TUL1,TUL2,IR,IR1,IR2,Ax,Bx,Cx,Dx,SX,}$
$\text{3UKI,RR2,RYH,RYH1,RYH2,YMXM,RH0,CX,CPO,DXR,DT,YLST,}$
$\text{4ATBL,TCHAR,TRFC,RH0V,RH1V,ERFW,FMU,FMV,C100,NKC,NCP,}$
$\text{5NKP,NKPR,NF,P,TFST,TFP2,TFM2,TP2,TEPS,HEV,HEV1,OLSS,TLIM,}$
$\text{COMMON}$ $\text{II,12,13,14,15,16,17,18,19,20,21,22,23,}$
$\text{KINT=INT}$

$\text{DO 170 I=KINT,NP}$

$\text{10 IF(I(I))=1,12,12,100}$

$\text{12 TUL(I)=MAX1(TX1(I),TX2(I))}$

$\text{11 IF(TUL(I),LE,TABL) GO TO 20}$

$\text{10 I=1}$

$\text{GO TO 100}$

$\text{20 IF(I2-I)=25,21,21}$

$\text{21 IF(I2-NKV)=23,23,25}$

$\text{22 IF(TK(I)-TKV(I))>35,55,30}$

$\text{25 WRITE(6,626) TX2(I)}$

$\text{26 FORMAT(H10,2E7)}$

$\text{THE RANGE OF ONE OF THE AERATION PROPERTY CURVE FIT}$

$\text{IC WAS EXCEEDED AT A TEMPERATURE OF 1PE12,5)$}

$\text{ERR2=1,0}$

$\text{GO TO 356}$

$\text{30 I=I+1}$

$\text{GO TO 21}$

$\text{35 IF(TK(I)-TKV(I))<40,55,50}$

$\text{40 I=I-1}$

$\text{GO TO 20}$

$\text{50 YK(I)=XKV(I)+((XKV(I)-XKV(I-1)))/(TKV(I)-TKV(I-1)))}$

$\text{1*=(X2(I)-TKV(I-1))}$

$\text{GO TO 60}$

$\text{60 YK(I)=XKV(I)}$

$\text{61 IF(T2-I)=25,56,61}$

$\text{62 IF(T2=NCPV)=62,62,25}$

$\text{63 IF(T2(TK-I)-TCPV(I2))>=0,65,65}$

$\text{65 T2=T2+1}$

$\text{GO TO 61}$

$\text{70 IF(T2(I)-TCPV(I2))<75,55,80}$

$\text{75 T2=T2-1}
GO TO 60
80 CP(I)=CPV(I2-1)+((CPV(I2)-CPV(I2-1))/(TCPV(I2)-TCPV(I2-1)))
   1*(TX2(I)=TCPV(I2-1))
   GO TO 90
85 CP(I)=CPV(I2)
90 RHO(I)=RHOV
   GO TO 170
100 TUL(I)=AMAX1(TUL(I),TX2(I))
   IF(TUL(I)=TCHAR) 110,110,115
   IF(RHO(I)=RHOV+(RHOV-RHOC)*((TUL(I)=TBL)/(TBL-TCHAR))
   YK(I)=CHARK+(ABLK-CHARK)*((RHO(I)=RHOC)/(RHOV-RHOC))
   CP(I)=CHARC+(ABLC-CHARC)*((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)=TX2(I)
120 IF(I3=1) 25,25,121
121 IF(I3=122,122,25
122 IF(TTUL(I)=TKC(I3)) 124,125,123
123 I3=I3+1
   GO TO 121
124 IF(TTUL(I)=TKC(I3-1)) 125,125,13
125 I3=I3-1
   GO TO 120
130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))
   GO TO 130
135 YK(I)=XKC(I3)
140 IF(I4=1) 25,25,141
141 IF(I4-NCPC) 142,142,25
142 IF(TTUL(I)=TCPC(I4)) 150,165,145
145 I4=I4+1
   GO TO 140
150 IF(TTUL(I)=TCPC(I4-1)) 155,165,140
155 I4=I4-1
   GO TO 140
160 CP(I)=CPV(I4-1)+((CPV(I4)-CPV(I4-1))/(TCPV(I4)-TCPV(I4-1)))
   GO TO 160
165 CP(I)=CPV(I4)
166 RHO(I)=RHOC
170 CONTINUE

C
C DETERMINATION OF PROPFR RACK-UP SHIELD MATERIAL PROPERTY
C
DO 300 I=1,NMR
   NXR(I)=XBM(I)/((XNPM(I)-1.0)*12.0)
   LKP=NKPB(I)
   LCP=NCBP(I)
   NN=NPM(I)
   NO 260 J=1,NN
200 IF(I5=1) 203,203,201
201 IF(I5-LKP) 202,202,203
202 IF(TX2T(J,I)=TKX(IS,J)) 206,220,205
203 WRITE(6,204) J,TX2T(J,I)
204 FORMAT(1HO,3PH THE RANGE OF ONE OF THE NUMBER 1P,71H BACKUP STRUC
C
C
1TURF PROPERTIES CURVE FITS WAS EXECUTED AT A TEMPERATURE OF 1PF12.5

FRR2=1.0
GO TO 355
205 I5=I5+1
GO TO 201
206 1F(TX2T(J,I)-TXK(T5-1,I)) 210,220,215
210 I5=I5-1
GO TO 200
215 XKB(J,I)=YK(I5-1,I)+(XK(I5,I)-YK(I5-1,I))/(TXK(I5,I)-TXK(I5-1,I))
1+(XK(T5,I)-TXK(I5-1,I))
GO TO 230
220 XKB(J,I)=YK(I5,I)
230 1F(I6-1)=P03,P03,231
231 1F(I6-LCP) 232,323,233
232 1F(TX2T(J,I)-TCP(T6,1)) 234,245,233
233 I6=I6-1
GO TO 230
234 1F(TX2T(J,I)-TCP(I6-1,I)) 235,245,240
235 I6=I6-1
GO TO 230
240 CPB(J,I)=CPX(T6-1,I)+((CPX(I6,I)-CPX(T6-1,I))/(TCP(I6,I)-TCP(T6-1,
1)))*TX2T(J,I)-TCP(T6-1,I))
GO TO 280
245 CPB(J,I)=CPX(T6,1)
280 CONTINUE
I5=2
IF=2
300 CONTINUE
310 1F(DMP) 355,355,390
320 WRITE(6,330)
330 FORMAT('I*X32H PROPERTIES OF ABLATION MATERIAL/)
340 WRITE(6,335)
350 FORMAT('I*X5,H5YK(I),9X,5HCP(I),9X,6HRH0(I)/)
360 WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,360)
370 FORMAT('I*X5,1PF12,5,2X,1PF12,5,2X,1PE12,5)
380 WRITE(6,345)
395 FORMAT('I*X35H PROPERTIES OF BACK-UP STRUCTURE/)
400 WRITE(6,346)
410 FORMAT('I*X5,RHVRK(J,I),7X,1AHCPR(J,I),7X,1AWROBH(I),7X,7HFPEB(I),7X,7)
17HEMRB(I),9X,9AHDRX(I)/)
420 DO 350 J=1,399
430 WRITE(6,349) J=1,399
440 WRITE(6,348) YK(J,I),CP(RJ,I),RHOBH(I),E(RJ,I),FMR(J,I),FMR(I),D(I)
450 CONTINUE
350 CONTINUE
360 CONTINUE
370 CONTINUE
380 CONTINUE
390 CONTINUE
FND
95 NRHO(KI) = ((RHOY1(KI) - RHOY2(KI)) / NT) * DX
96 IF(KI = NP) GO TO 97
97 NRHO(KI) = NRHO(KI) / 2.0
GO TO 98
98 IF(KI = INT) GO TO 96, 96, 98
110 NRHO(KI) = 0.0
120 XMT = XMT + DRHO(KI)
XMDG(KI) = XMT
150 WRITE(6, 160) XMDG(KI), DRHO(KI), RHOY2(KI), RHOY1(KI)
160 FORMAT(1X, SHXMDG=, 1PE12.5, 2X, 5HDRHO=, 1PF12.5, 2X, 6HRHOY2=, 1PE12.5, 2X, 6HRHOY1=, 1PF12.5)
190 KI = KI + 1
200 CONTINUE
RETURN
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, OXID)

OXID = XMDO + 4000.0 / 3600.0
OXID = 0.0
RETURN
FND
SUBROUTINE SWUFT
C
C THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES
C
C BY SOLVING THE TRI-DIAGONAL MATRIX
C
DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),DP(200)
CP(1)=C(1)/B(1)
DP(1)=D(1)/B(1)
DO 100 I=2,N
CP(I)=C(I)/(B(I)-A(I)*CP(I-1))
DP(I)=D(I)/(B(I)-A(I)*DP(I-1))
100 CONTINUE
T(N)=DP(N)
NM1=N-1
DO 200 J=1,NM1
I=N-J
T(I)=CP(I)-CP(I)*T(I+1)
200 CONTINUE
IF(DMP) 300,330,250
250 WRITE(6,260)
260 FORMAT(/1X,4X,HCOEFFICIENTS CALCULATED BY SUBROUTINE SWUFT//)
WRITE(6,270)
270 FORMAT(6X,SHCP(I),10X,SHDP(I),10X,4HT(I)//)
WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)
275 FORMAT(2X,1PE12.5,2X,1PF12.5)
300 RETURN
END
THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS REMOVAL RATE

SUBROUTINE REC(SMDC, XLOST, TRFC, DT, RHOC, TS, SR, TX2, NREC, NRS, FRP5, DMP)

DIMENSION TS(50), SR(50)

IF(TX2>TRFC) 10,20,20

10 XMDC=0.0

XLOST=0.0

<DOT>0.0

GO TO 60

20 IF(NRS=1) 25,25,21

21 IF(NRS=NHC) 22,22,25

22 IF(TX2=TS(NRS)) 32,40,30

25 WRITE(6,26) TX2

26 FORMAT(1HO,7RH THE RANGE OF THE SURFACE RECESSIO TABLE WAS EXCEEDED)

1FD AT A TEMPERATURE OF ,1PE12.5)

FRP5=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

<DOT=5X*300.0

IF(DMP) 60,60,52

52 WRITE(6,54) SX,XLOST,XMDC

54 FORMAT(1HO,3HSX=,1PE12.5,SX,X6H<LOST=,1PE12.5,SX,X5HXMDC=,1PE12.5)

60 RETURN

END
**SIBFTC TEMP**  
**C** THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION  
**C** IN THE HEAT SHIELD STRUCTURE  
**SUBROUTINE TEMP0**  
**C**

**DIMENSION TIL(12), HEADNG(12), XIDNT(12,12), TKC(20), XKC(20),**  
1PC(120), TKV(20), XKV(20), TCPV(20), CPV(20), TIME(300), QCDC(300),**  
20RAD(300), VEL(300), XNPM(12), NPKP(12), NCPK(12), TXK(20,12), XK(20,12),**  
3,TCP(20,12), CPX(20,12), RHOBX(12), XMB(12), EMFB(12), EMBR(12), HXX(19),**  
4, GAPX(12), FTEST(12), RTEST(12), TMFDI(2001), TIL(1200), TX(2000),**  
5,TXK(100,12), TICL(200), TUL2(200), XH(50), IR(50), I1(50),**  
6,IR2(50), TIL(50), IEM(50), TY(200), A(200), R(200), C(200), PI(200),**  
7,R(50), RHO(50), CP(50), DXR(12), XK(10,12), CB(10,12), XMDG(50),**  
8, YK(50), AB(10,12), RAB(10,12), CB(10,12), DB(10,12), SR(10,12),**  
9, RR1(10,12), RR2(10,12), H(12), S(50), NPM(12),**  
**DIMENSION TTUL(50), RHOY1(50), RHOY2(50), DRHO(50), TCP(20)  
**C**

**COMMON** TKC, XKC, TCP, CPCM, TKV, XKV, TCPV, CPV, XNPM, RHO, RX, XAM, EMBR,**  
1FMB, NPKP, NCPK, TXK, X, TCP, CPX, GAPX, FTEST, RTEST, TEMDI, TX1,**  
2TX2, TX2T, TUL, TUL1, TUL2, IR, ISA, IR2, A, B, C, 0, S, R, AB, BB, CR, DB, SB,**  
3R1, R2, IR, RHY, RHOY2, RXD, RXD, RHO, CP, YK, XR, CP8, DXR, DT, VLOT,**  
4TAR, TCHARG, TRFC, RHO, RHO, FLOW, FMV, EMC, FX300, NKC, NCP, NRV, NCP,**  
5NPM, NPRS, NPF, FTEST, TEMDI, X0, TEN, TEN, FENV, FEV, DBLOSS, TLIM, TINT,**  
**COMMON** 11, 12, 13, 14, 15, 16, GIN, IN, DX, XMT, TL, VL, BL, NMP, FRP1, ERR,**  
1FR3, FR4, HV, VPT, CHARK, CHARC, ABLK, ABLG, XMDCH, H**

**C**

**x=0.0**  
**T(FTEST2) 30.1, 10.0, 20.0**

**100 NO 150 L=1,NPF**  
**TX1(L)=TEMPI**  
**TX2(L)=TEMPI**  
**TUL1(L)=TX1(L)**  
**TUL2(L)=TX2(L)**  
**TFMDI(L)=TEMPI**

**150 CONTINUE**  
**NO 160 I=1,NMR**  
**J=NPM(I)**  
**NO 155 M=1,JN**  
**TX2(M+1)=TEMPI**

**155 CONTINUE**  
**160 CONTINUE**  
**GO TO 320**

**200 NO 220 L=1,NP**  
**TFMDI(L)=TX0+((TENV-TX0)/TL)**X**  
**TX1(L)=TFMDI(L)**  
**TX2(L)=TX1(L)**  
**TUL1(L)=TX1(L)**  
**TUL2(L)=TX1(L)**  
**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)**X**  
**TX1(L)=TFMDI(L)**  
**TX2(L)=TFMDI(L)**
I

TX2I(J+I)=TEMNI(L)
x=X+DVB(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 TESTP IS A NEGATIVE NUMBER
300 WRITE(6,310)
310 FORMAT(1HO,72H THE VALUE OF TESTP WAS NEGATIVE, SUBROUTINE TEMPD SHOULDN'T HAVE BEEN CALLED.)
FRR1=1.0
320 RETURN
END
SUBRUTINE DON2
C THIS SUBRUTINE 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, INX)
C
DIMENSION XARRAY(50), TARRAY(50), XNODE(50), TEMP(50), XNODEV(50)
C
K=0
NXT=0.0
DO 100 I=1, NA
IF (XLSTV.LE. NXT) GO TO 150
K=K+1
100 NXT=DXT+UX

K=NA-K
XK=K
XNODEV(I)=XLSTV
TFMP(I)=TARRAY(I)
DO 200 I=1, KK
XNODE(I)=XK*DX-XLSTV
CALL DISCT3(XNODE(I), XARRAY, TARRAY, NA, TFMP(I+1))
XNODEV(I+1)=XK*DX

200 XK=XK+1.0
RFURM
FND

70
SUBFTC UINTP
SUBROUTINE UINTP(X,XTBL,Y,YTBL,N,J)
DIMENSION XTBL(50),YTBL(50)
I=J
IF(I.GT.N.OR.I.LT.2) I=2
10 IF(XTBL(I-1).LE.X.AND.X.LE.XTBL(I)) GO TO 40
   IF(X.GT.XTBL(I)) GO TO 30
20 I=I-1
   IF(I.GE.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-XTBL(I-1))/(XTBL(I)-XTBL(I-1))
   Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT
FTRKNN
FMD
$!IBIC 1507
SUBROUTINE ISOBHM(DEPTH,TFMP,ROND,N,ANS)
DIMENSION DEPTH(1),TFMP(1)
ANSZ=1,
K=1
DO 100 I=1,K
 IF(TEMP(I)-ROND)<1.3
 1 ANS=DFPHTH(I)
  GO TO 100
 IF(TEMP(I+1)-ROND)<100.100.4
 4 ANS=(DFPHTH(I+1)-ROND)*((DEPTH(I+1)-DEPTH(I))/TFMP(I+1)-TFMP(I))
  GO TO 100
 5 ANS=(TEMP(I)-ROND)*(DFPHTH(I+1)-DFPHTH(I))/(TFMP(I)-TEMP(I+1))+DEPTH(I)
100 CONTINUE
 IF(ROND.EQ.TFMP(N)) ANS=DFPHTH(N)
 RETURN
END
SIBFTC SAVE
SIVROHINTF SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,D,T,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((TIMK.LT.(D.+.DT)).OR.(TIME.GT.(TFINAL-.DT)))GO TO 4
GO TO (1,.+1),NX1
1 IF((ABS(SAVEF(1)-SAVEF(2))).L.E..001).OR.((ABS(SAVEF(2)-SAVEF(3))
1,L.E..001))GO TO 5
1 IF((SAVEF(1),LT,SAVEF(3)),AND.((SAVEF(2),GT,SAVEF(3))).OR.((SAVEF(2)
11),LT,SAVEF(2)),AND.((SAVEF(1),LT,SAVEF(3))).USE=SAVEF(2)
5 THING=SAVEF(2)
GO TO 4
2 IF((ABS(SAVEF(3)-SAVEF(2))).L.E..001).OR.((ABS(SAVEF(2)-SAVEF(3))
1,L.E..001))GO TO 6
1 IF((SAVEF(1),LT,SAVEF(3)),AND.((SAVEF(2),GT,SAVEF(3))).OR.((SAVEF(2)
11),GT,SAVEF(2)),AND.((SAVEF(1),LT,SAVEF(3))).USE=SAVEF(3)
6 THING=SAVEF(3)
GO TO 4
3 IF((ABS(SAVEF(1)-SAVEF(3))).L.E..001).OR.((ABS(SAVEF(2)-SAVEF(1))
1,L.E..001))GO TO 6
1 IF((SAVEF(1),LT,SAVEF(2)),AND.((SAVEF(1),GT,SAVEF(3))).OR.((SAVEF(1)
11),GT,SAVEF(1)),AND.((SAVEF(2),LT,SAVEF(1))).USE=SAVEF(1)
7 THING=SAVEF(1)
GO TO 4
4 NX1=NX1+1
IF(NX1,.EQ.4)NX1=1
RETURN
END
SHFTC DISCT3
SUBROUTINE DISCT3(XA, TABX, TARY, NY, ANS)
DIMENSION TABX(1), TARY(1)
CALL DISSFR(XA, TARY(1), NY, P, NNN)
NNN=3
CALL LAGAN(XA, TARY(NN), TABX(NN), NNN, ANS)
RETURN
END

SUBROUTINE DISSER (X, TAB, I, NX, ID, NPX)

C DIMENSION TAB(2000)

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)-X) 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)-X) 40,35,35

35 NPX=NDIS-ID
RETURN

40 NPX=NDIS+1
RETURN
END
SUBROUTINE LAGRAN (XA, X, Y, N, ANS)
DIMENSION X(200), Y(200)
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

RFWIND 1
READ (11) TITLE(I), I=1,12
READ (11) X(I), Y(I), Y3(I), Y4(I)
Y(I) = Y3(I)*12. + Y1(I)
Y4(I) = Y4(I)*12. + Y1(I)
I=2
READ (11) X(I), Y(I), Y3(I), Y4(I)
TF(X(I)-5001.,10,20,20)
10 Y3(I) = Y3(I)*12. + Y1(I)
Y4(I) = Y4(I)*12. + Y1(I)
I=1
GO TO 30
20 NPLOT=I+1
YM1=Y1(I)
YM2=Y2(I)
YM3=Y3(I)
YMU=Y4(I)
DO 40 K = 2, NNPLOT
TF (Y(K), GT, YM1) YM1 = Y1(K)
TF (Y2(K), GT, YM2) YM2 = Y2(K)
TF (Y3(K), GT, YM3) YM3 = Y3(K)
TF (Y4(K), GT, YMU) YMU = Y4(K)
40 CONTINUE
1000 FORMAT(1H1,12A6))
CALL ACCEND(X, Y1, Y2, Y3, Y4, NNPLOT)
XMAX=X(NNPLOT)
CALL APLLOT(X, Y1, XMAX, YM1, TITLE, NNPLOT)
CALL PPLLOT(X, Y2, XMAX, YM2, TITLE)
CALL MPLLOT(X, Y3, Y4, 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, NNPLOT)
1001 FORMAT(5E20.8)
WRITE(6,1002)XMAX, YM1, YM2, YM3, YMU, NNPLOT
1002 FORMAT(6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
YM4=F10.4,5H)
READ (11) TITLE(I), I=1,12
READ (11) X(I), Y(I), Y3(I), Y4(I)
I=2
TF(X(I)-5001.,30,50,50)
50 WRITE(6,1003)(TITLE(I), I=1,12)
1003 FORMAT(//12A6)
RRETURN
FND
SUBROUTINE ACCEND(X,Y,A,B,C,N)
DIMENSION X(1),Y(1),A(1),B(1),C(1)
K=1
101 SMALL=X(K)
   DO 100 I=K,N
   DUMMY=X(I)
   SMALL=AMIN1(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
$SIBFCT APLOT
SUBROUTINE APLOT (X,Y,XLIM,YLIM,TITLE,IPLOT)
DIMENSION X(300),Y(300),XTITLE(30),YTITLE(30)
DIMENSION TIME(7),ALONGX(7),NCOM,XYZMAX,IFIX
COMMON /APC/ ALLOW(7),ALONGX(7),NPL0T,ZERO,YMAX,IFIX
B7 (XTITLE(I),I=1,10)/3AH
B7 (YTITLE(I),I=1,10)/3AH
TIME (SEC.) / 0060
SURFACE REFGSSION (IN.) / 0070
ZERO=0.
ALLOW(1)=50.
ALLOW(2)=100.
ALLOW(3)=250.
ALLOW(4)=500.
ALLOW(5)=1000.
ALLOW(6)=2500.
ALLOW(7)=5000.
NPL0T=IPLOT
D0 10 I=1,7
11 I=I
IF (XLIM .GT. ALLOW(I)) Pll,20,10
10 CONTINUE
WRITE (6,1000) XLIM,YLIM
1000 FORMAT(//77H APL0T CANNOT BE DONE BECAUSE EITHER XLIM EXCEEDS 5N
1000 OR YLIM EXCEEDS 5N, /6H XLIM=1255,5X,6H YLIM=1255 // 19H WE
2NOW ON TO BL0T //////)
RETURN
20 YMAX=ALLOW(I)
IFIX=I
I0 40 I=1,4
11 I=I
IF (YLIM .GT. ALLOW(I)) 50,50,40
50 CONTINUE
GO TO 30
30 YMAX=ALLOW(I)/100.
CALL RETURN (1,23,1023,24,224,18,18,5,5)
CALL PLOT ((1,4,0,MAX,YMAX,ZERO,YMAX,X,Y,NPL0T,1,14))
ALONGX(I)=0.0
ALONGY(I)=0.0
I0 60 I=1,6
CALL LAPI (X (ALONGX(I),1))
CALL LAPI (Y (ALONGY(I),1))
ALONGX(I+1)=ALONGX(I)+.5*YMAX
ALONGY(I+1)=ALONGY(I)+.5*YMAX
CALL PRINT (200,1975,12,10,3A,XT1LE)
CALL PRINT (47,200,0,19,3A,YTITLE)
CALL PRINT (123,1000,12,0,72,TITLE)
CALL NMPLOT
RETURN
END
$IBFIT PC PLOT
SUBROUTINE PLOT (X,Y, XLIM, YLIM, TITLE)
DIMENSION X(300), Y(300), YTITLE(10), ALONGY(7), YTITLE(10)
DIMENSION TITLE(12)
COMMON /ARC/ ALLOW(7), ALONGX(7), N PLOT, ZP 0, XMAX, TFIX
DATA (XTITLE(I), I=1,10) / 3AH TIME (SEC) 
DATA (YTITLE(I), I=1,10) / 3AH PONDLINE TEMPERATURE (R) 
ALONGY(1)=0,0
DO 10 I=1,7
10 CONTINUE
WRITE (6,1000) YLIM
1000 FORMAT(///, 37H P PLOT WILL NOT BE DONE BECAUSE YLIM= F12.5 ,///)
RETURN
20 YMAX = AL LOW (IT)
 CALL RSTAR
 CALL CRUGN(123,1027,24,024,1A,1A,5,5 )
 CALL PLOT1 (1.1, ZER 0, XMAX, ZERO, YMAX, X, Y, N PLOT, 1, IH )
 DO 30 I=1,6
 CALL LARP1X (ALONGX(I),1)
 CALL LARP1Y (ALONGY(I),1)
30 ALONGY(I+1) = ALONGY(I) + .2* YMAX
 CALL PRINT(200, 975, 12, 0, 3A, XTITLE)
 CALL PRINT(47, 200, 12, 3A, YTITLE)
 CALL PRINT(123, 1000, 12, 0, 72, TITLE)
 CALL RMSPhif
 RETURN
END
$IBFTC CPlot
CHEMISTRY CPlot (X,Y1,Y2,XLIM,Y1,IM1,YLIMP,TITLE,Y)
DIMENSION X(300), Y1(300), Y2(300), YTITLE(10), YY(2000), XTITLE(10)
DIMENSION TITLE(2), Y(300), ALONG(7)
DIMENSION CURVE(1), VRUG(4), VRUG(7)
COMMON /ARC/ ALLOW(7), ALONG(7), NPL, ZPG, XM, YMAX, IFIX
DATA (VRUG(I), I=1,4) / 100.0,50.0,20.0,10.0 /
DATA (VRUG(I), I=1,7) / 1.0,2.0,3.0,4.0,5.0,6.0,7.0 /
DATA (XTITLE(I), I=1,10)/ 'TKE (SFC.)' /
DATA (YTITLE(I), I=1,10)/ 'DISTANCE (IN.)' /
DATA ONE/H/1000 / TW/4/8/1000 /
DATA WONE/1/1000 / T00/1/142 /
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(I)
CURVE(1) = ONE
HFACTR=HUG(1,IFIX)
SYMBOL=WON
YRUG=MAX1 (Y1,IM1,YLIMP)
NCRVE= 1
NO 1 = T1,NPL
1 YY(I) = Y1(I)
NO 7 = T1,4
I = I
IF YRUG*100. = ALLOW(I)6 ,K ,7
7 CONTINUE
WRITE (6,1000) Y1,IM1,YLIMP
1000 FORMAT (/// 4H CPlot will not be done because Y1,YLIMP=12.5,1NH OR
1Y1,YLIMP= F12.5 /// )
RETURN
6 YMAX = ALLOw (I1)/100.
VFACR=VRUG(1)
CALL RSTPM
CALL RITION (123,1024,24,024,18,1A,5,5)
J=1
70 DO 10 J=3,NPL
I= I
1 IF YY(I) = Y(I) )20,1N,10
10 CONTINUE
NO NPT=NPL+J+1
11 = J + NPT/
TVLOC=(YMAX-YY(LL)) * T1,A,UFACR .24, -4.
THLOC= X(LL)*18. /VFACR +123. , -48.
CALL PRINT(I,OC,TVLOC, A,0,4,CURVE)
CALL PLOT111,1,7,VO, YMAX, ZERO, YMAX, X(J), YY(J), NPT ,1,SYMBOL )
IF (NCRVE= 1 ) 90,85,90
95 DO 40 I=1,NPL
40 AS Y(J)=YY(I)
C RV(1)=TWO
SYMBOL=WON
NCRVE= 2
J=1
GO TO 70
20 NPT=I-J
11 = J + NPT/
TVLOC=(YMAX-YY(LL)) * 1 A,UFACR .24, -4.
THLOC= X(LL)*18. /VFACR +123. , -48.
CALL PRINT(I,OC,TVLOC, A,0,4,CURVE)
}
CALL PLO11(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,SYMOP)
00 50 IJ= JJ, NPLT
JJ= IJ
IF(YY(IJ)= Y(J)) 50,40,40
50 CONTINUE
IF(NCHREV=-1) 90,R5,90
40 JJ= J
GO TO 70
90 A= ONGY(I)=0.0
DO 100 T=1,6
CALL LARFI(X(AI ONGX(I), 1))
CALL LAREIL(Y(AI ONGY(I), 1))
100 A= ONGY(I+1)=AI ONGY(I) + .2*YMAX
CALL PRINT(200,975,12,0,3A+XTITLE)
CALL PRINT(47,200,0,12,3A+YTITLE)
CALL PRINT(127,1000,12,0,72,TITLE)
CALL OMPINFO
WFTLKN
FDO
## 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 TCHR</td>
</tr>
<tr>
<td>CHARK</td>
<td>Thermal conductivity of material at TCHR</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>
</tr>
<tr>
<td>ERR1, ERR2</td>
<td>Control numbers for printing error statements when an input or calculational mistake is made</td>
</tr>
<tr>
<td>ERR3, ERR4</td>
<td></td>
</tr>
<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>
</tr>
<tr>
<td>FRAD</td>
<td>factor to correct radiative heating rate for various body locations</td>
</tr>
<tr>
<td>PTEST</td>
<td>test to determine mode of heat transfer into front surface of backup materials</td>
</tr>
<tr>
<td>FORTRAN</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>FV</td>
<td>view factor for external environment</td>
</tr>
<tr>
<td>G</td>
<td>defined by FORTRAN statement</td>
</tr>
<tr>
<td>GAPX</td>
<td>gap width between backup materials</td>
</tr>
<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>
</tr>
<tr>
<td>HEADNG</td>
<td>any 72 alphanumeric characters used to identify each input section</td>
</tr>
<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>
</tr>
<tr>
<td>HW</td>
<td>wall enthalpy computed from enthalpy - temperature table</td>
</tr>
<tr>
<td>HX</td>
<td>enthalpy values in enthalpy table</td>
</tr>
<tr>
<td>IEM</td>
<td>test used to determine if front surface is virgin or char for using proper emissivity</td>
</tr>
<tr>
<td>IPRC</td>
<td>variable print frequency in time-step table</td>
</tr>
<tr>
<td>IPRCT</td>
<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>
</tr>
<tr>
<td>IRL1</td>
<td>test used in determining node density at TX1 temperature</td>
</tr>
<tr>
<td>IR2</td>
<td>test used in determining node density at TX2 temperature</td>
</tr>
<tr>
<td>NCASE</td>
<td>number of problems to be run</td>
</tr>
<tr>
<td>NCPB</td>
<td>number of points in each backup material specific heat table</td>
</tr>
<tr>
<td>NCPC</td>
<td>number of points in char specific heat temperature table</td>
</tr>
<tr>
<td>NCPV</td>
<td>number of points in virgin specific heat temperature table</td>
</tr>
<tr>
<td>NKC</td>
<td>number of points in char thermal conductivity - temperature table</td>
</tr>
<tr>
<td>FORTRAN</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>NKPB</td>
<td>number of points in each backup material thermal conductivity table</td>
</tr>
<tr>
<td>NKV</td>
<td>number of points in virgin thermal conductivity temperature table</td>
</tr>
<tr>
<td>NMB</td>
<td>number of materials in backup structure</td>
</tr>
<tr>
<td>NP</td>
<td>number of node points in ablation material</td>
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<tr>
<td>NPBS</td>
<td>total number of node points in backup structure</td>
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<tr>
<td>NPF</td>
<td>total number of points in heat shield structure (NP + NPBS)</td>
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<tr>
<td>NPL/T</td>
<td>output plot control number</td>
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<tr>
<td>NPM</td>
<td>number of nodes per material in backup</td>
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<td>NHP</td>
<td>number of points in enthalpy–temperature table</td>
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<tr>
<td>NPTT</td>
<td>number of points in time-step table</td>
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<tr>
<td>NREC</td>
<td>number of points in surface recession–temperature or time table</td>
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86
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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>temperature at fixed locations in ablation material as defined by XC</td>
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<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

Calculate surface heating conditions

Transfer to subroutine TEMPDT determines initial temperature distribution

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 calculates thermal properties

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

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

Transfer to subroutine
calculates fixed
location temperatures

Transfer to subroutine
distributes temperature
for printing
Performs isotherm
calculations

Transfer to subroutine
calculates gas
accumulation rate

Transfer to subroutine
calculates fixed
location temperatures

Transfer to subroutine
Setup data for
plot program

If time is less than
surface heating
calculation

Check
LPL@ = NCASE

Check
NCASE

Rewind 11

Go to initialization
of program constants

Initialize program to
initial input conditions

Go to initialization
of next problem

End File II
Rev End II
### TABLE I. - SAMPLE PROBLEM INPUT

(a) Coding sheet

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**NOTE:** WRITE NUMBERS 10, LETTERS 'RGZ0', SYMBOLS / **

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**msc Form 244 (Apr 1962)**
### TABLE I.- SAMPLE PROBLEM INPUT - Continued

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**NOTE:** WRITE NUMBERS 10, LETTERS IGZOC, SYMBOLS */*
### TABLE I. - SAMPLE PROBLEM INPUT - Concluded

(a) Coding sheet

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

(b) Fortran data card listing

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

TYPICAL CHARGING ABLATION MATERIAL PROPERTIES

NO TRAJECTORY - Q=95 ST/SEC=SOFT

BACKUP MATERIAL 0.1 INCHES THICK

INITIAL TEMPERATURE IS CONSTANT

92
TABLE I - SAMPLE PROBLEM INPUT - Concluded

(b) Fortran data card listing

| +3200,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 |
|+3200,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 |
|+3200,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 |
|+3200,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 |
|+3200,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 | +00+7000,00 |
**TABLE II. - SAMPLE PROBLEM OUTPUT**

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

**INPUT DATA.**

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<th>TIME LIMIT</th>
<th>INITIAL TIME</th>
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<tbody>
<tr>
<td>6.000E+02</td>
<td>0.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TIME</th>
<th>TIME STEP</th>
<th>PREINT CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0000E-01</td>
<td>100</td>
</tr>
<tr>
<td>6.000E+02</td>
<td>1.0000E-01</td>
<td>100</td>
</tr>
</tbody>
</table>

**FCNVS = 1.0000E+00  FRAN = 0.0000E+00**

**TYPICAL CHARRING ABLATION MATERIAL PROPERTIES**

| TBL =          | 1.0000E+00 |
| FBLD =         | 0.0         |
| HW =           | 2.5000E+02 |
| CMAR =         | 4.30000E-01|
| NP =           | 31          |
| NK =           | 2           |
| NCP =          | ?           |
| NKV =          | 9           |
| NCVP =         | 2           |
| NREC =         | 2           |

**VIRGIN MATERIAL**

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>CONDUCTIVITY</th>
<th>TEMPERATURE</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.60000E+02</td>
<td>6.50000E-02</td>
<td>3.60000E+02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>5.60000E+02</td>
<td>6.50000E-02</td>
<td>5.60000E+02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>6.60000E+02</td>
<td>6.50000E-02</td>
<td>6.60000E+02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>7.60000E+02</td>
<td>6.50000E-02</td>
<td>7.60000E+02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>8.60000E+02</td>
<td>6.50000E-02</td>
<td>8.60000E+02</td>
<td>4.30000E-01</td>
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<tr>
<td>9.60000E+02</td>
<td>6.50000E-02</td>
<td>9.60000E+02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>1.06000E+03</td>
<td>7.00000E-02</td>
<td>1.06000E+03</td>
<td>7.00000E-02</td>
</tr>
</tbody>
</table>

**CHAR MATERIAL**

<table>
<thead>
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<th>TEMPERATURE</th>
<th>CONDUCTIVITY</th>
<th>TEMPERATURE</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.46000E+04</td>
<td>1.20000E-01</td>
<td>1.46000E+04</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>1.00000E+04</td>
<td>1.20000E-01</td>
<td>1.00000E+04</td>
<td>4.30000E-01</td>
</tr>
</tbody>
</table>

**SURFACE RECESSION TABLE**

<table>
<thead>
<tr>
<th>TIME</th>
<th>5X = 1/N/SEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>9.00000E+04</td>
</tr>
<tr>
<td>6.00000E+02</td>
<td>9.00000E+04</td>
</tr>
</tbody>
</table>

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

**NO. OF TRAJECTORY POINTS = 7**
TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

<table>
<thead>
<tr>
<th>TIME</th>
<th>Ω CONVECTIVE</th>
<th>Ω RADIATIVE</th>
<th>VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000E 02</td>
<td>7.84000E 01</td>
<td>0.0</td>
<td>2.92500E 04</td>
</tr>
<tr>
<td>6.00000E 02</td>
<td>9.60000E 01</td>
<td>0.0</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>1.60000E 02</td>
<td>6.30000E-02</td>
</tr>
<tr>
<td>4.60000E 02</td>
<td>6.50000E-02</td>
</tr>
<tr>
<td>5.60000E 02</td>
<td>6.50000E-02</td>
</tr>
<tr>
<td>6.60000E 02</td>
<td>6.60000E-02</td>
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<tr>
<td>7.60000E 02</td>
<td>6.70000E-02</td>
</tr>
<tr>
<td>8.60000E 02</td>
<td>6.80000E-02</td>
</tr>
<tr>
<td>9.60000E 02</td>
<td>6.90000E-02</td>
</tr>
<tr>
<td>1.06000E 03</td>
<td>7.00000E-02</td>
</tr>
<tr>
<td>1.16000E 03</td>
<td>7.10000E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.60000E 02</td>
<td>4.30000E-01</td>
</tr>
<tr>
<td>1.10000E 03</td>
<td>4.30000E-01</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DENSITY</th>
<th>THICKNESS</th>
<th>EMISSIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.40000E 01</td>
<td>1.00000E-01</td>
<td>9.00000E-01</td>
</tr>
<tr>
<td>9.00000E-01</td>
<td>3.00000E 00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<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>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></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>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

HEAT TRANSFER TO CAFIN ENVIRONMENT - HENV=0.0

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>FILM COEFFICIENT</th>
<th>VIEW FACTOR</th>
<th>Q LOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.60000E 02</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</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.

<table>
<thead>
<tr>
<th>TIME</th>
<th>QCONVECTIVE</th>
<th>QRADIATIVE</th>
<th>VELOCITY</th>
<th>GAS ABLATION RATE</th>
<th>CHAR ABLATION RATE</th>
<th>TOTAL ABLATION RATE</th>
<th>RECESSION DEPTH</th>
<th>QHOT WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.90000E 00</td>
<td>9.50000E 01</td>
<td>0.00000E 00</td>
<td>2.92500E 04</td>
<td>5.40000E 00</td>
<td>5.40000E 00</td>
<td>5.40000E 00</td>
<td>9.00000E-03</td>
<td>8.99282E 01</td>
</tr>
</tbody>
</table>

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

#### TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.79022E 03</td>
<td>2.33046E 03</td>
<td>1.06300E 03</td>
<td>6.38075E 02</td>
<td>5.47600E 02</td>
<td>5.32434E 02</td>
<td>5.30003E 02</td>
</tr>
<tr>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
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<td>5.30000E 02</td>
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<td>5.30000E 02</td>
<td>5.30000E 02</td>
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<tr>
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<td>5.30000E 02</td>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
<td>5.30000E 02</td>
</tr>
</tbody>
</table>

#### TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<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>
</tr>
</tbody>
</table>

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

#### TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.80936E 03</td>
<td>2.87678E 03</td>
<td>1.64575E 03</td>
<td>9.77202E 02</td>
<td>6.76978E 02</td>
<td>5.66204E 02</td>
<td>5.39999E 02</td>
</tr>
<tr>
<td>5.37857E 02</td>
<td>5.31499E 02</td>
<td>5.30254E 02</td>
<td>5.30073E 02</td>
<td>5.30005E 02</td>
<td>5.30002E 02</td>
<td>5.30000E 02</td>
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<tr>
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<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 02</td>
<td>5.29999E 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>
</tr>
</tbody>
</table>

#### TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<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>
</tr>
</tbody>
</table>

### TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 3.00000E 01 SECONDS

#### TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.99000E 01</td>
<td>2.96720E 01</td>
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<td>3.44720E 01</td>
<td>3.44720E 01</td>
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<tr>
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<td>5.29999E 02</td>
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</tr>
</tbody>
</table>

#### TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>5.29999E 02</td>
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<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>
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 ablator 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 so 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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