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AN ANALYSIS OF A CHARRING ABLATION
THERMAL PROTECTION SYSTEM

By Donald M. Curry
Manned Spacecraft Center

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 end

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.

end

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
$\dot{m}_c$	mass loss rate of char material
$\dot{m}_g$	gas ablation rate
NP	number of nodes in ablation material

n	order of reaction
$Q_{in.}$	net heat rate into front surface
$\dot{q}_{c\ blow}$	hot wall convective heat flux with blowing
$\dot{q}_{comb}$	heat flux due to combustion
$\dot{q}_{cw}$	cold wall convective heat flux without blowing
$\dot{q}_{rad}$	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_{env}	cabin environment temperature
T'	temperature of node at end of time step
T_{∞}	radiation heat sink temperature
VL	thickness of ablation material
X	distance from surface to any point
ΔH_c	heat of combustion per unit weight of char
ΔX	thickness of a node
$\Delta\theta$	time step $(\theta' - \theta)$
ϵ	emissivity of material
η	transpiration cooling efficiency
θ	initial time
θ'	final time
ξ	transform for the ablation material

ρ	density
σ	Stefan-Boltzmann constant
ψ	blocking effectiveness function

Subscripts:

c	charred state
i	node number
j	material number
v	virgin state

PROGRAM DESCRIPTION

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

(1) Stability of the equations for all applications.

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

(3) A minimum of input per problem.

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

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

The following surface boundary condition options are provided:

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

(2) Surface temperature as a function of time.

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

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

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

(2) Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision, ΔX. The exact values are approached more and more closely as ΔX 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

$$\frac{\partial}{\partial X}\left(k\frac{\partial T}{\partial X}\right) = \rho c_p \frac{\partial T}{\partial \theta} \tag{1}$$

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

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

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:

$$\frac{\rho c_p}{k}\frac{(\Delta X)^2}{\Delta\theta} \geq 2$$

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.

Liebmann (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:

$$\frac{\left(T'_{i-1} - T'_i\right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left(T'_i - T'_{i+1}\right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X \left(T'_i - T_i\right)}{\Delta\theta} \qquad (3)$$

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

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T'_{i-1} - \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right) T'_i + \left(\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right) T'_{i+1} = -\left(\frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right) T_i \qquad (4)$$

Equation (4) is of the form

$$AT'_{i-1} + BT'_i + CT'_{i+1} = D \qquad (5)$$

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:

$$\dot{q}_{rad} = F\epsilon\sigma\left({T'_i}^4 - {T_\infty}^4\right) \qquad (6)$$

This term cannot be used in an implicit solution since the unknown temperature T_i' is to be the 4th power. The 4th power unknown can be eliminated by the following linearizations:

$$\left(T_i'\right)^4 = \left(T_i + \Delta T\right)^4 = T_i^{\,4}\left(1 + \frac{\Delta T}{T_i}\right)^4 \tag{7}$$

where

$$\Delta T = T_i' - T_i$$

let

$$Z \equiv \frac{\Delta T}{T_i}$$

and rewrite equation (7) as

$$\left(T_i'\right)^4 = \left(T_i\right)^4 (1 + Z)^4 \tag{8}$$

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

$$(1 + Z)^4 \cong 1 + 4Z \tag{9}$$

Now substituting equation (9) into equation (8)

$$\left(T_i'\right)^4 \cong \left(T_i\right)^4 (1 + 4Z) = \left(T_i\right)^4 \left(1 + 4\,\frac{\Delta T}{T_i}\right)$$

$$\cong 4T_i^{\,3}T_i' - 3T_i^{\,4} \tag{10}$$

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

Therefore, equation (6) can now be written

$$\dot{q}_{rad} = F\epsilon\sigma\left(4T_i^{\,3}T_i' - 3T_i^{\,4} - T_\infty^{\,4}\right) \tag{11}$$

Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

$$
\begin{aligned}
B_1T_1 + C_1T_2 \qquad\qquad\qquad\qquad\qquad &= D_1 \\
A_2T_1 + B_2T_2 + C_2T_3 \qquad\qquad\quad &= D_2 \\
A_3T_2 + B_3T_3 + C_3T_4 \qquad &= D_3 \\
\vdots \qquad \vdots \qquad\qquad\qquad\quad &\;\;\vdots \\
A_NT_{N-1} + B_NT_N &= D_N
\end{aligned}
$$

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.

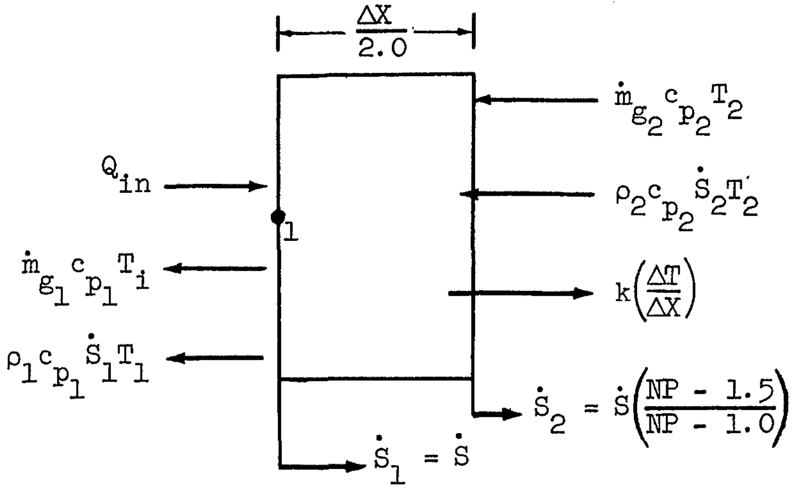
(4) Local thermal equilibrium is maintained between the gas and porous char matrix.

(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 ΔX 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

$$\frac{d}{d\theta}\left(\frac{1}{2}\,\Delta X\;\rho_1 c_{p_1} T_1\right) = \frac{1}{2}\,\Delta X\;\rho_1 c_{p_1}\frac{dT_1}{d\theta} + \frac{1}{2}\,\rho_1 c_{p_1} T_1\,\frac{d(\Delta X)}{d\theta}$$

$$= Q_{in} + \dot{m}_{g_2} c_{p_2} T_2' + \rho_2 \dot{S}_2 c_{p_2} T_2' - \dot{m}_{g_1} c_{p_1} T_1'$$

$$- \rho_1 c_{p_1} \dot{S}_1 T_1' - k_{1-2}\left(\frac{\Delta T}{\Delta X}\right) \qquad (12)$$

where

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

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

$$Q_{in} + \dot{m}_{g_2} c_{p_2} T'_2 - \dot{m}_{g_1} c_{p_1} T'_1 - \dot{S}\rho_1 c_{p_1} T'_1 - \frac{\left(T'_1 - T'_2\right)}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}}$$

$$+ \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0}\right) T'_2 = \rho_1 c_{p_1} \frac{\Delta X}{2}\left(\frac{T'_1 - T_1}{\Delta\theta}\right)$$

$$- \frac{1}{2}\rho_1 c_{p_1} T'_1 \left(\frac{\dot{S}}{NP - 1}\right) \qquad (12a)$$

Then, rearranging and collecting terms yield

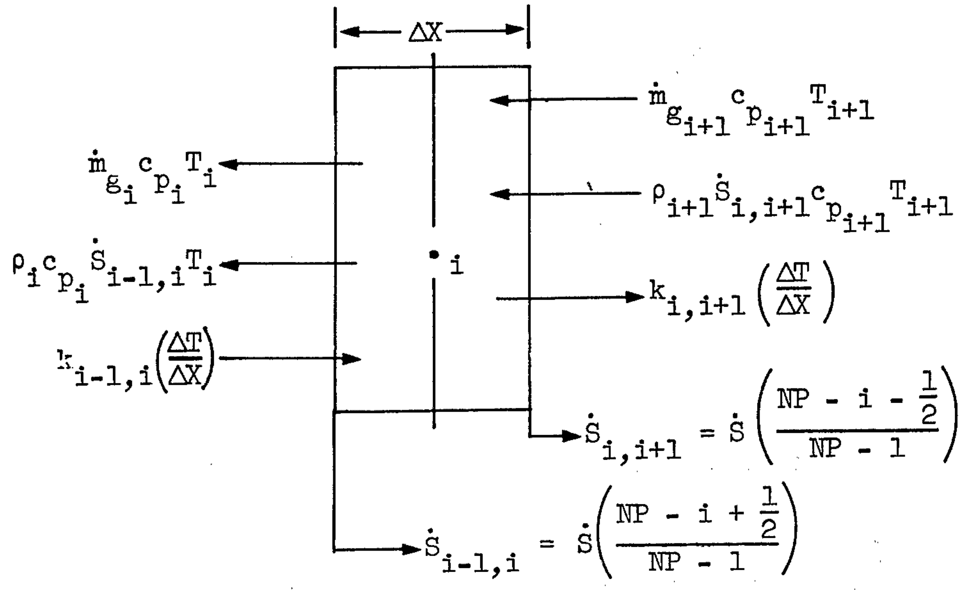
$$- \left[\dot{m}_{g_1} c_{p_1} + \dot{S}\rho_1 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} - \frac{1}{2}\rho_1 c_{p_1} \left(\frac{\dot{S}}{NP - 1}\right)\right] T'_1$$

$$+ \left[\dot{m}_{g_2} c_{p_2} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0}\right)\right] T'_2$$

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

(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

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

$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T_{i+1}' + k_{i-1,i} \left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}'$$

$$- k_{i,i+1} \left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (13)$$

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

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right)T'_{i-1} - \Bigg[\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}$$

$$+ \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\Bigg]T'_i$$

$$+ \left[\dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right]T'_{i+1}$$

$$= -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} T_i \qquad (13a)$$

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), $\dot{m}_{g_i} = \dot{m}_{g_{i+1}}$

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

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i}\frac{dT_i}{d\theta} - \rho_i c_{p_i} T'_i\left(\frac{\dot{S}}{NP - 1}\right) - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d$$

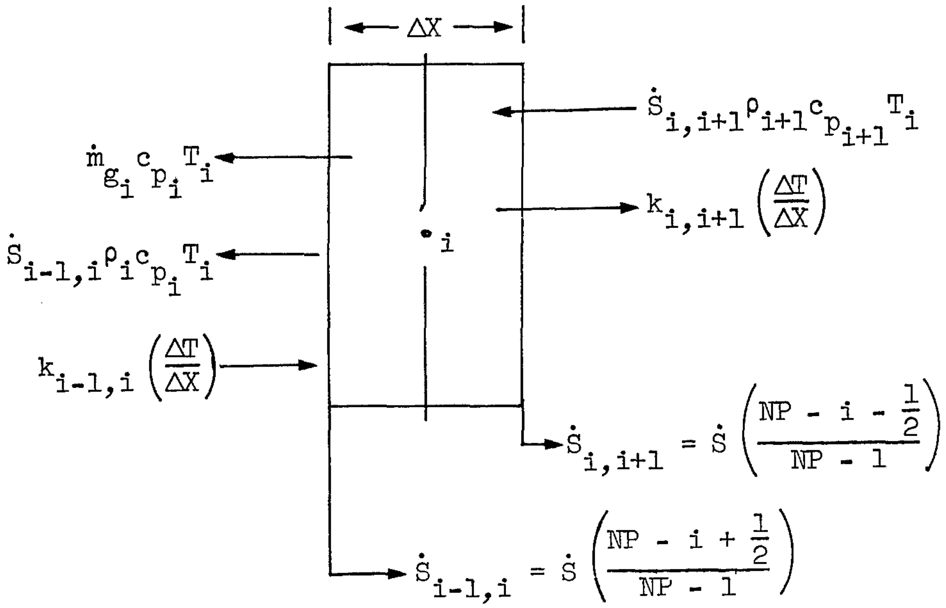
$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T'_{i+1} + k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T'_{i+1}$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T'_i - \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T'_i \qquad (14)$$

Rearranging,

$$\begin{aligned}
&\left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left[\dot{m}_{g_i}c_{p_i} + \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right. \\
&\qquad \left. + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right]T'_i + \left[\dot{m}_{g_{i+1}}c_{p_{i+1}}\right. \\
&\qquad\qquad \left. + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_{i+1}c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right]T'_{i+1} \\
&\qquad\qquad\qquad = -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta}T_i - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right)H_d \qquad (14a)
\end{aligned}$$

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



The heat balance equation for this node is

$$\frac{d}{d\theta}\left(\Delta X\rho_i c_{p_i} T_i\right) = \Delta X\rho_i c_{p_i}\frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i'\left(\frac{\dot{S}}{NP - 1}\right) - \dot{m}_{g_i} H_d$$

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

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (15)$$

Rearranging yields

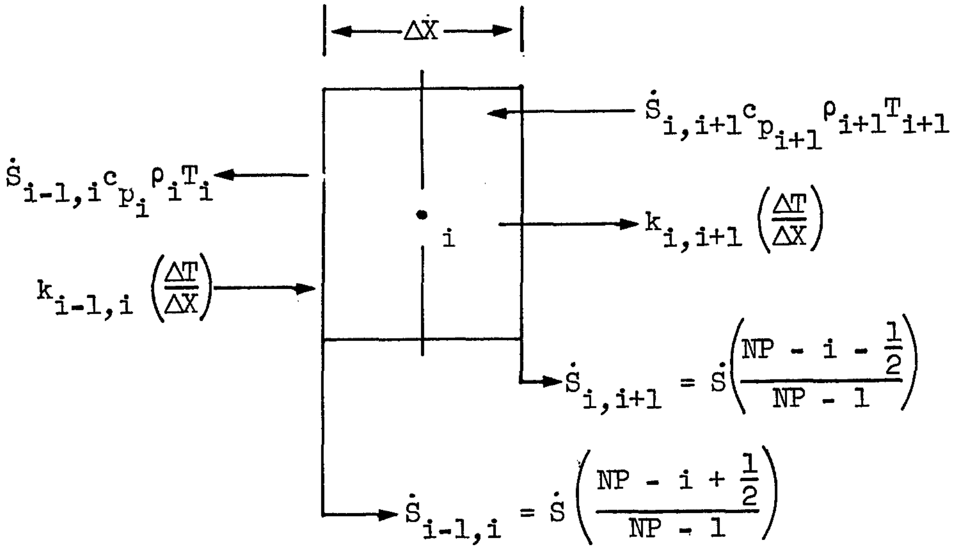
$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T_{i-1}' - \Bigg[\dot{m}_{g_i} c_{p_i} + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}$$

$$+ \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\Bigg] T_i'$$

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

$$= -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} T_i - \dot{m}_{g_i} H_d \qquad (15a)$$

The physical model for an interior node in the virgin material is



The heat balance for this nonablating node is

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

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

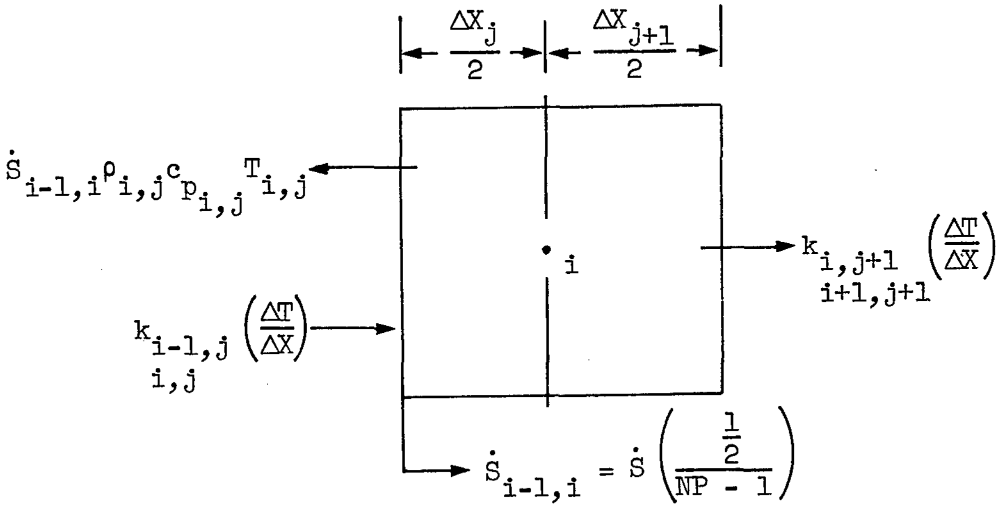
$$- \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (16)$$

Rearranging,

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left[\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right]T'_i$$

$$+ \left[\frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_{i+1}c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right]T'_{i+1} = -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta}T_i \qquad (16a)$$

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



For this interface, $T'_{i,j} = T'_{i,j+1}$.

The heat balance equation for this node is

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

$$= \left(\frac{\Delta X_j\rho_{i,j}c_{p_{i,j}} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2}\right)\frac{dT_i}{d\theta} - \frac{1}{2}\left(\frac{\dot{S}}{NP - 1}\right)c_{p_{i,j}}\rho_{i,j}T'_i$$

$$= k_{\substack{i-1,j\\ i,j}}\left(\frac{\Delta T}{\Delta X}\right) - c_{p_{i,j}}\rho_{i,j}\dot{S}\left(\frac{\frac{1}{2}}{NP - 1}\right)T'_i - k_{\substack{i,j+1\\ i+1,j+1}}\left(\frac{\Delta T}{\Delta X}\right) \tag{17}$$

Rearranging yields

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

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

$$= -\left(\frac{\Delta X_j c_{p_{i,j}}\rho_{i,j} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2\Delta\theta}\right)T_i \tag{17a}$$

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

(1) Interior node material:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - \frac{\left(T'_{i,j} - T'_{i+1,j}\right)}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta\theta} \left(T'_{i,j} - T_{i,j}\right) \tag{18}$$

Rearranging, equation (18) becomes

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

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

$$= -\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta\theta} T_{i,j} \tag{18a}$$

(2) <u>First</u> and <u>last</u> nodes of two interior materials with <u>no</u> gap:

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

$$= \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta}\right) \left(T'_{i,j} - T_{i,j}\right) \tag{19}$$

For this case, $T'_{i,j} = T'_{i,j+1}$

Rearranging, equation (19) becomes

$$\begin{aligned}
&\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left[\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right. \\
&\qquad \left. + \left(\frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j + \rho_{i,j+1}c_{p_{i,j+1}}\Delta X_{j+1}}{2\,\Delta\theta}\right)\right]T'_{i,j} \\
&\qquad + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right)T'_{i+1,j+1} \\
&\qquad = -\left(\frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j + c_{p_{i,j+1}}\rho_{i,j+1}\Delta X_{j+1}}{2\,\Delta\theta}\right)T_{i,j}
\end{aligned} \tag{19a}$$

(3) <u>First node</u> of interior material <u>with an air gap</u> between materials:

$$\begin{aligned}
&h_j\left(T'_{i-1,j} - T'_{i,j+1}\right) + \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T'^{4}_{i-1,j} - T'^{4}_{i,j+1}\right) \\
&-\left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) = \frac{\rho_{i,j+1}c_{p_{i,j+1}}\Delta X_{j+1}}{2\,\Delta\theta}\left(T'_{i,j+1} - T_{i,j+1}\right)
\end{aligned} \tag{20}$$

Equation (20) may be linearized by using the approximation

$$T'^{4} \cong 4T^3T' - 3T^4$$

as discussed in the Program Description section.

Therefore, rearranging and linearizing, equation (20) becomes

$$\left[h_j + \left(\frac{4\sigma T^3_{i-1,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right]T'_{i-1,j} - \left[h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right.$$

$$\left. + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \frac{\rho_{i,j+1}c_{p_{i,j+1}}\Delta X_{j+1}}{2\,\Delta\theta}\right]T'_{i,j+1}$$

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

$$-\left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i-1,j}\right) \qquad (20a)$$

(4) <u>Last node</u> of an interior material <u>with an air gap</u> between materials:

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

$$-\left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T'^{4}_{i,j} - T'^{4}_{i,j+1}\right) = \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\,\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \qquad (21)$$

Rearranging and linearizing, equation (21) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left[h_j + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \left(\frac{4\sigma T^3_{i,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right.$$

$$\left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\right]T'_{i,j} + \left[h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right]T'_{i,j+1}$$

$$= -\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}T_{i,j} + \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i,j}\right) \tag{21a}$$

(5) Final node in backup structure:

(a) Adiabatic surface —

$$\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \tag{22}$$

Rearranging, equation (22) becomes

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

$$\left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\right)T'_{i,j} = -\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}T_{i,j} \tag{22a}$$

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

$$\left(\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) - h_{env}\left(T'_{i,j} - T_{env}\right)$$

$$- F_{env}\sigma\left(T'^{4}_{i,j} - T^{4}_{env}\right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \qquad (23)$$

Rearranging, equation (23) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left(h_{env} + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + F_{env}\sigma 4T^{3}_{i,j}\right.$$

$$\left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\right)T'_{i,j} = - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\,T_{i,j}$$

$$- h_{env}T_{env} - F_{env}\sigma\left(3T^{4}_{i,j} + T^{4}_{env}\right) \qquad (23a)$$

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 spacially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric test data for the particular material being investigated. Figure 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,

$$\dot{\rho}_i = \frac{\rho_i' - \rho_i}{\Delta\theta} \tag{24}$$

and

$$\dot{m}_{g_i} = \sum_{i}^{NP} \dot{\rho}_i \Delta X_i \tag{25}$$

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

$$\frac{d\rho}{d\theta} = -A\left(\rho - \rho_c\right)^n e^{-\frac{E}{RT}} \tag{26}$$

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):

$$\dot{q}_{block} \equiv \eta \dot{m}_g \left(H_T - H_w\right) \tag{27}$$

Therefore,

$$\dot{q}_{c,blow} = \dot{q}_{cw}\left(\frac{H_T - H_w}{H_T - H_{300}}\right) - \dot{q}_{block} \tag{28}$$

However, equation (28) is unsatisfactory for high blowing rates, since $\dot{q}_{block}$ can become greater than $\dot{q}_{cw}$. An experimental curve of blocking effectiveness $\psi = \frac{\dot{q}_{c,blow}}{\dot{q}_{cw}}$ as a function of the mass transfer parameter $\frac{\dot{m}_g H_T}{\dot{q}_{cw}}$ 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

$$\dot{q}_{comb} = \dot{m}_c \, \Delta H_c \tag{29}$$

where ΔH_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 $\left(T_i \geq T_{char}\right)$

$$k_c = f\ (\text{temp})$$

$$c_{p_c} = f\ (\text{temp})$$

$$\rho_c = \text{constant}$$

(2) Reaction zone $\left(T_{abl} \leq T_i < T_{char}\right)$

$$\rho = f\ (\text{temp}) = \rho_v + \left(\rho_v - \rho_c\right)\left(\frac{T_i - T_{abl}}{T_{abl} - T_{char}}\right)$$

$$k = f(\rho) = k_c + \left(k_v - k_c\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

$$c_p = f(\rho) = c_{p_c} + \left(c_{p_v} - c_{p_c}\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

(3) Virgin zone $\left(T_i < T_{abl}\right)$

$$\rho_v = \text{constant}$$

$$k_v = f\ (\text{temp})$$

$$c_{p_v} = f\ (\text{temp})$$

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.

$$\left[\left(\frac{\partial T}{\partial \theta}\right)_{\xi=0} = 0; \; k\left(\frac{\partial T}{\partial X}\right)_{X=0} = \dot{S}\rho c_p \, \Delta T\right]$$

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 3.05×10^{-3}in./sec. Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located at a depth of 1.0 inch. The disagreement could be attributed to several possible errors: thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, et cetera) is presently being investigated.

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

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

CONCLUDING REMARKS

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

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

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

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

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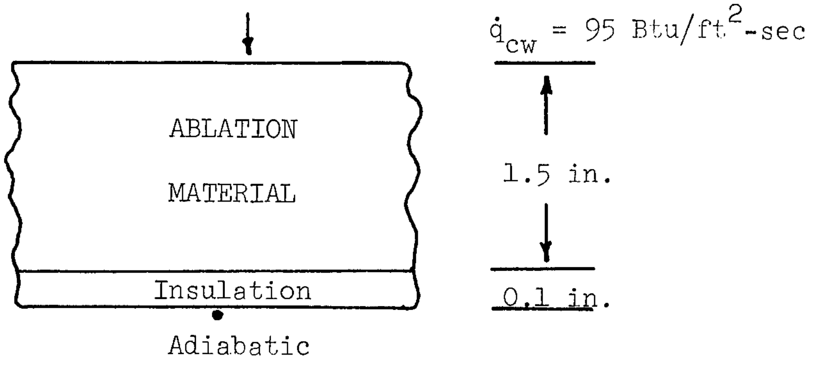
APPENDIX A

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:



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

APPENDIX B

PROGRAM USAGE INSTRUCTIONS

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

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

Input Nomenclature

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

NCASE	number of problems to be run successively
HEAD	any 72 alphabetical and/or numerical characters
TITLE	control card for reading in new input for successive problems 1. blank card – new data will be read in 2. Six asterisks in columns 1 to 6. Skip to next read statement
TLIM	time limit of problem, sec
TINT	starting time of problem, sec
NPTT	number of points in time-step table (the minimum value of NPTT is 2)
NPLØT	output plot control
=1	plot routine will be used
=0	plot routine will be ignored

TTABLE	time in time-step table, sec
DELTT	time step to be used for each calculation – starting at time TTABLE, sec
IPRC	variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals
FCØNV	factor to correct convective heating rate for various body locations
FRAD	factor to correct radiative heating for various body locations
TABL	temperature at which ablation starts, $^{\circ}$R
TCHAR	temperature at which ablation stops, $^{\circ}$R
TREC	surface temperature, $^{\circ}$R, <u>or</u> time at which char removal is to start, sec
RHØV	density of virgin ablation material, lb/ft^3
RHØC	density of mature char material, lb/ft^3
FBLØW	blowing efficiency of ablation gases in reducing convective heating
EMV	emissivity of virgin ablation material
EMC	emissivity of charred ablation material
H300	enthalpy of air at 300° K, 129.06 Btu/lbm
VL	initial thickness of virgin ablation material, in.
HV	heat of degradation of virgin material, Btu/lbm
VPT	test to determine if the reaction zone and char zone thermal properties are irreversible with temperature
=0	properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT)
=1	properties are reversible
FV	view factor for external environment
TV	sink temperature of external environment, $^{\circ}$R

CHARK	thermal conductivity of material at TCHAR, Btu/ft-hr-°R
CHARC	specific heat of material at TCHAR, Btu/lbm-°R
ABLK	thermal conductivity of material at TABL, Btu/ft-hr-°R
ABLC	specific heat of material at TABL, Btu/lbm-°R
NP	number of node points in ablation material
NKC	number of points in char thermal conductivity - temperature table
NCPC	number of points in char specific heat - temperature table
NKV	number of points in virgin thermal conductivity - temperature table
NCPV	number of points in virgin specific heat - temperature table
NREC	number of points in surface recession - temperature <u>or</u> time table
TKC	temperature values in char thermal conductivity - temperature table, °R
XKC	thermal conductivity values in char thermal conductivity - temperature table, Btu/ft-hr-°R
TCPC	temperature values in char specific heat - temperature table, °R
CPC	specific heat values in char specific heat - temperature table, Btu/lbm-°R
TKV	temperature values in virgin thermal conductivity - temperature table, °R
XKV	thermal conductivity values in virgin thermal conductivity - temperature table, Btu/ft-hr-°R
TCPV	temperature values in virgin specific heat - temperature table, °R
CPV	specific heat values in virgin specific heat temperature table, Btu/lbm-°R
TS	temperature, °R, or time, sec, values in the surface recession 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 <u>each individual</u> material in backup structure
NKPB	number of points in <u>each</u> individual backup structure material thermal conductivity – temperature table
NCPB	number of points in <u>each individual</u> backup structure material specific heat – temperature table
XIDNT	any 72 alphanumeric characters used to describe <u>each individual</u> material in the backup structure
TXK	temperature values in backup material thermal conductivity – temperature table, $^{\circ}$R
XK	thermal conductivity values in backup material thermal conductivity – temperature table, Btu/ft–hr–$^{\circ}$R
TCP	temperature values in backup material specific heat – temperature tables, $^{\circ}$R
CPX	specific heat values in backup material specific heat – temperature tables, Btu/lbm-$^{\circ}$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/ft^2-hr-$^\circ$R
GAPX	width of gap between adjacent materials in backup, in.
FTEST, BTEST	tests to determine the mode of heat transfer between materials for the front and backface of each material respectively
=0	conduction only between materials
=+1	convective heat transfer only
=-1	radiation only or radiation and convection heat transfer
TENV	temperature of interior cabin environment, $^\circ$R
HENV	film coefficient to interior cabin environment, Btu/ft^2-hr-$^\circ$R
FENV	view factor and emissivity product for radiative heat transfer to cabin interior
QL0SS	boundary condition between last node of the backup structure and cabin environment
=0	adiabatic surfaces
=+1	radiation and/or convective loss
TEST2	determines the proper heat shield initial temperature distribution
=0	constant, uniform initial temperature distribution
=-1	arbitrary initial temperature distribution
=+1	linear temperature distribution
TEMPI	temperature to be used when constant temperature distribution option is used, $^\circ$R
TX0	initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, $^\circ$R
TEMDI	arbitrary temperature distribution values, to be used only if TEST2 is negative, $^\circ$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 NPLØT. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPLØT 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 FC0NV and FRAD. These numbers are entered as floating-point numbers and must end in columns 12 and 24.

(c) Ablation material section

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

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

10. Enter TABL, TCHAR, TREC, RH0V, RH0C, and FBL0W. 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 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, QC0N, 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: RH0BX, XBM, EMFB, and EMBB. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

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

(f) Interior environment section

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

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

34. Enter the following: TENV, HENV, FENV, and QL0SS. The values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48.

(g) Initial temperature section

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

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

37. Enter TEST2, TEMPI, and TX0. 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, RHØV = RHØC, 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, QCØN, 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, $^\circ$R

11. Temperature distribution in backup structure, $^\circ$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, $^\circ$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

```
$IBFTC MAIN                                                             A0000
C                                                                       A0010
C     STRUCTURES AND MECHANICS DIVISION                                 A0020
C     THERMO-STRUCTURES BRANCH                                          A0030
C     THERMAL PROTECTION SYSTEMS SECTION                                A0040
C                                                                       A0050
C     THIS PROGRAM DETERMINES THE PERFORMANCE OF A CHARRING ABLATOR     A0060
C                                                                       A0070
C     ANALYSIS AND PROGRAM DEVELOPED BY DONALD M. CURRY  *  ES32        A0080
C                                                                       A0090
      DIMENSION ESAVE1(3),ESAVE2(3),ESAVE3(3)                           A0100
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),      A0110
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),     A0120
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)A0130
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBB(12),HXX(12)A0140
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),       A0150
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),     A0160
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),      A0170
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),      A0180
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),         A0190
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)                         A0200
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)          A0210
      DIMENSION TIMEP(300),PRES(300),XC(50),TX2C(50),XV(50),XDV(50)     A0220
      DIMENSION TS(50),SR(50)                                           A0230
      DIMENSION TTABLE(20),DELTT(20),IPRC(20)                           A0240
      DIMENSION ASAVE1(3),ASAVE2(3),ASAVE3(3),BSAVE1(3),BSAVE2(3),      A0250
     1BSAVE3(3),CSAVE1(3),CSAVE2(3),CSAVE3(3),HEAD(12),                 A0260
     1DSAVE1(3),DSAVE2(3),DSAVE3(3)                                     A0270
      DIMENSION XRA(30),YA(30)                                          A0280
C                                                                       A0290
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,     A0300
     1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,     A0310
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,     A0320
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,       A0330
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,   A0340
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT    A0350
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,   A0360
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H                     A0370
C                                                                       A0380
 3000 FORMAT(12A6)                                                      A0390
 3001 FORMAT(1X,12A6)                                                   A0400
 3002 FORMAT(6E12.8)                                                    A0410
 3003 FORMAT(6I5)                                                       A0420
 3004 FORMAT(1I5)                                                       A0430
 3005 FORMAT(2I5)                                                       A0440
 3007 FORMAT(2I5,1E14.8)                                                A0450
 3008 FORMAT(///1X,12A6)                                                A0460
 3009 FORMAT(1H1,1X,12A6)                                               A0470
 3010 FORMAT(4E12.8)                                                    A0480
 3011 FORMAT(2E12.8,I6,I5,F13.8,E12.8)                                  A0490
 3012 FORMAT(2E12.8,I6)                                                 A0500
      DATA PRVOUS/0545454545454/                                        A0510
      REWIND 11                                                         A0520
      STOP=9999.                                                        A0530
      READ(5,3003)NCASE                                                 A0540
      LPLOT=0                                                           A0550
      JCNT=0                                                            A0560
```

```
   50 NK=1                                                              A0570
      I1=2                                                              A0580
      I2=2                                                              A0590
      I3=2                                                              A0600
      I4=2                                                              A0610
      I5=2                                                              A0620
      I6=2                                                              A0630
      I17=2                                                             A0640
      INT=1                                                             A0650
      XLOST=0.0                                                         A0660
      XMT=0.0                                                           A0670
      XMDT=0.0                                                          A0680
      ERR1=0.0                                                          A0690
      ERR2=0.0                                                          A0700
      ERR3=0.0                                                          A0710
      ERR4=0.0                                                          A0720
      ICT=0                                                             A0730
      ICONT=0                                                           A0740
      XMDC=0.0                                                          A0750
      NKP=1                                                             A0760
      XLSTV=0.0                                                         A0770
      NRS=2                                                             A0780
      ERR5=0.0                                                          A0790
      IPCT=0                                                            A0800
      ICTP=0                                                            A0810
      IPLOT=1                                                           A0820
      NXA=1                                                             A0830
      NXB=1                                                             A0840
      NXC=1                                                             A0850
      NXD=1                                                             A0860
      SAVY3=-100.                                                       A0870
      SAVY4X=-100.                                                      A0880
      SX0=0.0                                                           A0890
      SDOT=0.0                                                          A0900
C                                                                       A0910
C     GENERAL TITLE OF PROBLEM                                          A0920
  100 READ(5,3000) (HEAD(K),K=1,12)                                     A0930
      WRITE(6,3009) (HEAD(K),K=1,12)                                    A0940
      LPLOT=LPLOT+1                                                     A0950
      WRITE (11)(HEAD(I),I=1,12)                                        A0960
      WRITE(6,110)                                                      A0970
  110 FORMAT(//1X,11HINPUT DATA.//)                                     A0980
      READ(5,3000) (TITLE(L),L=1,12)                                    A0990
      IF(TITLE(1).EQ.PRVOUS) GO TO 150                                  A1000
      READ(5,3011)TLIM,TINT,NPTT,NPLOT,DMP,TDMP                         A1010
      READ(5,3012) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)                A1020
      T=TINT                                                            A1030
      DTS=DELTT(1)                                                      A1040
      DT=DELTT(1)/3600.0                                                A1050
      WRITE(6,120) TLIM,TINT,NPTT                                       A1060
  120 FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X,5 A1070
     1HNPTT=,I4)                                                        A1080
      WRITE(6,122)                                                      A1090
  122 FORMAT(//8X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL)           A1100
      WRITE(6,124) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)                A1110
  124 FORMAT(5X,1PE10.4,6X,1PE10.4,9X,I4)                               A1120
C                                                                       A1130
```

```
C     LOCATION FACTORS FOR CONVECTIVE AND RADIATIVE HEATING                 A1140
  150 READ(5,3000) (TITLE(L),L=1,12)                                        A1150
      IF(TITLE(1).EQ.PRVOUS) GO TO 200                                      A1160
      READ(5,3002) FCONV,FRAD                                               A1170
      WRITE(6,155) FCONV,FRAD                                               A1180
  155 FORMAT(1H0,6HFCONV=,1PE12.5,4X5HFRAD=,1PE12.5/)                       A1190
C                                                                           A1200
C     PROPERTIES OF ABLATION MATERIAL                                       A1210
  200 READ(5,3000) (TITLE(L),L=1,12)                                        A1220
      IF(TITLE(1).EQ.PRVOUS) GO TO 300                                      A1230
      READ(5,3000) (HEADNG(K),K=1,12)                                       A1240
      READ(5,3002) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,VL,HV,      A1250
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC                                       A1260
      READ(5,3003) NP,NKC,NCPC,NKV,NCPV,NREC                                A1270
      READ(5,3002) (TKC(K),XKC(K),K=1,NKC)                                  A1280
      READ(5,3002) (TCPC(M),CPC(M),M=1,NCPC)                                A1290
      READ(5,3002) (TKV(L),XKV(L),L=1,NKV)                                  A1300
      READ(5,3002) (TCPV(N),CPV(N),N=1,NCPV)                                A1310
      READ(5,3002) (TS(I),SR(I),I=1,NREC)                                   A1320
      WRITE(6,3008) (HEADNG(K),K=1,12)                                      A1330
      WRITE(6,210) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,VL,HV,      A1340
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC                                       A1350
  210 FORMAT(1H0,5HTABL=,1PE12.5,3X,6HTCHAR=,1PE12.5,3X,5HTREC=,1PE12.5,    A1360
     13X,5HRHOV=,1PE12.5,3X,5HRHOC=,1PE12.5,21X/1X,6HFBLOW=,1PE12.5,4X,4    A1370
     2HEMV=,1PE12.5,4X,4HEMC=,1PE12.5,3X,5HH300=,1PE12.5,5X,3HVL=,1PE12.    A1380
     35/4X,3HHV=,1PE12.5,4X,4HVPT=,1PE12.5,5X,3HFV=,1PE12.5,5X,3HTV=,1PE    A1390
     112.5,2X,6HCHARK=,1PE12.5/1X,6HCHARC=,1PE12.5,3X,5HABLK=,1PE12.5,3X    A1400
     2,5HABLC=,1PE12.5/)                                                    A1410
      VLI=VL                                                                A1420
      VL=VL/12.0                                                            A1430
      VLV=VL                                                                A1440
      WRITE(6,220) NP,NKC,NCPC,NKV,NCPV,NREC                                A1450
  220 FORMAT(2X,3HNP=,1I4,4X,4HNKC=,1I4,4X,5HNCPC=,1I4,4X,4HNKV=,1I4,4X,    A1460
     15HNCPV=,1I4,4X,5HNREC=,1I4)                                           A1470
      WRITE(6,221)                                                          A1480
  221 FORMAT(/32X,15HVIRGIN MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H    A1490
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)          A1500
      KLLL=MIN0(NKV,NCPV)                                                   A1510
      WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPV(L),L=1,KLLL)                  A1520
  222 FORMAT(2X,1PE12.5,4X,1PE12.5,18X,1PE12.5 ,3X,1PE12.5)                 A1530
      IF(NKV-NCPV) 223,227,225                                              A1540
  223 KLLLL=KLLL+1                                                          A1550
      WRITE(6,224) (TCPV(L),CPV(L),L=KLLLL,NCPV)                            A1560
  224 FORMAT(48X,1PE12.5,3X,1PE12.5)                                        A1570
      GO TO 227                                                             A1580
  225 KLLLL=KLLL+1                                                          A1590
      WRITE(6,226) (TKV(L),XKV(L),L=KLLLL,NKV)                              A1600
  226 FORMAT(2X,1PE12.5,4X,1PE12.5)                                         A1610
  227 WRITE(6,228)                                                          A1620
  228 FORMAT(//33X,14HCHAR  MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H    A1630
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)          A1640
      KLLL=MIN0(NKC,NCPC)                                                   A1650
      WRITE(6,222) (TKC(L),XKC(L),TCPC(L),CPC(L),L=1,KLLL)                  A1660
      IF(NKC-NCPC) 230,235,232                                              A1670
  230 KLLLL=KLLL+1                                                          A1680
      WRITE(6,224) (TCPC(L),CPC(L),L=KLLLL,NCPC)                            A1690
      GO TO 235                                                             A1700
```

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  232 KLLLL=KLLL+1                                                      A1710
      WRITE(6,226) (TKC(L),XKC(L),L=KLLLL,NKC)                          A1720
  235 WRITE(6,240)                                                      A1730
  240 FORMAT(//28X,23HSURFACE RECESSION TABLE//25X,11HTEMPERATURE,8X,11H A1740
     1SR - IN/SEC)                                                      A1750
      WRITE(6,245) (TS(I),SR(I),I=1,NREC)                               A1760
  245 FORMAT(24X,1PE12.5,7X,1PE12.5)                                    A1770
C                                                                       A1780
C     PROPERTIES OF TRAJECTORY                                          A1790
  300 READ(5,3000) (TITLE(L),L=1,12)                                    A1800
      IF(TITLE(1).EQ.PRVOUS) GO TO 400                                  A1810
      READ(5,3000) (HEADNG(L),L=1,12)                                   A1820
      READ(5,3004) NTRAPT                                               A1830
      READ(5,3010) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)          A1840
      WRITE(6,3008) (HEADNG(L),L=1,12)                                  A1850
      WRITE(6,310) NTRAPT                                               A1860
  310 FORMAT(1H0,27H NO. OF TRAJECTORY POINTS =,1I4)                    A1870
      WRITE(6,320)                                                      A1880
  320 FORMAT(//8X,4HTIME,8X,12HQ CONVECTIVE,4X,11HQ RADIATIVE,7X,8HVELOC A1890
     1ITY)                                                              A1900
      WRITE(6,330) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)          A1910
  330 FORMAT(1P4E16.5)                                                  A1920
C                                                                       A1930
C     PROPERTIES OF BACK-UP STRUCTURE                                   A1940
  400 READ(5,3000) (TITLE(L),L=1,12)                                    A1950
      IF(TITLE(1).EQ.PRVOUS) GO TO 500                                  A1960
      WRITE(6,410)                                                      A1970
  410 FORMAT(//10X,31H PROPERTIES OF BACKUP STRUCTURE/)                 A1980
      READ(5,3007) NMB,NPBS,BL                                          A1990
      READ(5,3002) (XNPM(K),K=1,NMB)                                    A2000
      READ(5,415) (NKPB(I),NCPB(I),I=1,NMB)                             A2010
  415 FORMAT(10I5)                                                      A2020
      DO 420 K=1,NMB                                                    A2030
      NPM(K)=XNPM(K)+0.00000002                                         A2040
  420 CONTINUE                                                          A2050
      WRITE(6,425) NMB,NPBS,BL                                          A2060
  425 FORMAT(/4X,35HNO. OF MATERIALS IN BACK-UP SHIELD=,1I4/4X,40HTOTAL  A2070
     1NUMBER OF NODES IN BACK-UP SHIELD=,1I4/4X,28HTHICKNESS OF BACK-UP  A2080
     2SHIELD=,1PE12.5//)                                                A2090
      BL=BL/12.0                                                        A2100
      DO 440 I=1,NMB                                                    A2110
      LK=NKPB(I)                                                        A2120
      LCP=NCPB(I)                                                       A2130
      READ(5,3000) ((XIDNT(K,I)),K=1,12)                                A2140
      READ(5,3002) ((TXK(J,I),XK(J,I)),J=1,LK)                          A2150
      READ(5,3002) ((TCP(J,I),CPX(J,I)),J=1,LCP)                        A2160
      WRITE(6,432) (XIDNT(K,I),K=1,12)                                  A2170
  432 FORMAT(//12A6)                                                    A2180
      WRITE(6,433)                                                      A2190
  433 FORMAT(//20X,7HTHERMAL,38X,8HSPECIFIC/3X,11HTEMPERATURE,4X,12HCOND A2200
     1UCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)                            A2210
      KLLL=MIN0(LK,LCP)                                                 A2220
      DO 434 N=1,KLLL                                                   A2230
      WRITE(6,222) (TXK(N,I),XK(N,I),TCP(N,I),CPX(N,I))                 A2240
  434 CONTINUE                                                          A2250
      IF(LK-LCP) 435,440,437                                            A2260
  435 KLLLL=KLLL+1                                                      A2270
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      DO 436 N=KLLLL,LCP                                                A2280
      WRITE(6,224) (TCP(N,I),CPX(N,I))                                  A2290
  436 CONTINUE                                                          A2300
      GO TO 440                                                         A2310
  437 KLLLL=KLLL+1                                                      A2320
      DO 438 N=KLLLL,LK                                                 A2330
      WRITE(6,226) (TXK(N,I),XK(N,I))                                   A2340
  438 CONTINUE                                                          A2350
  440 CONTINUE                                                          A2360
      READ(5,3002) (RHOBX(L),XBM(L),EMEB(L),EMBB(L),L=1,NMB)            A2370
      READ(5,3002)    (H(J),GAPX(J),FTEST(J),BTEST(J),J=1,NMB)          A2380
      WRITE(6,450)                                                      A2390
  450 FORMAT(///55X,10HEMISSIVITY/8X,8HMATERIAL,5X,7HDENSITY,7X,9HTHICKN  A2400
     1ESS,7X,5HFRONT,9X,4HBACK,7X,14HNODES/MATERIAL/)                   A2410
      DO 460 LLJ=1,NMB                                                  A2420
      WRITE(6,455) LLJ,RHOBX(LLJ),XPM(LLJ),EMEB(LLJ),EMBB(LLJ),XNPM(LLJ)  A2430
  455 FORMAT(11X,1I1,8X,1PE10.4,4X,1PE10.4,4X,1PE10.4,4X,1PE10.4,6X,1PE1  A2440
     10.4/)                                                             A2450
  460 CONTINUE                                                          A2460
      WRITE(6,465)                                                      A2470
  465 FORMAT(//4X,60HADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP  A2480
     1STRUCTURE//11X,8HMATERIAL,5X,16HFILM COEFFICIENT,5X,13HGAP THICKNE  A2490
     2SS,8X,5HFTEST,13X,5HBTEST)                                        A2500
      DO 480 J=1,NMB                                                    A2510
      WRITE(6,470) J,  H(J),GAPX(J),FTEST(J),BTEST(J)                   A2520
  470 FORMAT(13X,1I3,12X,1PE10.4,9X,1PE10.4,7X,1PE11.4,7X,1PE11.4/)     A2530
  480 CONTINUE                                                          A2540
C                                                                       A2550
C     PROPERTIES OF ENVIRONMENT                                         A2560
  500 READ(5,3000) (TITLE(L),L=1,12)                                    A2570
      IF(TITLE(1).EQ.PRVOUS) GO TO 600                                  A2580
      READ(5,3000) (HEADNG(L),L=1,12)                                   A2590
      READ(5,3002) TENV,HENV,FENV,QLOSS                                 A2600
      WRITE(6,3008) (HEADNG(L),L=1,12)                                  A2610
      WRITE(6,520) TENV,HENV,FENV,QLOSS                                 A2620
  520 FORMAT(/4X,12HTEMPERATURE=,1PE12.5,4X,17HFILM COEFFICIENT=,1PE12.5  A2630
     1,4X,12HVIEW FACTOR=,1PE12.5,4X,7HQ LOST=,1PE12.5)                 A2640
C                                                                       A2650
C     INITIAL TEMPERATURE DISTRIBUTION                                  A2660
  600 READ(5,3000) (TITLE(L),L=1,12)                                    A2670
      IF(TITLE(1).EQ.PRVOUS) GO TO 700                                  A2680
      READ(5,3000) (HEADNG(L),L=1,12)                                   A2690
      NPF=NP+NPBS                                                       A2700
      TL=VL+BL                                                          A2710
      XNP=NP                                                            A2720
      DX=VL/(XNP-1.0)                                                   A2730
      DXX=DX                                                            A2740
      READ(5,3002) TEST2,TEMPI,TX0                                      A2750
      IF(TEST2) 610,620,620                                             A2760
  610 READ(5,3002) (TEMDI(K),K=1,NPF)                                   A2770
      DO 615 K=1,NPF                                                    A2780
      TX1(K)=TEMDI(K)                                                   A2790
      TX2(K)=TX1(K)                                                     A2800
      TUL1(K)=TX1(K)                                                    A2810
      TUL2(K)=TX1(K)                                                    A2820
  615 CONTINUE                                                          A2830
      L=NP+1                                                            A2840
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      DO 619 I=1,NMB
      LN=NPM(I)
      DO 617 J=1,LN
      TX2T(J,I)=TEMDI(L)
      L=L+1
  617 CONTINUE
  619 CONTINUE
      GO TO 625
  620 CALL TEMPD
  625 WRITE(6,3008) (HEADNG(L),L=1,12)
      IF(TEST2) 630,635,640
  630 WRITE(6,632)
  632 FORMAT(4X,52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBRITARY/
     1)
      WRITE(6,633) (TEMDI(K),K=1,NPF)
  633 FORMAT(1P8E12.5)
      GO TO 645
  635 WRITE(6,637) TEMPI
  637 FORMAT(//4X,64HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM
     1AND EQUAL TO ,1PE10.4/)
      GO TO 645
  640 WRITE(6,641)
  641 FORMAT(4X,54HLINEAR TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIEL
     1D/)
      WRITE(6,633) (TEMDI(L),L=1,NPF)
  645 IF(DMP) 700,700,646
  646 WRITE(6,647)
  647 FORMAT(//)
  648 WRITE(6,649) (TX1(L),TX2(L),L=1,NPF)
  649 FORMAT(2X,1PE12.5,4X,1PE12.5)
      WRITE(6,650)
  650 FORMAT(//)
C
C     ENTHALPY AS A FUNCTION OF TEMPERATURE
  700 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 725
      READ(5,3004) NHP
      READ(5,3002) (HX(K),TW(K),K=1,NHP)
  725 DO 728 I=1,NP
      TR(I)=0
      TR1(I)=0
      TR2(I)=0
      TFM(I)=0
      XMDG(I)=0.0
  728 CONTINUE
      WRITE(6,730)
  730 FORMAT(1H1,12HOUTPUT DATA,//)
      XC(1)=0.0
      DO 740 I=2,NP
      XC(I)=XC(I-1)+DX
  740 CONTINUE
  750 IF(T-TIME(NK)) 765,770,760
  760 NK=NK+1
      IF(NK-NTRAPT) 750,750,762
  762 WRITE(6,763) NK
  763 FORMAT(1H0,33H THE VALUE OF NK IS IN ERROR, NK=,1I4)
      GO TO 905
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  765 IF(NK-2) 762,766,766                                                  A3420
  766 QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIME(NK-1)))        A3430
     1*(T-TIME(NK-1))                                                       A3440
      QCONX=FCONV*QCONX                                                     A3450
      QRADX=QRAD(NK-1)+((QRAD(NK)-QRAD(NK-1))/(TIME(NK)-TIME(NK-1)))        A3460
     1*(T-TIME(NK-1))                                                       A3470
      QRADX=FRAD*QRADX                                                      A3480
      VELX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIME(NK-1)))            A3490
     1*(T-TIME(NK-1))                                                       A3500
      GO TO 775                                                             A3510
  770 QCONX=FCONV*QCON(NK)                                                  A3520
      QRADX=FRAD*QRAD(NK)                                                   A3530
      VELX=VEL(NK)                                                          A3540
C                                                                           A3550
C     COMPUTE HEAT BLOCKAGE AT FRONT SURFACE                                A3560
  775 IF(I17-1) 778,778,776                                                 A3570
  776 IF(I17-NHP) 777,777,778                                               A3580
  777 IF(TX2(INT)-TW(I17)) 782,788,780                                      A3590
  778 WRITE(6,779) TX2(INT)                                                 A3600
  779 FORMAT(1H0,80H THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS    A3610
     1EXCEEDED AT A TEMPERATURE OF,1E10.4)                                  A3620
      GO TO 905                                                             A3630
  780 I17=I17+1                                                             A3640
      GO TO 776                                                             A3650
  782 IF(TX2(INT)-TW(I17-1)) 784,788,786                                    A3660
  784 I17=I17-1                                                             A3670
      GO TO 775                                                             A3680
  786 HW=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))                A3690
     1*(TX2(INT)-TW(I17-1))                                                 A3700
      GO TO 789                                                             A3710
  788 HW=HX(I17)                                                            A3720
  789 HTX=H300+((VELX**2)/50056.5)                                          A3730
      QBLOCK=(FBLOW*XMDG(INT)*(HTX-HW))/3600.0                              A3740
C                                                                           A3750
C     COMPUTE HEAT IN DUE TO SURFACE COMBUSTION                             A3760
      XMDO=XMDC                                                             A3770
      CALL OXIDAT(XMDO,QOXID)                                               A3780
C                                                                           A3790
C     COMPUTE Q-HOT WALL                                                    A3800
      IF(TDMP.EQ.0.) GO TO 4001                                             A3810
      IF(T.GE.TDMP) DMP=1.0                                                 A3820
 4001 Z=(HTX-HW)/(HTX-H300)                                                 A3830
      IF(Z-1.0) 790,792,793                                                 A3840
  790 IF(Z) 791,791,793                                                     A3850
  791 QHW=0.0                                                               A3860
      GO TO 1790                                                            A3870
  792 QHW=QCONX                                                             A3880
      GO TO 1790                                                            A3890
  793 QHW=Z*QCONX                                                           A3900
 1790 ZZZ=(QHW-QBLOCK)/QHW                                                  A3910
      IF(ZZZ-0.2) 1798,1798,1794                                            A3920
 1798 QBLOCK=0.8*QHW                                                        A3930
C                                                                           A3940
C     NET HEAT INTO FRONT SURFACE                                           A3950
 1794 IF(IEM(INT)) 795,795,797                                              A3960
  795 IF(TX2(INT)-TCHAR) 796,796,797                                        A3970
  796 EMX=EMV                                                               A3980
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      GO TO 798                                                         A3990
  797 IFM(INT)=1                                                        A4000
      FMX=EMC                                                           A4010
  798 QIN=QRADX+QHW+QOXID-QBLOCK-(4.8333E-13)*FMX*FV*((TX2(INT)**4)-    A4020
     1(TV**4))                                                          A4030
      IF(DMP) 804,804,800                                               A4040
  800 WRITE(6,801)                                                      A4050
  801 FORMAT(///)                                                       A4060
      WRITE(6,802) QCONX,QRADX,VELX,HTX,HW,Z,QBLOCK,QHW,QOXID,QIN       A4070
  802 FORMAT(1X,6HQCONX=,1PE12.5,2X,6HQRADX=,1PE12.5,2X,5HVELX=,1PE12.5, A4080
     12X,4HHTX=,1PE12.5,2X,3HHW=,1PE12.5/1X,2HZ=,1PE12.5,2X,7HQBLOCK=,1P A4090
     2E12.5,2X,4HQHW=,1PE12.5,2X,6HQOXID=,1PE12.5,2X,4HQIN=,1PE12.5/)   A4100
  804 QIN=QIN*3600.0                                                    A4110
C                                                                       A4120
C     CHECK FOR FRONT SURFACE RECESSION (CHAR LAYER REMOVAL)            A4130
      CALL RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2(1),NREC,NRS,ERR5,SX0 A4140
     1,SDOT,DMP)                                                        A4150
      IF(ERR5) 8050,8050,905                                            A4160
 8050 VLV=VLV-XLOST                                                     A4170
      XLSTV=XLSTV+XLOST                                                 A4180
      XLSTI=XLSTV*12.0                                                  A4190
      DXV=VLV/(XNP-1.0)                                                 A4200
      XV(1)=0.0                                                         A4210
      DO 1780 I=2,NP                                                    A4220
      XV(I)=XV(I-1)+DXV                                                 A4230
 1780 CONTINUE                                                          A4240
      DX=DXV                                                            A4250
      IF(ERR4) 806,806,805                                              A4260
  805 GO TO 905                                                         A4270
  806 CALL COEFF(NPFT,SDOT)                                             A4280
      IF(DMP) 8069,8069,8061                                            A4290
 8061 WRITE(6,8062)                                                     A4300
 8062 FORMAT(/1X,23H COEFFICIENTS FOR SWUFT/)                           A4310
      DO 8066 I=1,NPFT                                                  A4320
      WRITE(6,8064)  A(I),B(I),C(I),D(I),I                              A4330
 8064 FORMAT(1H0,5HA(I)=,1PE12.5,2X,5HB(I)=,1PE12.5,2X,5HC(I)=,1PE12.5,2 A4340
     1X,5HD(I)=,1PE12.5,2X,2HI=,I3)                                     A4350
 8066 CONTINUE                                                          A4360
 8069 IF(ERR2) 807,807,805                                              A4370
  807 IF(ERR3) 810,810,808                                              A4380
  808 WRITE(6,809) IKK                                                  A4390
  809 FORMAT(1H0,18H THE VALUE OF IKK=,1I4)                             A4400
      GO TO 905                                                         A4410
  810 CALL SWUFT(A,B,C,D,TY,NPFT,DMP)                                   A4420
  827 DO 828 I=1,NP                                                     A4430
      TX1(I)=TX2(I)                                                     A4440
      TX2(I)=TY(I)                                                      A4450
  828 CONTINUE                                                          A4460
      CALL DON2(XLOST,XV,TX2,NP,XC,TX2C,XDV,KKV,XLSTV,DXX)              A4470
  830 CALL ABLATE                                                       A4480
      XMDT=XMDG(INT)+XMDC                                               A4490
      LT=NP+1                                                           A4500
      DO 1815 I=1,NMB                                                   A4510
      LLT=NPM(I)                                                        A4520
      IF(I.EQ.1) GO TO 1812                                             A4530
      IF(GAPX(I-1).EQ.0.) GO TO 1812                                    A4540
      KKT=1                                                             A4550
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      GO TO 1813                                                        A4560
 1812 KKT=2                                                             A4570
 1813 DO 1815 J=KKT,LLT                                                 A4580
      TX2T(J,I)=TY(LT)                                                  A4590
      LT=LT+1                                                           A4600
 1815 CONTINUE                                                          A4610
      DO 1819 I=1,NMB                                                   A4620
      IF(I.EQ.1) GO TO 1816                                             A4630
      IF(GAPX(I-1).EQ.0.) GO TO 1817                                    A4640
      GO TO 1819                                                        A4650
 1816 TX2T(1,1)=TY(NP)                                                  A4660
      GO TO 1819                                                        A4670
 1817 LX=NPM(I-1)                                                       A4680
      TX2T(1,I)=TX2T(LX,I-1)                                            A4690
 1819 CONTINUE                                                          A4700
      LM=NP+1                                                           A4710
      DO 833 I=1,NMB                                                    A4720
      LZ=NPM(I)                                                         A4730
      DO 833 J=1,LZ                                                     A4740
      TX2(LM)=TX2T(J,I)                                                 A4750
      LM=LM+1                                                           A4760
  833 CONTINUE                                                          A4770
      DO 5834 I=2,NPTT                                                  A4780
      IF(T-TTABLE(I)) 5835,5835,5834                                    A4790
 5835 DTS=DELTT(I-1)                                                    A4800
      IPRCT=IPRC(I-1)                                                   A4810
      DT=DELTT(I-1)/3600.0                                              A4820
      GO TO 5836                                                        A4830
 5834 CONTINUE                                                          A4840
      DTS=DELTT(NPTT)                                                   A4850
      IPRCT=IPRC(NPTT)                                                  A4860
      DT=DELTT(NPTT)/3600.0                                             A4870
 5836 ICT=ICT+1                                                         A4880
 5838 VLTEM=SAVY3                                                       A4890
      CALL ISOTHM(XV,TX2,1060. ,NP,SAVEIT)                              A4900
      SAVEIT=SAVEIT+XLSTV                                               A4910
      IF(SAVY3.LT.SAVEIT)SAVY3=SAVEIT                                   A4920
      IF(VLTEM.EQ.SAVY3)GO TO 839                                       A4930
      SAVX=T                                                            A4940
      SAVY1=XLSTI                                                       A4950
      SAVY2=TX2(NP)                                                     A4960
      CALL ISOTHM(XV,TX2,1460.,NP,SAVY4)                                A4970
  839 BLTEM=SAVY4X                                                      A4980
      CALL ISOTHM(XV,TX2,1460.,NP,WEKEEP)                               A4990
      WEKEEP=WEKEEP+XLSTV                                               A5000
      IF(SAVY4X.LT.WEKEEP)SAVY4X=WEKEEP                                 A5010
      IF(BLTEM.EQ.SAVY4X)GO TO 838                                      A5020
      SAVEXX=T                                                          A5030
      SAVY1X=XLSTI                                                      A5040
      SAVY2X=TX2(NP)                                                    A5050
      CALL ISOTHM(XV,TX2,1060.,NP,SAVY3X)                               A5060
  838 CONTINUE                                                          A5070
      IF(IPRCT-ICT) 835,835,840                                         A5080
  835 WRITE(6,837) T,QCONX,QRADX,VELX,XMDG(INT),XMDC,XMDT,XLSTI,QHW     A5090
  837 FORMAT(1H0,5HTIME=,                                               A5100
     1                    1PE12.5,2X,12HQCONVECTIVE=,1PE12.5,2X,11HQRADIAT  A5110
     1IVE=,1PE12.5,2X,9HVELOCITY=,1PE12.5/1X,18HGAS ABLATION RATE=,1PE12  A5120
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```
     2.5,2X,19HCHAR ABLATION RATE=,1PE12.5,2X,20HTOTAL ABLATION RATE=,1P  A5130
     3F12.5/1X,16HRECESSION DEPTH=,1PE12.5,2X,10HQHOT WALL=,1PE12.5)      A5140
  840 T=T+DTS                                                             A5150
  841 IF(NPLOT.NE.1) GO TO 842                                            A5160
      CALL SAVE(ASAVE1,ASAVE2,ASAVE3,USEA,NXA,XLSTI,DTS,TLIM,T,VALUEA)    A5170
      CALL SAVE(BSAVE1,BSAVE2,BSAVE3,USEB,NXB,TX2(NP),DTS,TLIM,T,VALUEB)  A5180
      CALL ISOTHM(XV,TX2,1060.,NP,Y3)                                     A5190
      CALL SAVE(CSAVE1,CSAVE2,CSAVE3,USEC,NXC,Y3,DTS,TLIM,T,VALUEC)       A5200
      CALL ISOTHM(XV,TX2,1460.,NP,Y4)                                     A5210
      CALL SAVE(DSAVE1,DSAVE2,DSAVE3,USED,NXD,Y4,DTS,TLIM,T,VALUED)       A5220
      IF(USEA.NE.0.0)GO TO 9842                                           A5230
      IF(USEB.NE.0.0)GO TO 9842                                           A5240
      IF(USEC.NE.0.0)GO TO 9842                                           A5250
      IF(USED.NE.0.0)GO TO 9842                                           A5260
      GO TO 9843                                                          A5270
 9842 XPLOT=T-DTS                                                         A5280
      YPLOT1=VALUEA                                                       A5290
      IF(USEA.NE.0.0)YPLOT1=USEA                                          A5300
      YPLOT2=VALUEB                                                       A5310
      IF(USEB.NE.0.0)YPLOT2=USEB                                          A5320
      YPLOT3=VALUEC                                                       A5330
      IF(USEC.NE.0.0)YPLOT3=USEC                                          A5340
      YPLOT4=VALUED                                                       A5350
      IF(USED.NE.0.0)YPLOT4=USED                                          A5360
      WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4                         A5370
 9843 IF(ICTP.NE.0) GO TO 842                                             A5380
      ICTP=1                                                              A5390
      XPLOT=T                                                             A5400
      YPLOT1=XLSTI                                                        A5410
      YPLOT2=TX2(NP)                                                      A5420
      CALL ISOTHM(XV,TX2,1060.,NP,YPLOT3)                                 A5430
      CALL ISOTHM(XV,TX2,1460.,NP,YPLOT4)                                 A5440
      WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4                         A5450
  842 IF(IPRCT-ICT) 845,845,900                                           A5460
  845 WRITE(6,850) T                                                      A5470
      IPCT=IPCT+1                                                         A5480
      IF(IPCT.EQ.2)IPCT=0                                                 A5490
      IF(IPCT.EQ.0)ICTP=0                                                 A5500
  850 FORMAT(1H0,72HTEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END O  A5510
     1F THE TIME STEP, T= ,1PE12.5,1X,7HSECONDS//)                        A5520
      WRITE(6,860)                                                        A5530
  860 FORMAT(4X,49HTEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL//)   A5540
      KKV=KKV+1                                                           A5550
      WRITE(6,862) (TX2C(I),I=1,KKV)                                      A5560
  862 FORMAT(6X,1PE12.5,1P5F16.5)                                         A5570
      IJ=NP+1                                                             A5580
      WRITE(6,864)                                                        A5590
  864 FORMAT(//4X,49HTEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE//  A5600
     1)                                                                   A5610
      WRITE(6,862) (TX2(I),I=IJ,NPF)                                      A5620
      WRITE(6,865)                                                        A5630
  865 FORMAT(//)                                                          A5640
      ICT=0                                                               A5650
  900 CONTINUE                                                            A5660
      IF(T-TLIM) 750,750,905                                              A5670
  905 IF(NPLOT.NE.1) GO TO 909                                            A5680
      XAVY3=SAVY3-SAVY1/12.                                               A5690
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```
      XAVY4X=SAVY4X-SAVY1X/12.                                          A5700
      IF(SAVX.EQ.XPLOT)GO TO 9005                                       A5710
      WRITE(11)SAVX,SAVY1,SAVY2,XAVY3,SAVY4                             A5720
 9005 IF(SAVEXX.EQ.XPLOT)GO TO 9006                                     A5730
      SAV4I=SAVY4X*12.                                                  A5760
 9006 SAV3I=SAVY3*12.                                                   A5750
      WRITE(11)SAVEXX,SAVY1X,SAVY2X,SAVY3X,XAVY4X                       A5740
      WRITE(6,929)SAV3I,SAV4I                                           A5770
  929 FORMAT(1H0,23HMAXIMUM 1060 ISOTHERM =E16.8,2X23HMAXIMUM 1460 ISOTH A5780
     1ERM =E16.8)                                                       A5790
      WRITE (11)STOP,STOP,STOP,STOP,STOP                                A5800
  909 IF(LPLOT.NE.NCASE)GO TO 911                                       A5810
      DATA END/6H  END /                                                A5820
      WRITE(11)END,END,END,END,END,END,END,END,END,END,END,END          A5830
      QUIT=8888.                                                        A5840
      WRITE(11)QUIT,QUIT,QUIT,QUIT,QUIT                                 A5850
      END FILE 11                                                       A5860
      REWIND 11                                                         A5870
  911 IF(TEST2) 910,930,930                                             A5880
  910 DO 920 JJK=1,NPF                                                  A5890
      TX1(JJK)=TEMDI(JJK)                                               A5900
      TX2(JJK)=TX1(JJK)                                                 A5910
      TUL1(K)=TX1(K)                                                    A5920
      TUL2(K)=TX1(K)                                                    A5930
  920 CONTINUE                                                          A5940
      IL=NP+1                                                           A5950
      DO 926 I=1,NMB                                                    A5960
      ILN=NPM(I)                                                        A5970
      DO 924 J=1,ILN                                                    A5980
      TX2T(J,I)=TEMDI(IL)                                               A5990
      IL=IL+1                                                           A6000
  924 CONTINUE                                                          A6010
  926 CONTINUE                                                          A6020
      GO TO 940                                                         A6030
  930 CALL TEMPD                                                        A6040
  940 T=TINT                                                            A6050
      DX=DXX                                                            A6060
      DTS=DELTT(1)                                                      A6070
      DT=DELTT(1)/3600.0                                                A6080
      VLV=VL                                                            A6090
      GO TO 50                                                          A6100
      END                                                               A6110
```

```
$IBFTC COEF
C     THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX
      SUBROUTINE COEFF(NPFT,SDOT)
C
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
     1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,EMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
      CALL PROP
      YNP=NP
      S(INT)=(RHO(INT)*DX*CP(INT))/(2.0*DT)
      R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT))+(1.0/YK(INT+1))))
      A(INT)=0.0
      B(INT)=(-((XMDG(INT)+XMDC)*CP(INT)+S(INT)+R(INT)-RHO(INT)*CP(INT)
     1*(SDOT/(2.0*(YNP-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)=(-(QIN+S(INT)*TX2(INT))) +(XMDG(INT)-XMDG(INT+1))*HV
      NPP=NP-1
      JNT=INT+1
      DO 10 I=JNT,NPP
      XI=I
      S(I)=(RHO(I)*DX*CP(I))/DT
      R(I)=(1.0)/((DX/(2.0*YK(I)))+(DX/(2.0*YK(I+1))))
      A(I)=R(I-1)
      B(I)=(-(XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+ RHO(I)*CP(I)*SDOT*((YNP-XI
     1-0.5)/(YNP-1.0))))
      C(I)=XMDG(I+1)*CP(I+1)+R(I)+RHO(I+1)*CP(I+1)*SDOT*((YNP-XI-0.5)
     1/(YNP-1.0))
      D(I)=(-(S(I)*TX2(I))) +(XMDG(I)-XMDG(I+1))*HV
   10 CONTINUE
      R(NP)=(1.0)/((DXB(1)   /(2.0*XKB(1,1)))+(DXB(1)   /(2.0*XKB(2,1))))
      S(NP)=(RHO(NP)*DX*CP(NP)+RHOBX(1)* CPB(1,1)*DXB(1))/(2.0*DT)
      A(NP)=R(NP-1)
      B(NP)=(-(XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP)))
      C(NP)=R(NP)
      D(NP)=(-S(NP)*TX2(NP)) +XMDG(NP)*HV
      DO 200 I=1,NMB
      IF(I-1) 20,20,30
   20 AB(1,I)=A(NP)
      BB(1,I)=B(NP)
      CB(1,I)=C(NP)
      DB(1,I)=D(NP)
```

```
      GO TO 65                                                           B0600
   30 L=NPM(I-1)                                                         B0610
      IF(FTEST(I)) 45,40,45                                              B0620
   40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/ B0630
     1(2.0*DT)                                                           B0640
      RB1(1,I)=(1.0)/((DXB(I-1)/(2.0*XKB(L,I-1)))+(DXB(I-1)/(2.0*XKB(L-1 B0650
     1,I-1))))                                                           B0660
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))   B0670
      AB(1,I)=RB1(1,I)                                                   B0680
      BB(1,I)=(-(RB1(1,I)+RB2(1,I)+SB(1,I)))                             B0690
      CB(1,I)=RB2(1,I)                                                   B0700
      DB(1,I)=(-(SB(1,I)*TX2T(1,I)))                                     B0710
      GO TO 65                                                           B0720
   45 IF(FTEST(I)) 50,40,55                                              B0730
   50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I)-1.0)                       B0740
      GO TO 60                                                           B0750
   55 G=0.0                                                              B0760
   60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I))/(2.0*DT)                        B0770
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))   B0780
      AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1)**3)                              B0790
      BB(1,I)=(-(H(I-1)+4.0*G*(TX2T(1,I   )**3)+RB2(1,I)+SB(1,I)))       B0800
      CB(1,I)=RB2(1,I)                                                   B0810
      DB(1,I)=3.0*G*((TX2T(L,I-1)**4)-(TX2T(1,I)**4))-SB(1,I)*TX2T(1,I)  B0820
   65 LF=NPM(I)-1                                                        B0830
      DO 100 J=2,LF                                                      B0840
      SB(J,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT                              B0850
      RB1(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J-1,I)))+(DXB(I)/(2.0*XKB(J,I)))) B0860
      RB2(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J+1,I)))+(DXB(I)/(2.0*XKB(J,I)))) B0870
      AB(J,I)=RB1(J,I)                                                   B0880
      BB(J,I)=(-(RB1(J,I)+RB2(J,I)+SB(J,I)))                             B0890
      CB(J,I)=RB2(J,I)                                                   B0900
      DB(J,I)=(-(SB(J,I)*TX2T(J,I)))                                     B0910
  100 CONTINUE                                                           B0920
      IF(I-NMB) 110,250,250                                              B0930
  110 LNF=NPM(I)                                                         B0940
      IF(BTEST(I)) 120,115,120                                           B0950
  115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(1,I+1)*DXB(I+ B0960
     11))/(2.0*DT)                                                       B0970
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF B0980
     1,I))))                                                             B0990
      RB2(LNF,I)=(1.0)/((DXB(I+1)/(2.0*XKB(1,I+1)))+(DXB(I+1)/           B1000
     1(2.0*XKB(2,I+1))))                                                 B1010
      AB(LNF,I)=RB1(LNF,I)                                               B1020
      BB(LNF,I)=(-(RB1(LNF,I)+RB2(LNF,I)+SB(LNF,I)))                     B1030
      CB(LNF,I)=RB2(LNF,I)                                               B1040
      DB(LNF,I)=(-(SB(LNF,I)*TX2T(LNF,I)))                               B1050
      GO TO 200                                                          B1060
  120 IF(BTEST(I)) 125,115,127                                           B1070
  125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1)-1.0)                       B1080
      GO TO 130                                                          B1090
  127 G=0.0                                                              B1100
  130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0*DT)                    B1110
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF B1120
     1,I))))                                                             B1130
      AB(LNF,I)=RB1(LNF,I)                                               B1140
      BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3)))    B1150
      CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I+1)**3)                              B1160
      DB(LNF,I)=3.0*G*((TX2T(1,I+1)**4)-(TX2T(LNF,I)**4))-SB(LNF,I)*TX2T B1170
     1(LNF,I)                                                            B1180
  200 CONTINUE                                                           B1190
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```
  250 MN=NPM(NMB)
      IF(QLOSS) 270,260,270
  260 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
      RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*XK
     1B(MN,NMB))))
      AB(MN,NMB)=RB1(MN,NMB)
      BB(MN,NMB)=(-(RB1(MN,NMB)+SB(MN,NMB)))
      CB(MN,NMB)=0.0
      DB(MN,NMB)=(-(SB(MN,NMB)*TX2T(MN,NMB)))
      GO TO 280
  270 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
      RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*X
     1KB(MN,NMB))))
      AB(MN,NMB)=RB1(MN,NMB)
      BB(MN,NMB)=(-(RB1(MN,NMB)+HENV+(1.73E-09)*FENV*4.0*(TX2T(MN,NMB)**
     13)+SB(MN,NMB)))
      CB(MN,NMB)=0.0
      DB(MN,NMB)=(-(HENV*TENV+FENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM
     1B)**4))+SB(MN,NMB)*TX2T(MN,NMB)))
  280 L=NP+1
      DO 300 I=1,NMB
      K=NPM(I)
      IF(I.EQ.1) GO TO 282
      IF(GAPX(I-1).EQ.0.) GO TO 282
      KT=1
      GO TO 285
  282 KT=2
  285 DO 290 J=KT,K
      A(L)=AB(J,I)
      B(L)=BB(J,I)
      C(L)=CB(J,I)
      D(L)=DB(J,I)
      IF(DMP) 289,289,286
  286 WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(
     1L),L
  287 FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,
     11PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,2HJ=,I3,2X,2HI=,I3/1X,5HA(L)=,1PE
     212.5,2X,5HB(L)=,1PE12.5,2X,5HC(L)=,1PE12.5,2X,5HD(L)=,1PE12.5,2X,2
     3HL=,I3)
  289 L=L+1
  290 CONTINUE
  300 CONTINUE
      NPFT=L-1
      RETURN
      END
```

```
$IBFTC PRP
C      THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE
C        HEAT SHIELD STRUCTURE
       SUBROUTINE PROP
C
       DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
      2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMEB(12),EMBB(12),HXX(12)
      4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
      6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
      7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
      8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
      9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
       DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
       COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
      1EMEB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
      3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
      4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
      5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,EENV,QLOSS,TLIM,TINT
       COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
      1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
       KINT=INT
       DO 170 I=KINT,NP
    10 IF(IR(I)) 12,12,100
    12 TUL(I)=AMAX1(TX1(I),TX2(I))
       IF(TUL(I).LE.TABL) GO TO 20
       IR(I)=1
       GO TO 100
    20 IF(I1-1  25,2 ,21
    21 IF(I1-NKV) 22,22,25
    22 IF(TX2(I)-TKV(I1)) 35,55,30
    25 WRITE(6,26) TX2(I)
    26 FORMAT(1H0,87H THE RANGE OF ONE OF THE ABLATION PROPERTY CURVE FIT
      1S WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5)
       ERR2=1.0
       GO TO 355
    30 I1=I1+1
       GO TO 21
    35 IF(TX2(I)-TKV(I1-1)) 40,55,50
    40 I1=I1-1
       GO TO 20
    50 YK(I)=XKV(I1-1)+((XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1)))
      1*(TX2(I)-TKV(I1-1))
       GO TO 60
    55 YK(I)=XKV(I1)
    60 IF(I2-1) 25,25,61
    61 IF(I2-NCPV) 62,62,25
    62 IF(TX2(I)-TCPV(I2)) 70,85,65
    65 I2=I2+1
       GO TO 61
    70 IF(TX2(I)-TCPV(I2-1)) 75,85,80
    75 I2=I2-1
```

```
      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
  110 RHO(I)=RHOV+(RHOV-RHOC)*((TUL(I)-TABL)/(TABL-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-NKC) 122,122,25
  122 IF(TTUL(I)-TKC(I3)) 124,135,123
  123 I3=I3+1
      GO TO 121
  124 IF(TTUL(I)-TKC(I3-1)) 125,135,130
  125 I3=I3-1
      GO TO 120
  130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))
     1*(TTUL(I)-TKC(I3-1))
      GO TO 140
  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 141
  150 IF(TTUL(I)-TCPC(I4-1)) 155,165,160
  155 I4=I4-1
      GO TO 140
  160 CP(I)=CPC(I4-1)+((CPC(I4)-CPC(I4-1))/(TCPC(I4)-TCPC(I4-1)))
     1*(TTUL(I)-TCPC(I4-1))
      GO TO 166
  165 CP(I)=CPC(I4)
  166 RHO(I)=RHOC
  170 CONTINUE
C
C     DETERMINATION OF PROPER BACK-UP SHIELD MATERIAL PROPERTY
C
      DO 300 I=1,NMB
      DXB(I)=XBM(I)/((XNPM(I)-1.0)*12.0)
      LKP=NKPB(I)
      LCP=NCPB(I)
      NN=NPM(I)
      DO 280 J=1,NN
  200 IF(I5-1) 203,203,201
  201 IF(I5-LKP) 202,202,203
  202 IF(TX2T(J,I)-TXK(I5,I)) 206,220,205
  203 WRITE(6,204) I,TX2T(J,I)
  204 FORMAT(1H0,32H THE RANGE OF ONE OF THE NUMBER ,I2,71H BACKUP STRUC
```

```
     1TURE PROPERTY CURVE FITS WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5
     2)
      ERR2=1.0
      GO TO 355
  205 I5=I5+1
      GO TO 201
  206 IF(TX2T(J,I)-TXK(I5-1,I)) 210,220,215
  210 I5=I5-1
      GO TO 200
  215 XKB(J,I)=XK(I5-1,I)+((XK(I5,I)-XK(I5-1,I))/(TXK(I5,I)-TXK(I5-1,I))
     1)*(TX2T(J,I)-TXK(I5-1,I))
      GO TO 230
  220 XKB(J,I)=XK(I5,I)
  230 IF(I6-1) 203,203,231
  231 IF(I6-LCP) 232,232,203
  232 IF(TX2T(J,I)-TCP(I6,I)) 234,245,233
  233 I6=I6+1
      GO TO 231
  234 IF(TX2T(J,I)-TCP(I6-1,I)) 235,245,240
  235 I6=I6-1
      GO TO 230
  240 CPB(J,I)=CPX(I6-1,I)+((CPX(I6,I)-CPX(I6-1,I))/(TCP(I6,I)-TCP(I6-1,
     1I)))*(TX2T(J,I)-TCP(I6-1,I))
      GO TO 280
  245 CPB(J,I)=CPX(I6,I)
  280 CONTINUE
      I5=2
      I6=2
  300 CONTINUE
  310 IF(DMP) 355,355,320
  320 WRITE(6,330)
  330 FORMAT(/1X,32H PROPERTIES OF ABLATION MATERIAL/)
      WRITE(6,335)
  335 FORMAT(/5X,5HYK(I),9X,5HCP(I),9X,6HRHO(I)/)
      WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,NP)
  340 FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
      WRITE(6,345)
  345 FORMAT(//1X,32H PROPERTIES OF BACK-UP STRUCTURE/)
      WRITE(6,347)
  347 FORMAT(/5X,8HYKB(J,I),7X,8HCPB(J,I),7X,8HRHOBX(I),7X,7HEMEB(I),8X,
     17HEMBB(I),9X,6HDXB(I)/)
      DO 350 I=1,NMB
      KL=NPM(I)
      DO 349 J=1,KL
      WRITE(6,348) XKB(J,I),CPB(J,I),RHOBX(I),EMEB(I),EMBB(I),DXB(I)
  348 FORMAT(3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1
     1PE12.5)
  349 CONTINUE
  350 CONTINUE
  355 RETURN
      END
```

```
$IBFTC ABL
C     THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE
C        ABLATING NODES
      SUBROUTINE ABLATE
C
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXP(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
     1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
      XMT=0.0
      LINT=INT
      KI=NP
      IF(DMP) 8,8,3
    3 WRITE(6,5)
    5 FORMAT(//1X,29HMASS FLOW FROM ABLATING NODES//)
    8 DO 200 KKI=LINT,NP
      IF(IR1(KI)) 11,11,12
   11 IF(TX1(KI).LE.TABL) GO TO 9
   12 TUL1(KI)=AMAX1(TUL1(KI),TX1(KI))
      IR1(KI)=1
      GO TO 20
    9 IF(TX1(KI)-TABL) 10,10,20
   10 RHOY1(KI)=RHOV
      GO TO 50
   20 IF(TUL1(KI)-TCHAR) 40,30,30
   30 RHOY1(KI)=RHOC
      GO TO 50
   40 RHOY1(KI)=RHOV+(RHOV-RHOC)*((TUL1(KI)-TABL)/(TABL-TCHAR))
   50 IF(IR2(KI)) 52,52,54
   52 IF(TX2(KI).LE.TABL) GO TO 56
   54 TUL2(KI)=AMAX1(TUL2(KI),TX2(KI))
      IR2(KI)=1
      GO TO 70
   56 IF(TX2(KI)-TABL) 60,60,70
   60 RHOY2(KI)=RHOV
      GO TO 95
   70 IF(TUL2(KI)-TCHAR) 90,80,80
   80 RHOY2(KI)=RHOC
      GO TO 95
   90 RHOY2(KI)=RHOV+(RHOV-RHOC)*((TUL2(KI)-TABL)/(TABL-TCHAR))
```

```
   95 DRHO(KI)=((RHOY1(KI)-RHOY2(KI))/DT)*DX                           D0570
      IF(KI-NP) 97,96,96                                               D0580
   96 DRHO(KI)=DRHO(KI)/2.0                                            D0590
      GO TO 98                                                         D0600
   97 IF(KI-INT) 96,96,98                                              D0610
   98 IF(DRHO(KI)) 110,120,120                                         D0620
  110 DRHO(KI)=0.0                                                     D0630
  120 XMT=XMT+DRHO(KI)                                                 D0640
      XMDG(KI)=XMT                                                     D0650
      IF(DMP) 190,190,150                                              D0660
  150 WRITE(6,160) XMDG(KI),DRHO(KI),RHOY2(KI),RHOY1(KI)               D0670
  160 FORMAT(1X,5HXMDG=,1PE12.5,2X,5HDRHO=,1PE12.5,2X,6HRHOY2=,1PE12.5,2 D0680
     1X,6HRHOY1=,1PE12.5)                                              D0690
  190 KI=KI-1                                                          D0700
  200 CONTINUE                                                         D0710
      RETURN                                                           D0720
      END                                                              D0730
```

```
$IBFTC OXID                                                             F0000
C                                                                       F0010
C     THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION     F0020
C     IT IS ASSUMED THAT OXYGEN AND CARBON REACT  TO FORM CO ONLY.      F0030
C                                                                       F0040
      SUBROUTINE OXIDAT(XMDO,QOXID)                                     F0050
C                                                                       F0060
      QOXID=XMDO*4000.0/3600.0                                          F0070
      QOXID=0.0                                                         F0080
      RETURN                                                            F0090
      END                                                               F0100
```

```
$IBFTC SWUFT
C      THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES
C      BY SOLVING THE TRI-DIAGONAL MATRIX
       SUBROUTINE SWUFT(A,B,C,D,T,N,DMP)
       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)-A(I)*DP(I-1))/(B(I)-A(I)*CP(I-1))
  100  CONTINUE
       T(N)=DP(N)
       NM1=N-1
       DO 200 J=1,NM1
       I=N-J
       T(I)=DP(I)-CP(I)*T(I+1)
  200  CONTINUE
       IF(DMP) 300,300,250
  250  WRITE(6,260)
  260  FORMAT(//1X,43HCOEFFICIENTS CALCULATED BY SUBROUTINE SWUFT//)
       WRITE(6,270)
  270  FORMAT(6X,5HCP(I),10X,5HDP(I),10X,4HT(I)/)
       WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)
  275  FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
  300  RETURN
       END
```

```
$IBFTC REC
C
C      THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS
C      REMOVAL RATE
C
      SUBROUTINE RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2,NREC,NRS,ERRS,
     1SX0,SDOT,DMP)
C
      DIMENSION TS(50),SR(50)
      IF(TX2-TREC) 10,20,20
   10 XMDC=0.0
      XLOST=0.0
      SDOT=0.0
      GO TO 60
   20 IF(NRS-1)25,25,21
   21 IF(NRS-NREC) 22,22,25
   22 IF(TX2-TS(NRS)) 32,40,30
   25 WRITE(6,26) TX2
   26 FORMAT(1H0,75H THE RANGE OF THE SURFACE RECESSION TABLE WAS EXCEED
     1ED AT A TEMPERATURE OF ,1PE12.5)
      ERRS=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*SX*DT
      XMDC=(XLOST*RHOC)/DT
      SDOT=SX*300.0
      IF(DMP) 60,60,52
   52 WRITE(6,54) SX,XLOST,XMDC
   54 FORMAT(1H0,3HSX=,1PE12.5,3X,6HXLOST=,1PE12.5,3X,5HXMDC=,1PE12.5)
   60 RETURN
      END
```

```
$IBFTC TEMP                                                             H0000
C     THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION   H0010
C     IN THE HEAT SHIELD STRUCTURE                                      H0020
      SUBROUTINE TEMPD                                                  H0030
C                                                                       H0040
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),      H0050
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),     H0060
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)H0070
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)H0080
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),       H0090
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),     H0100
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),      H0110
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),      H0120
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),         H0130
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)                         H0140
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)          H0150
C                                                                       H0160
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,     H0170
     1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,     H0180
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,     H0190
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,       H0200
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,   H0210
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT    H0220
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,   H0230
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H                     H0240
C                                                                       H0250
      X=0.0                                                             H0260
      IF(TEST2) 300,100,200                                             H0270
  100 DO 150 L=1,NPF                                                    H0280
      TX1(L)=TEMPI                                                      H0290
      TX2(L)=TEMPI                                                      H0300
      TUL1(L)=TX1(L)                                                    H0310
      TUL2(L)=TX2(L)                                                    H0320
      TEMDI(L)=TEMPI                                                    H0330
  150 CONTINUE                                                          H0340
      DO 160 I=1,NMB                                                    H0350
      JN=NPM(I)                                                         H0360
      DO 155 M=1,JN                                                     H0370
      TX2T(M,I)=TEMPI                                                   H0380
  155 CONTINUE                                                          H0390
  160 CONTINUE                                                          H0400
      GO TO 320                                                         H0410
  200 DO 220 L=1,NP                                                     H0420
      TEMDI(L)=TX0+((TENV-TX0)/TL)**X                                   H0430
      TX1(L)=TEMDI(L)                                                   H0440
      TX2(L)=TX1(L)                                                     H0450
      TUL1(L)=TX1(L)                                                    H0460
      TUL2(L)=TX1(L)                                                    H0470
      X=X+DX                                                            H0480
  220 CONTINUE                                                          H0490
      L=NP+1                                                            H0500
      DO 270 I=1,NMB                                                    H0510
      KJ=NPM(I)                                                         H0520
      DO 250 J=1,KJ                                                     H0530
      TEMDI(L)=TX0+((TENV-TX0)/TL)**X                                   H0540
      TX1(L)=TEMDI(L)                                                   H0550
      TX2(L)=TEMDI(L)                                                   H0560
```

```
      TX2T(J,I)=TEMPI(L)
      X=X+DXB(I)
      L=L+1
  250 CONTINUE
      X=X+(GAPX(I)/12.0)
  270 CONTINUE
      GO TO 320
C     AN ARBRITARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT
C      DATA IF TEST2 IS A NEGATIVE NUMBER
  300 WRITE(6,310)
  310 FORMAT(1H0,79H THE VALUE OF TEST2 WAS NEGATIVE, SUBROUTINE TEMPD S
     1HOULD NOT HAVE BEEN CALLED.)
      ERR1=1.0
  320 RETURN
      END
```

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

```
$IBFTC UINTRP                                                           J0000
      SUBROUTINE UINTRP(X,XTBL,Y,YTBL,N,J)                              J0010
      DIMENSION XTBL(50),YTBL(50)                                       J0020
      I=J                                                               J0030
      IF(I.GT.N.OR.I.LT.2) I=2                                          J0040
   10 IF(XTBL(I-1).LE.X.AND.X.LE.XTBL(I)) GO TO 40                      J0050
      IF(X.GT.XTBL(I)) GO TO 30                                         J0060
   20 I=I-1                                                             J0070
      IF(I.GE.2) GO TO 10                                               J0080
      I=2                                                               J0090
      GO TO 40                                                          J0100
   30 I=I+1                                                             J0110
      IF(I.LE.N) GO TO 10                                               J0120
      I=N                                                               J0130
   40 FRACT=(X-XTBL(I-1))/(XTBL(I)-XTBL(I-1))                           J0140
      Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT                             J0150
      RETURN                                                            J0160
      END                                                               J0170
```

```
$IBFTC ISOT
      SUBROUTINE ISOTHM(DEPTH,TEMP,BOND,N,ANS)
      DIMENSION DEPTH(1),TEMP(1)
      ANS=-1.
      K=N-1
      DO 100 I=1,K
      IF(TEMP(I)-BOND)2,1,3
    1 ANS=DEPTH(I)
      GO TO 100
    2 IF(TEMP(I+1)-BOND)100,100,4
    4 ANS=DEPTH(I+1)-(TEMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I+1)-
     1TEMP(I))
      GO TO 100
    3 IF(TEMP(I+1)-BOND)5,100,100
    5 ANS=(TEMP(I)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I)-TEMP(I+1))+DEPTH
     1(I)
  100 CONTINUE
      IF(BOND.EQ.TEMP(N))ANS=DEPTH(N)
      RETURN
      END
```

```
$IBFTC SAVE
      SUBROUTINE SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,DT,TFINAL,TIME,
     1THING)
      DIMENSION SAVE1(1),SAVE2(1),SAVE3(1)
      USE=0.0
      SAVE1(NX1)=VALUE
      NX2=NX1-1
      IF(NX2.EQ.0)NX2=3
      SAVE2(NX2)=VALUE
      NX3=NX2-1
      IF(NX3.EQ.0)NX3=3
      SAVE3(NX3)=VALUE
      IF((TIME.LT.(2.*DT)).OR.(TIME.GE.(TFINAL-3.*DT)))GO TO 4
      GO TO (1,2,3),NX1
    1 IF(((ABS(SAVE2(1)-SAVE2(2))).LE..001).OR.(ABS(SAVE2(2)-SAVE2(3))
     1.LE..001))GO TO 5
      IF(((SAVE2(1).LT.SAVE2(2)).AND.(SAVE2(2).GT.SAVE2(3))).OR.((SAVE2(
     11).GT.SAVE2(2)).AND.(SAVE2(2).LT.SAVE2(3))))USE=SAVE2(2)
    5 THING=SAVE2(2)
      GO TO 4
    2 IF(((ABS(SAVE3(1)-SAVE3(2))).LE..001).OR.(ABS(SAVE3(2)-SAVE3(3))
     1.LE..001))GO TO 6
      IF(((SAVE3(1).LT.SAVE3(2)).AND.(SAVE3(2).GT.SAVE3(3))).OR.((SAVE3(
     11).GT.SAVE3(2)).AND.(SAVE3(2).LT.SAVE3(3))))USE=SAVE3(2)
    6 THING=SAVE3(2)
      GO TO 4
    3 IF(((ABS(SAVE1(1)-SAVE1(2))).LE..001).OR.(ABS(SAVE1(2)-SAVE1(3))
     1.LE..001))GO TO 6
      IF(((SAVE1(1).LT.SAVE1(2)).AND.(SAVE1(2).GT.SAVE1(3))).OR.((SAVE1(
     11).GT.SAVE1(2)).AND.(SAVE1(2).LT.SAVE1(3))))USE=SAVE1(2)
    7 THING=SAVE1(2)
    4 NX1=NX1+1
      IF(NX1.EQ.4)NX1=1
      RETURN
      END
```

```
$IBFTC DISCT3                                                           M0000
      SUBROUTINE DISCT3(XA,TABX,TABY,NY,ANS)                            M0010
      DIMENSION TABX(1),TABY(1)                                         M0020
      CALL DISSER(XA,TABX,1,NY,2,NN)                                    M0030
      NNN=3                                                             M0040
      CALL LAGRAN(XA,TABX(NN),TABY(NN),NNN,ANS)                         M0050
      RETURN                                                            M0060
      END                                                               M0070
```

```
$IBFTC DISS                                                             W0000
      SUBROUTINE DISSER (XA,TAB,I,NX,ID,NPX)                            W0010
      DIMENSION TAB(2000)                                               W0020
C     DIMENSION TAB(2000)                                               W0030
      NPT=ID+1                                                          W0040
      NPB=NPT/2                                                         W0050
      NPU=NPT-NPB                                                       W0060
      IF (NX-NPT)   10,5,10                                             W0070
    5 NPX=I                                                             W0080
      RETURN                                                            W0090
   10 NLOW=I+NPB                                                        W0100
      NUPP=I+NX-(NPU+1)                                                 W0110
      DO 15 II=NLOW,NUPP                                                W0120
      NLOC=II                                                           W0130
      IF (TAB(II)-XA)   15,20,20                                        W0140
   15 CONTINUE                                                          W0150
      NPX=NUPP-NPB+1                                                    W0160
      RETURN                                                            W0170
   20 NL=NLOC-NPB                                                       W0180
      NU=NL+ID                                                          W0190
      DO 25 JJ=NL,NU                                                    W0200
      NDIS=JJ                                                           W0210
      IF (TAB(JJ)-TAB(JJ+1))   25,30,25                                 W0220
   25 CONTINUE                                                          W0230
      NPX=NL                                                            W0240
      RETURN                                                            W0250
   30 IF (TAB(NDIS)-XA)   40,35,35                                      W0260
   35 NPX=NDIS-ID                                                       W0270
      RETURN                                                            W0280
   40 NPX=NDIS+1                                                        W0290
      RETURN                                                            W0300
      END                                                               W0310
```

```
$IBFTC LAGR                                                             T0000
      SUBROUTINE LAGRAN (XA,X,Y,N,ANS)                                  T0010
      DIMENSION X(200),Y(200)                                           T0020
C     DIMENSION X(200),Y(200)                                           T0030
      SUM=0.0                                                           T0040
      DO 3 I=1,N                                                        T0050
      PROD=Y(I)                                                         T0060
      DO 2 J=1,N                                                        T0070
      A=X(I)-X(J)                                                       T0080
      IF (A)   1,2,1                                                    T0090
    1 B=(XA-X(J))/A                                                     T0100
      PROD=PROD*B                                                       T0110
    2 CONTINUE                                                          T0120
    3 SUM=SUM+PROD                                                      T0130
      ANS=SUM                                                           T0140
      RETURN                                                            T0150
      END                                                               T0160
```

```
$IBFTC MORE
      DIMENSION TITLE(12),X(2000),Y1(2000),Y2(2000),Y3(2000),Y4(2000)
      REWIND 11
      READ(11) (TITLE(I),I=1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      Y3(1)=Y3(1)*12.+Y1(1)
      Y4(1)=Y4(1)*12.+Y1(1)
      I=2
   30 READ(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
      IF(X(I)-5001.)10,20,20
   10 Y3(I)=Y3(I)*12.+Y1(I)
      Y4(I)=Y4(I)*12.+Y1(I)
      I=I+1
      GO TO 30
   20 NPLOT=I-1
      YM1=Y1(1)
      YM2=Y2(1)
      YM3=Y3(1)
      YM4=Y4(1)
      DO 40 K = 2 , NPLOT
      IF (Y1(K).GT.YM1) YM1 = Y1(K)
      IF (Y2(K).GT.YM2) YM2 = Y2(K)
      IF (Y3(K).GT.YM3) YM3 = Y3(K)
      IF (Y4(K).GT.YM4) YM4 = Y4(K)
   40 CONTINUE
 1000 FORMAT(1H1,(12A6))
      CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLOT)
      XMAX=X(NPLOT)
       CALL APLOT (X,Y1,XMAX,YM1,TITLE,NPLOT)
      CALL BPLOT (X,Y2,XMAX,YM2,TITLE)
      CALL CPLOT (X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)
      WRITE(6,1000)(TITLE(I),I=1,12)
      WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLOT)
 1001 FORMAT(5E20.8)
      WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLOT
 1002 FORMAT(///6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
     1YM4=F10.4,2X6HNPLOT=I4)
      READ (11) (TITLE (I),I = 1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      I=2
      IF(X(1)-5001.)30,50,50
   50 WRITE(6,1003)(TITLE(I),I=1,12)
 1003 FORMAT(////12A6)
      RETURN
      END
```

```
$IBFTC ACCEN                                                            P0000
      SUBROUTINE ACCEND(X,Y,A,B,C,N)                                    P0010
      DIMENSION X(1),Y(1),A(1),B(1),C(1)                                P0020
      K=1                                                               P0030
  101 SMALL=X(K)                                                        P0040
      DO 100 I=K,N                                                      P0050
      DUMY=X(I)                                                         P0060
      SMALL=AMIN1(SMALL,DUMY)                                           P0070
      IF(SMALL.EQ.X(I))INDEX=I                                          P0080
  100 CONTINUE                                                          P0090
      X(INDEX)=X(K)                                                     P0100
      X(K)=SMALL                                                        P0110
      SAVE=Y(K)                                                         P0120
      Y(K)=Y(INDEX)                                                     P0130
      Y(INDEX)=SAVE                                                     P0140
      SAVEA=A(K)                                                        P0150
      A(K)=A(INDEX)                                                     P0160
      A(INDEX)=SAVEA                                                    P0170
      SAVEB=B(K)                                                        P0180
      B(K)=B(INDEX)                                                     P0190
      B(INDEX)=SAVEB                                                    P0200
      SAVEC=C(K)                                                        P0210
      C(K)=C(INDEX)                                                     P0220
      C(INDEX)=SAVEC                                                    P0230
      K=K+1                                                             P0240
      IF(K.EQ.N)RETURN                                                  P0250
      GO TO 101                                                         P0260
      END                                                               P0270
```

```
$IBFTC APLOT
      SUBROUTINE APLOT (X,Y,XLIM,YLIM,TITLE,IPLOT)
      DIMENSION X(300),YTITLE(10),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H                        TIME (SEC.)   /
      DATA (YTITLE(I),I=1,10)/38H    SURFACE RECESSION (IN.)           /
      ZERO=0.0
      ALLOW(1)=50.
      ALLOW(2)=100.
      ALLOW(3)=250.
      ALLOW(4)=500.
      ALLOW(5)=1000.
      ALLOW(6)=2500.
      ALLOW(7)=5000.
      NPLOT=IPLOT
      DO 10 I=1,7
      II=I
      IF(XLIM- ALLOW(I)) 20,20,10
   10 CONTINUE
   30 WRITE (6,1000) XLIM,YLIM
 1000 FORMAT(///77H APLOT CANNOT BE DONE BECAUSE EITHER XLIM EXCEEDED 50
     100. OR YLIM EXCEEDED 5. /6H XLIM=E12.5,5X,6H YLIM=E12.5 // 19H WE
     2NOW GO TO BPLOT /// )
      RETURN
   20 XMAX= ALLOW(II)
      IFIX=II
      DO 40 I=1,4
      II=I
      IF(YLIM *100. -ALLOW(I) )50,50,40
   40 CONTINUE
      GO TO 30
   50 YMAX =ALLOW(II) /100.
      CALL RSTERM
      CALL GRIDGN (123,1023,24,924,18,18,5,5)
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y,NPLOT,1,1H/)
      ALONGX(1)=0.0
      ALONGY(1)=0.0
      DO 60 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
      ALONGX(I+1)= ALONGX(I) +.2* XMAX
   60 ALONGY(I+1)= ALONGY(I) +.2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC RPLOT
      SUBROUTINE RPLOT (X,Y,XLIM,YLIM,TITLE)
      DIMENSION X(300),Y(300),YTITLE(10),ALONGY(7),XTITLE(10)
      DIMENSION TITLE(12)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H               TIME (SEC.)
      DATA (YTITLE(I),I=1,10)/38H      BONDLINE TEMPERATURE (R)
      ALONGY(1)=0.0
      DO 10 I=1,7
      II=I
      IF(YLIM -ALLOW(I)) 20,20,10
   10 CONTINUE
      WRITE (6,1000) YLIM
 1000 FORMAT(/// 37H RPLOT WILL NOT BE DONE BECAUSE YLIM= E12.5 ////)
      RETURN
   20 YMAX =ALLOW(II)
      CALL RSTERM
      CALL GRIDGN(123,1023,24,924,18,18,5,5 )
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y, NPLOT,1, 1H/ )
      DO 30 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
   30 ALONGY(I+1) = ALONGY(I) + .2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC CPLOT
      SUBROUTINE CPLOT (X,Y1,Y2,XLIM,YLIM1,YLIM2,TITLE, Y)
      DIMENSION X(300),Y1(300),Y2(300),YTITLE(10),YY(2000),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      DIMENSION CURVE(1),VBUG(4),HBUG(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (VBUG(I),I=1,4) / 100.0,50.0,20.0,10.0  /
      DATA (HBUG(I),I=1,7) / 1.0,2.0,5.0,10.0,20.0,50.0,100.0 /
      DATA (XTITLE(I),I=1,10)/38H                                TIME (SEC.)    /
      DATA (YTITLE(I),I=1,10)/38H      DISTANCE (IN.)                           /
      DATA ONE/4H1060 /,TWO/4H1460 /
      DATA WON/1H1 /,TOO/1H2  /
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(1)
      CURVE(1)=ONE
      HFACTR=HBUG(IFIX)
      SYMBOL=WON
      YBIG =AMAX1 (YLIM1,YLIM2 )
      NCURVE =1
      DO 1 I=1,NPLOT
    1 YY(I)= Y1(I)
      DO 7 I=1,4
      II= I
      IF(YBIG*100. -ALLOW(I))6,6,7
    7 CONTINUE
      WRITE (6,1000) YLIM1,YLIM2
 1000 FORMAT (/// 39H CPLOT WILL NOT BE DONE BECAUSE YLIM1=F12.5,10H OR
     1YLIM2= F12.5 //// )
      RETURN
    6 YMAX =ALLOW (II)/100.
      VFACTR=VBUG(II)
      CALL RSTFRM
      CALL GRIDGN (123,1023,24.924,18,18,5,5)
      J=1
   70 DO 10 I=J,NPLOT
      II= I
      IM1 =I-1
      IF( YY(I)-Y(I) )20,10,10
   10 CONTINUE
      NOPT=NPLOT-J+1
      LL=J + NOPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NOPT ,1,SYMBOL)
      IF (NCURVE-1 ) 90,85,90
   85 DO 86 I=1,NPLOT
   86 YY(I)=Y2(I)
      CURVE(1)=TWO
      SYMBOL=TOO
      NCURVE = 2
      J=1
      GO TO 70
   20 NPT=II-J
      LL=J +  NPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
```

```
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,1,SYMBOL)          S0570
      DO 50 IJ= II, NPLOT                                                  S0580
      JJ= IJ                                                               S0590
      IF(YY(IJ)- Y(IJ) )50,40,40                                           S0600
   50 CONTINUE                                                             S0610
      IF(NCURVE-1) 90,85,90                                                S0620
   40 J= JJ                                                                S0630
      GO TO 70                                                             S0640
   90 ALONGY(1)=0.0                                                        S0650
      DO 100 I=1,6                                                         S0660
      CALL LABELX(ALONGX(I), 1)                                            S0670
      CALL LABELY(ALONGY(I),1)                                             S0680
  100 ALONGY(I+1)=ALONGY(I) + .2*YMAX                                      S0690
      CALL PRINT(200,975,12,0,38,XTITLE)                                   S0700
      CALL PRINT(47,200,0,12,38,YTITLE)                                    S0710
      CALL PRINT(123,1000,12,0,72,TITLE)                                   S0720
      CALL DMPBUF                                                          S0730
      RETURN                                                               S0740
      END                                                                  S0750
```

APPENDIX D

PROGRAM TERMINOLOGY

FORTRAN	Description
A	"A" coefficient in matrix, single subscript
AB	"A" coefficient in matrix, double subscript
ABLC	specific heat of material at TABL
ABLK	thermal conductivity of material at TABL
B	"B" coefficient in matrix, single subscript
BB	"B" coefficient in matrix, double subscript
BL	Total thickness of backup structure
BLTEM	value of 1460 isotherm depth from previous time step
BTEST	test to determine mode of heat transfer out of back surface of backup materials
C	"C" coefficient in matrix, single subscript
CB	"C" coefficient in matrix, double subscript
CHARC	specific heat of material at TCHAR
CHARK	thermal conductivity of material at TCHAR
CP	specific heat of a node in ablation material
CPB	specific heat of backup material node
CPC	specific heat values in char specific heat table
CPV	specific heat values in virgin specific heat table
CPX	specific heat values in backup material specific heat tables
D	"D" coefficient in matrix, single subscript
DB	"D" coefficient in matrix, double subscript
DELTT	time step in the time step table

FORTRAN	Description
DMP	test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping)
DRHØ	local mass flow rate of ablation gas
DT	time step from the time step table in hours
DTS	time step from time step table in seconds
DX	thickness of a node in the ablation material
DXB	thickness of a node in a backup structure material
DXV	variable ablation node thickness $\left(= \frac{VLV}{NP - 1}\right)$
DXX	fixed ablation material node thickness $\left(= \frac{VLI}{NP - 1}\right)$
EMBB	emissivity of back surface of each material in backup
EMC	char material emissivity
EMFB	emissivity of front surface of each material in backup
EMV	virgin material emissivity
EMX	emissivity of front surface of ablation material
END	code word for plot routine
ERR1 ERR2 ERR3 ERR4	Control numbers for printing error statements when an input or calculational mistake is made
FBLØW	blowing efficiency in reducing convective heating
FCØNV	factor to correct convective heating rate for various body locations
FENV	emissivity - view factor product to cabin interior
FRAD	factor to correct radiative heating rate for various body locations
FTEST	test to determine mode of heat transfer into front surface of backup materials

FORTRAN	Description
FV	view factor for external environment
G	defined by FORTRAN statement
GAPX	gap width between backup materials
H	film coefficient between backup materials
H300	enthalpy of air at 300° K
HEAD	any 72 alphanumeric characters used to identify problems being run - printed at top of first page of output
HEADNG	any 72 alphanumeric characters used to identify each input section
HENV	film coefficient to cabin environment
HTX	total enthalpy
HV	heat of degradation of virgin material
HW	wall enthalpy computed from enthalpy – temperature table
HX	enthalpy values in enthalpy table
IEM	test used to determine if front surface is virgin or char for using proper emissivity
IPRC	variable print frequency in time-step table
IPRCT	present print control number
IR	test to determine if node temperature is greater than TABL
IR1	test used in determining node density at TX1 temperature
IR2	test used in determining node density at TX2 temperature
NCASE	number of problems to be run
NCPB	number of points in each backup material specific heat table
NCPC	number of points in char specific heat temperature table
NCPV	number of points in virgin specific heat temperature table
NKC	number of points in char thermal conductivity - temperature table

FORTRAN	Description
NKPB	number of points in each backup material thermal conductivity table
NKV	number of points in virgin thermal conductivity temperature table
NMB	number of materials in backup structure
NP	number of node points in ablation material
NPBS	total number of node points in backup structure
NPF	total number of points in heat shield structure (NP + NPBS)
NPLØT	output plot control number
NPM	number of nodes per material in backup
NHP	number of points in enthalpy – temperature table
NPTT	number of points in time-step table
NREC	number of points in surface recession – temperature or time table
NTRAPT	number of points in trajectory input table
NXA	dummy indices for subroutine SAVE
NXB	
NXC	
NXD	
NXE	
QBLØCK	amount of convective heat blocked due to mass injection into boundary layer
QCØN	trajectory table convective heating rates
QCØNX	cold wall convective heat rate at present time step
QHW	hot wall convective heat rate without blowing
QIN	net heat flux into front surface
QLØSS	boundary condition for heat transfer to cabin interior
QØXID	heating rate due to combustion

FORTRAN	Description
QRAD	trajectory table radiative heating rates
QRADX	radiative heat flux at present time step
QUIT	code word for plot routine
R	thermal resistance due to conductivity between nodes in the ablation material
RB1	thermal resistance due to conductivity between past and present node in backup material
RB2	thermal resistance due to conductivity between present and forward node in backup material
RHØ	density of an ablation material node
RHØBX	density of individual materials in backup
RHØC	mature char material density
RHØV	virgin ablation material density
RHØY1	density of node at past time step
RHØY2	density of node at present time step
S	thermal capacity of a node in the ablation material
SDØT	surface recession rate
SAVEIT	depth of 1060 isotherm at any given time
SAVEXX	time corresponding to maximum depth of 1460 isotherm
SAVX	time corresponding to maximum depth of 1060 isotherm
SAVY1	surface recession depth at maximum 1060 isotherm depth
SAVY2	bondline temperature at maximum 1060 isotherm depth
SAVY3	term that will contain maximum depth of 1060 isotherm
SAVY4	depth of 1460 isotherm at maximum 1060 isotherm depth
SAVY1X	surface recession depth at maximum 1460 isotherm depth
SAVY2X	bondline temperature at maximum 1460 isotherm depth

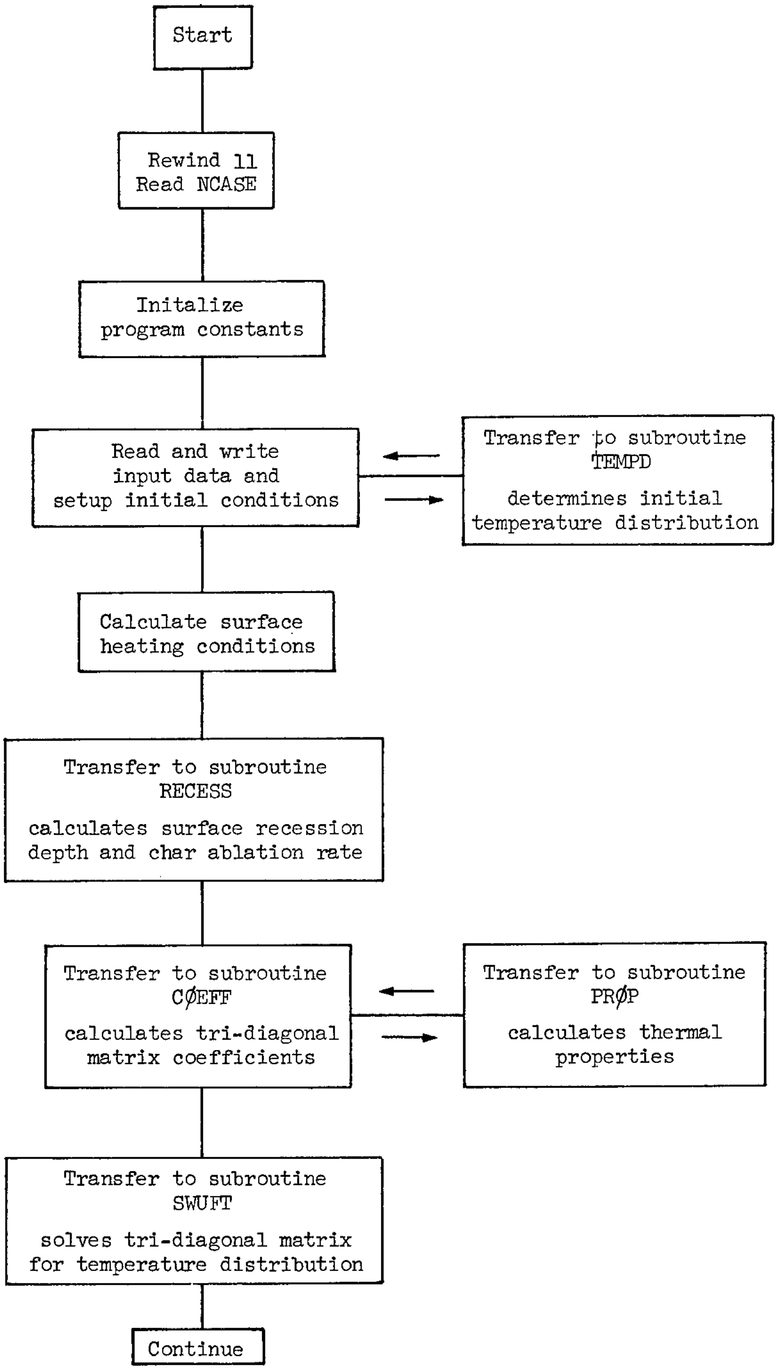
FORTRAN	Description
SAVY3X	depth of 1060 isotherm at maximum 1460 isotherm depth
SAVY4X	term that will contain maximum depth of 1460 isotherm
SR	surface recession values in surface recession table
T	present time
TABL	temperature at which ablation starts
TCHAR	temperature at which ablation stops
TCP	temperature values in backup material specific heat tables
TCPC	temperature values in char specific heat table
TCPV	temperature values in virgin specific heat table
TEMDI	arbitrary initial temperature distribution values
TEMPI	constant initial temperature distribution value
TENV	interior cabin temperature
TEST2	test to determine proper heat shield initial temperature distribution
TDMP	time to start dumping or printing information used in checkout of program (sets DMP = 1.0)
TIME	trajectory table time values
TINT	starting time of problem
TITLE	control card used for reading in new data for successive problems
TKC	temperature values in char thermal conductivity table
TKV	temperature values in virgin thermal conductivity table
TL	total thickness of heat shield structure (VL + BL)
TLIM	time limit of problem
TREC	surface temperature or time at which char removal is to start
TS	temperature or time values in surface recession table
TTABLE	time values in time-step table

FORTRAN	Description
TTUL	equals TUL if VPT = 0 or equals TX2 if VPT = 1 - used in computing char properties
TUL	maximum value of TX1 and TX2
TUL1	maximum TX1 values - used in computing gas ablation rate
TUL2	maximum TX2 values - used in computing gas ablation rate
TV	sink temperature of external environment
TW	temperature values in enthalpy table
TX1	temperature of nodes at past time step
TX2	temperature of nodes at present time step
TX2C	temperature at fixed locations in ablation material as defined by XC
TX2T	temporary storage of TX2 temperatures for computing thermal properties
TXK	temperature values in backup material thermal conductivity tables
TX0	initial temperature at front surface of heat shield for computing linear temperature gradient
TY	temperature distribution at forward time step
VEL	trajectory table velocity values
VELX	trajectory velocity at present time step
VL	initial virgin material thickness
VLI	initial ablation material thickness
VLTEM	value of 1060 isotherm depth from previous time step
VLV	variable ablation material thickness
VPT	test to determine if properties are irreversible with temperature
WEKEEP	depth of 1460 isotherm at any time
XBM	thickness of individual materials in backup
XC	fixed location of nodes in the ablation material
XI	node number

FORTRAN	Description
XIDNT	any 72 alphanumeric characters to identify each material
XK	thermal conductivity values in backup material thermal conductivity table
XKB	thermal conductivity of backup material node
XKC	thermal conductivity in char thermal conductivity table
XKV	thermal conductivity value in virgin thermal conductivity table
XL0ST	amount of solid ablation material lost in a time step due to surface movement
XLSTI	distance from original surface to present front surface location, inches
XLSTV	distance from original surface to present front surface location, feet
XMDC	mass loss rate of char
XMDG	mass gas ablation rate due to pyrolysis of virgin material
XMD0	mass flux rate of oxygen to surface
XMDT	total ablation rate
XNP	number of nodes in ablation material
XNPM	number of nodes per backup material
XPL0T	time to be written on tape and plotted
XV	location of nodes in variable ablation material thickness
YK	thermal conductivity of a node in ablation material
YPL0T1	recession depth to be written on tape and plotted
YPL0T2	bondline temperature to be written on tape and plotted
YPL0T3	1060 isotherm depth to be written on tape and plotted
YPL0T4	1460 isotherm depth to be written on tape and plotted
ZZZ	ratio to determine when the limiting value of heat blockage has been reached

APPENDIX E

GENERAL FLOW CHART



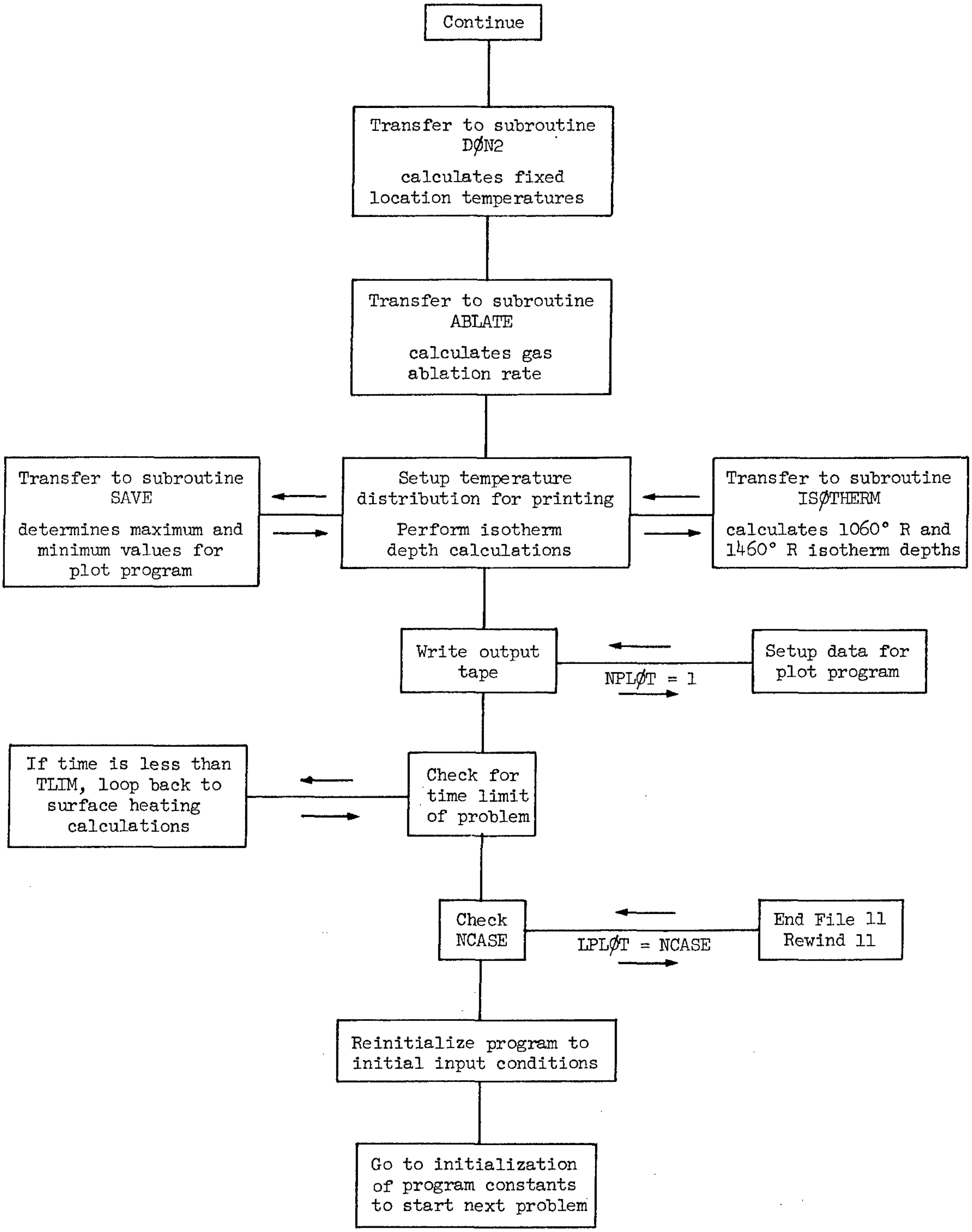
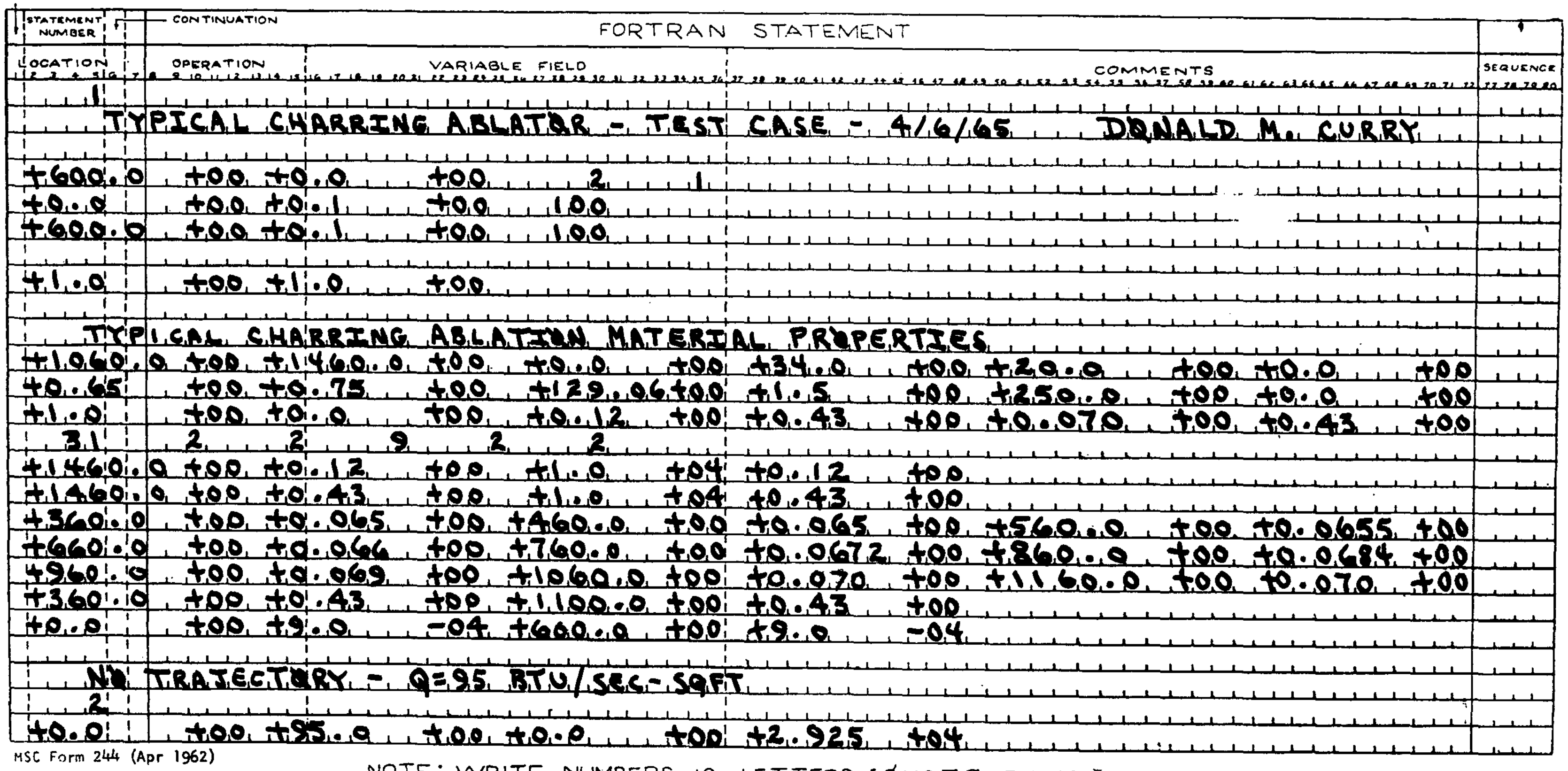

Continue
Transfer to subroutine D0N2
calculates fixed location temperatures
Transfer to subroutine ABLATE
calculates gas ablation rate
Transfer to subroutine SAVE
determines maximum and minimum values for plot program
Setup temperature distribution for printing
Perform isotherm depth calculations
Transfer to subroutine IS0THERM
calculates 1060° R and 1460° R isotherm depths
Write output tape
NPL0T = 1
Setup data for plot program
If time is less than TLIM, loop back to surface heating calculations
Check for time limit of problem
Check NCASE
LPL0T = NCASE
End File 11
Rewind 11
Reinitialize program to initial input conditions
Go to initialization of program constants to start next problem

TABLE I.- SAMPLE PROBLEM INPUT

(a) Coding sheet



```
    1
    TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65    DONALD M. CURRY

+600.0   +00 +0.0    +00     2     1
+0.0     +00 +0.1    +00   100
+600.0   +00 +0.1    +00   100

+1.0     +00 +1.0    +00

   TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00   +0.0     +00 +34.0   +00 +20.0    +00 +0.0     +00
+0.65    +00 +0.75    +00  +129.06+00 +1.5    +00 +250.0   +00 +0.0     +00
+1.0     +00 +0.0     +00  +0.12   +00 +0.43   +00 +0.070   +00 +0.43    +00
  31     2     2     9     2     2
+1460.0 +00 +0.12    +00  +1.0    +04 +0.12   +00
+1460.0 +00 +0.43    +00  +1.0    +04 +0.43   +00
+360.0   +00 +0.065   +00 +460.0   +00 +0.065  +00 +560.0   +00 +0.0655  +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684  +00
+960.0   +00 +0.069   +00 +1060.0  +00 +0.070  +00 +1160.0  +00 +0.070   +00
+360.0   +00 +0.43    +00 +1100.0  +00 +0.43   +00
+0.0     +00 +9.0     -04 +600.0   +00 +9.0    -04

   NO TRAJECTORY - Q=95 BTU/SEC-SQFT
    2
+0.0     +00 +95.0    +00 +0.0     +00 +2.925  +04
```

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

TABLE I.- SAMPLE PROBLEM INPUT - Continued

(a) Coding sheet

STATEMENT NUMBER — CONTINUATION

FORTRAN STATEMENT

LOCATION | OPERATION | VARIABLE FIELD | COMMENTS | SEQUENCE

```
+600.0  +00 +95.0     +00 +0.0       +00 +2.925   +04

     1  3    +0.1     +00
+3.0    +00
     9  2
   BACKUP MATERIAL                     0.1 INCHES THICK
+360.0  +00 +0.065    +00 +460.0     +00 +0.065   +00 +560.0    +00 +0.0655  +00
+660.0  +00 +0.066    +00 +760.0     +00 +0.0672  +00 +860.0    +00 +0.0684  +00
+960.0  +00 +0.069    +00 +1060.0    +00 +0.07    +00 +1160.0   +00 +0.07    +00
+360.0  +00 +0.43     +00 +1100.0    +00 +0.43    +00
+34.0   +00 +0.1      +00 +0.9       +00 +0.9     +00
+0.0    +00 +0.0      +00 +0.0       +00 +0.0     +00

  HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0
+560.0  +00 +0.0      +00 +0.0       +00 +0.0     +00

 INITIAL TEMPERATURE IS CONSTANT
+0.0    +00 +530.0    +00 +530.0     +00

    42
+0.0    +00 +0.0      +00 +342.9     +00 +1400.0  +00 +449.7    +00 +1800.0  +00
+617.2  +00 +2400.0   +00 +791.0     +00 +3000.0  +00 +978.0    +00 +3600.0  +00
+1113.0 +00 +4000.0   +00 +1200.0    +00 +4224.0  +00 +1300.0   +00 +4486.0  +00
+1400.0 +00 +4723.0   +00 +1500.0    +00 +4936.0  +00 +1600.0   +00 +5127.0  +00
+1700.0 +00 +5299.0   +00 +1800.0    +00 +5454.0  +00 +1900.0   +00 +5596.0  +00
```

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

3537-64

TABLE I.- SAMPLE PROBLEM INPUT - Concluded

(a) Coding sheet

FORTRAN STATEMENT

STATEMENT NUMBER | CONTINUATION | LOCATION | OPERATION | VARIABLE FIELD | COMMENTS | SEQUENCE

```
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00
+3200.0 +00 +7050.0 +00 +3300.0 +00 +7175.0 +00 +3400.0 +00 +7350.0 +00
+3500.0 +00 +7480.0 +00 +3600.0 +00 +7630.0 +00 +3700.0 +00 +7800.0 +00
+3800.0 +00 +7970.0 +00 +3900.0 +00 +8120.0 +00 +4000.0 +00 +8300.0 +00
+4100.0 +00 +8500.0 +00 +4200.0 +00 +8700.0 +00 +4300.0 +00 +8850.0 +00
+4400.0 +00 +9000.0 +00 +4500.0 +00 +9150.0 +00 +4600.0 +00 +9270.0 +00
```

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

3537-64

TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

```
 1
  TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65     DONALD M. CURRY

+600.0   +00 +0.0     +00      2     1
+0.0     +00 +0.1     +00    100
+600.0   +00 +0.1     +00    100

+1.0     +00 +1.0     +00

   TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00 +0.0     +00 +34.0    +00 +20.0    +00 +0.00    +00
+0.65    +00 +0.75    +00 +129.06 +00 +1.50    +00 +250.0   +00 +0.0     +00
+1.0     +00 +0.0     +00 +0.12    +00 +0.43    +00 +0.070   +00 +0.43    +00
  31     2    2     9     2     2
+1460.0 +00 +0.12    +00 +1.0     +04 +0.12    +00
+1460.0 +00 +0.43    +00 +1.0     +04 +0.43    +00
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.070   +00 +1160.0 +00 +0.070   +00
+360.00 +00 +0.43    +00 +1100.0 +00 +0.43    +00
+0.0     +00 +9.0     -04 +600.0   +00 +9.0     -04

   NO TRAJECTORY - Q=95 BTU/SEC-SQFT
   2
+0.0     +00 +95.0    +00 +0.0     +00 +2.925   +04
+600.0   +00 +95.0    +00 +0.0     +00 +2.925   +04

   1     3    +0.1     +00
+3.0     +00
   9     2
   BACKUP MATERIAL                      0.1 INCHES THICK
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.07    +00 +1160.0 +00 +0.07    +00
+360.00 +00 +0.43    +00 +1100.0 +00 +0.43    +00
+34.0    +00 +0.1     +00 +0.9     +00 +0.9     +00
+0.0     +00 +0.0     +00 +0.0     +00 +0.0     +00

 HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0
+560.0   +00 +0.0     +00 +0.0     +00 +0.0     +00

 INITIAL TEMPERATURE IS CONSTANT
+0.0     +00 +530.0   +00 +530.0   +00

  42
+0.0     +00 +0.0     +00 +342.9   +00 +1400.0 +00 +449.7   +00 +1800.0 +00
+617.2   +00 +2400.0 +00 +791.0   +00 +3000.0 +00 +978.0   +00 +3600.0 +00
+1113.0 +00 +4000.0 +00 +1200.0 +00 +4224.0 +00 +1300.0 +00 +4486.0 +00
+1400.0 +00 +4725.0 +00 +1500.0 +00 +4936.0 +00 +1600.0 +00 +5127.0 +00
+1700.0 +00 +5299.0 +00 +1800.0 +00 +5454.0 +00 +1900.0 +00 +5596.0 +00
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00
```

TABLE I - SAMPLE PROBLEM INPUT - Concluded

(b) Fortran data card listing

```
+3200.0   +00+7050.0   +00+3300.0   +00+7175.0   +00+3400.0   +00+7350.0   +00
+3500.0   +00+7480.0   +00+3600.0   +00+7630.0   +00+3700.0   +00+7800.0   +00
+3800.0   +00+7970.0   +00+3900.0   +00+8120.0   +00+4000.0   +00+8300.0   +00
+4100.0   +00+8500.0   +00+4200.0   +00+8700.0   +00+4300.0   +00+8850.0   +00
+4400.0   +00+9000.0   +00+4500.0   +00+9150.0   +00+4600.0   +00+9270.00  +00
```

TABLE II.- SAMPLE PROBLEM OUTPUT

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

INPUT DATA.


TIME LIMIT=6.0000E 02    INITIAL TIME=0.            NPTT=   2

       TIME           TIME STEP      PRINT CONTROL
    0.              1.0000E-01          100
    6.0000E 02      1.0000E-01          100

FCONV= 1.00000E 00    FRAD= 1.00000E 00



    TYPICAL CHARRING ABLATION MATERIAL PROPERTIES

TABL= 1.06000E 03   TCHAR= 1.46000E 03   TREC= 0.            RHOV= 3.40000E 01   RHOC= 2.00000E 01
FBLOW= 0.             EMV= 6.50000E-01    EMC= 7.50000E-01   H300= 1.29060E 02     VL= 1.50000E 00
   HV= 2.50000E 02    VPT= 0.              FV= 1.00000E 00     TV= 0.           CHARK= 1.20000E-01
CHARC= 4.30000E-01   ABLK= 7.00000E-02   ABLC= 4.30000E-01

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

                               VIRGIN MATERIAL
                   THERMAL                                              SPECIFIC
  TEMPERATURE    CONDUCTIVITY                          TEMPERATURE        HEAT
  3.60000E 02     6.50000E-02                          3.60000E 02    4.30000E-01
  4.60000E 02     6.50000E-02                          1.10000E 03    4.30000E-01
  5.60000E 02     6.55000E-02
  6.60000E 02     6.60000E-02
  7.60000E 02     6.72000E-02
  8.60000E 02     6.84000E-02
  9.60000E 02     6.90000E-02
  1.06000E 03     7.00000E-02
  1.16000E 03     7.00000E-02


                                CHAR  MATERIAL
                   THERMAL                                              SPECIFIC
  TEMPERATURE    CONDUCTIVITY                          TEMPERATURE        HEAT
  1.46000E 03     1.20000E-01                          1.46000E 03    4.30000E-01
  1.00000E 04     1.20000E-01                          1.00000E 04    4.30000E-01

                           SURFACE RECESSION TABLE

                           TIME            SR - IN/SEC
                       0.                  9.00000E-04
                       6.00000E 02         9.00000E-04


   NO TRAJECTORY - Q=95 BTU/SEC-SQFT

NO. OF TRAJECTORY POINTS =    2
```

TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

```
    TIME          Q CONVECTIVE     Q RADIATIVE        VELOCITY
 0.                9.50000E 01      0.                2.92500E 04
 6.00000E 02       9.50000E 01      0.                2.92500E 04

        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


                  THERMAL                                        SPECIFIC
TEMPERATURE     CONDUCTIVITY                  TEMPERATURE          HEAT
3.60000E 02      6.50000E-02                  3.60000E 02      4.30000E-01
4.60000E 02      6.50000E-02                  1.10000E 03      4.30000E-01
5.60000E 02      6.55000E-02
6.60000E 02      6.60000E-02
7.60000E 02      6.72000E-02
8.60000E 02      6.84000E-02
9.60000E 02      6.90000E-02
1.06000E 03      7.00000E-02
1.16000E 03      7.00000E-02


                                                        EMISSIVITY
     MATERIAL       DENSITY       THICKNESS        FRONT         BACK         NODES/MATERIAL

        1         3.4000E 01     1.0000E-01     9.0000E-01     9.0000E-01       3.0000E 00


 ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

        MATERIAL      FILM COEFFICIENT      GAP THICKNESS       FTEST              BTEST
           1              0.                  0.                0.                 0.


HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0

 TEMPERATURE= 5.60000E 02    FILM COEFFICIENT= 0.               VIEW FACTOR= 0.                Q LOST= 0.


INITIAL TEMPERATURE IS CONSTANT


 TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.3000E 02
```

TABLE II.- SAMPLE PROBLEM OUTPUT - Concluded

```
OUTPUT DATA.


TIME= 9.90000E 00  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.           VELOCITY= 2.92500E 04
GAS ABLATION RATE= 0.          CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 5.40000E 00
RECESSION DEPTH= 9.00000E-03  QHOT WALL= 8.99282E 01

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


   TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL


      3.79022E 03      2.33046E 03      1.06300E 03      6.38075E 02      5.47600E 02      5.32434E 02
      5.30289E 02      5.30030E 02      5.30002E 02      5.30000E 02      5.30000E 02      5.30000E 02
      5.30000E 02      5.30000E 02      5.29999E 02      5.30000E 02      5.30000E 02      5.30000E 02
      5.30000E 02      5.30000E 02      5.30000E 02      5.30000E 02      5.30000E 02      5.30000E 02
      5.30000E 02      5.30000E 02      5.30000E 02      5.29999E 02      5.30000E 02      5.30000E 02
      5.29999E 02

   TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE


      5.29999E 02      5.30000E 02      5.30000E 02



TIME= 1.99000E 01  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.           VELOCITY= 2.92500E 04
GAS ABLATION RATE= 2.90720E 01  CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 3.44720E 01
RECESSION DEPTH= 1.80000E-02  QHOT WALL= 8.99173E 01

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


   TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL


      3.80935E 03      2.87678E 03      1.64575E 03      9.77202E 02      6.72698E 02      5.66204E 02
      5.37857E 02      5.31496E 02      5.30254E 02      5.30038E 02      5.30005E 02      5.30000E 02
      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02
      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02
      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02      5.29999E 02
      5.29999E 02

   TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE


      5.29999E 02      5.29999E 02      5.29999E 02



TIME= 2.99000E 01  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.           VELOCITY= 2.92500E 04
GAS ABLATION RATE= 1.25330E 01  CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 1.79330E 01
RECESSION DEPTH= 2.70000E-02  QHOT WALL= 8.98427E 01
```

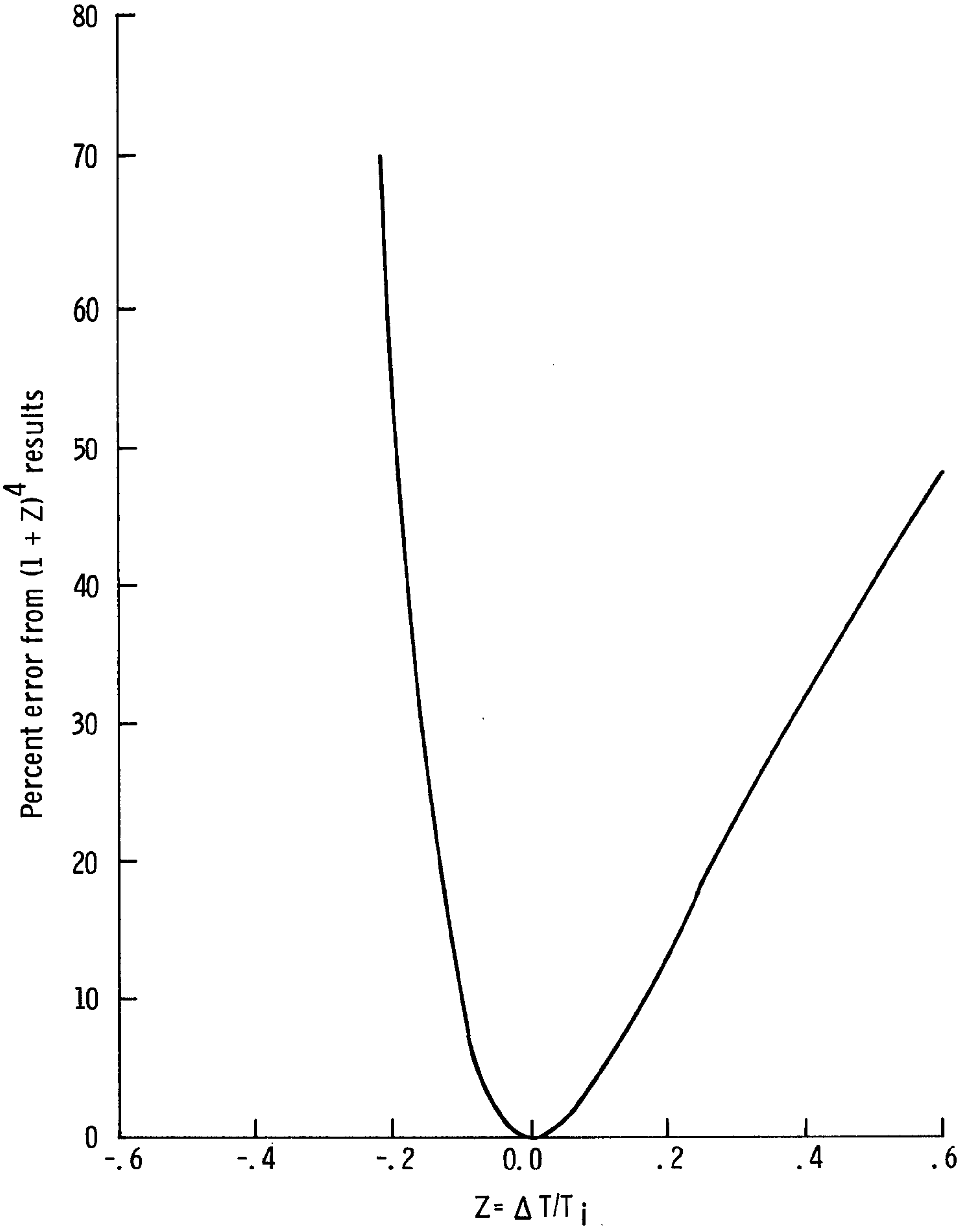


Figure 1. - Radiation temperature approximation error.

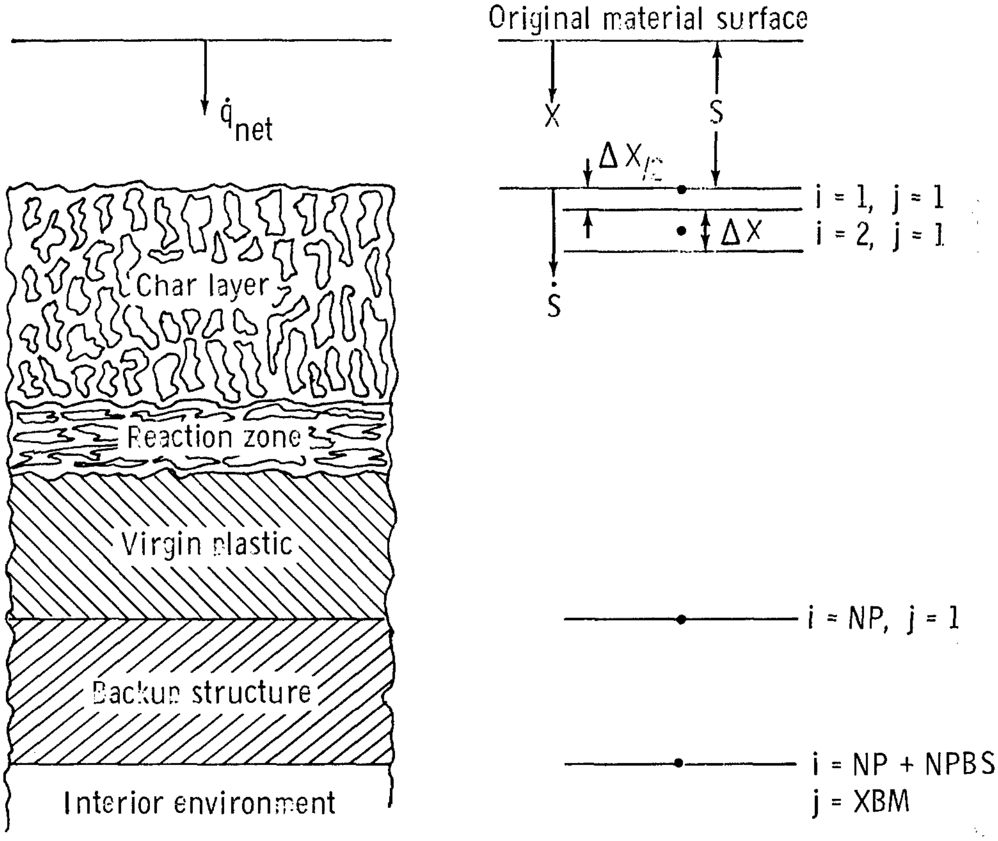


Figure 2. - Schematic diagram of charring ablator thermal protection system.

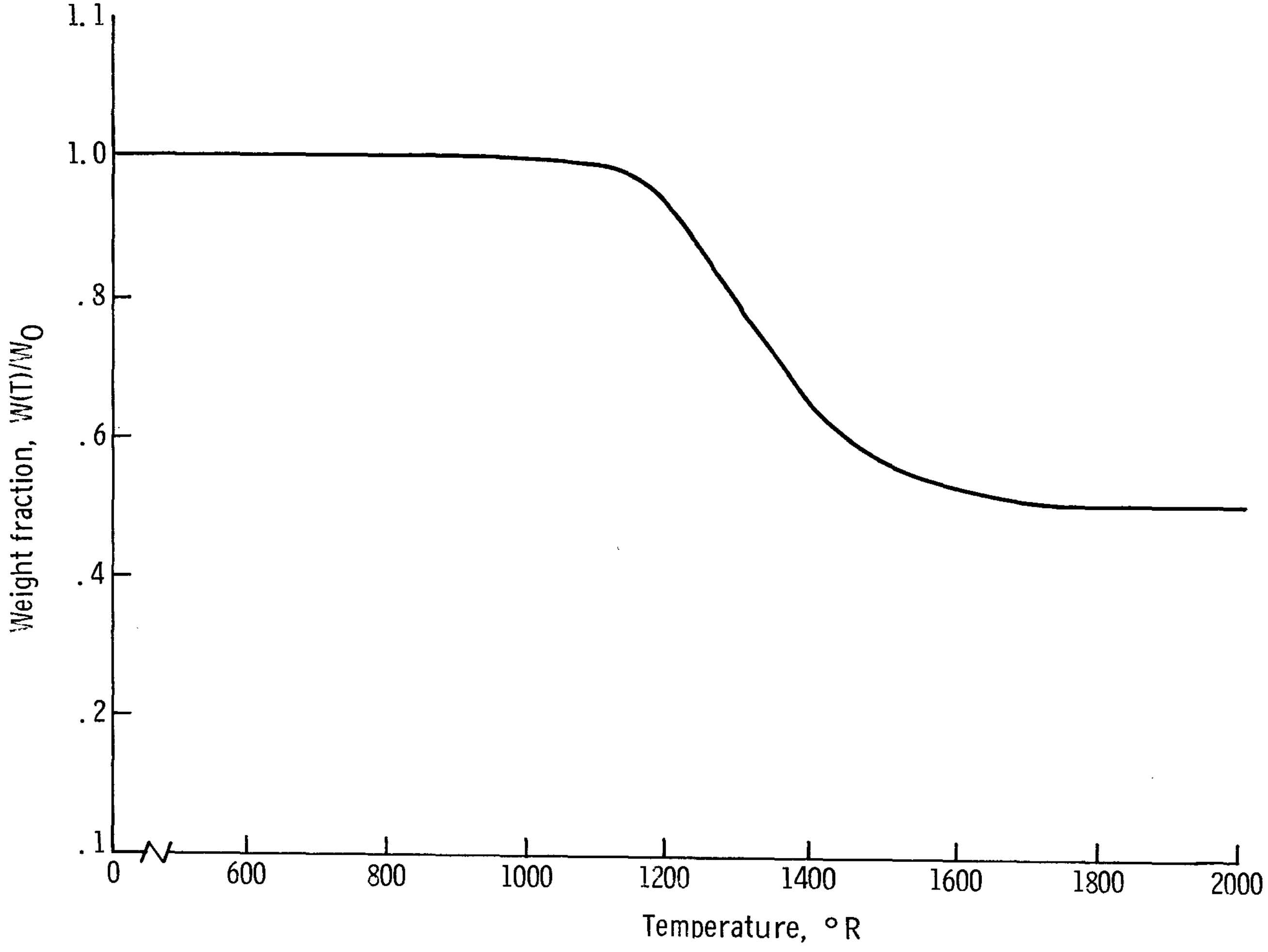


Figure 3. - Thermogravimetric data for typical charring ablation material.

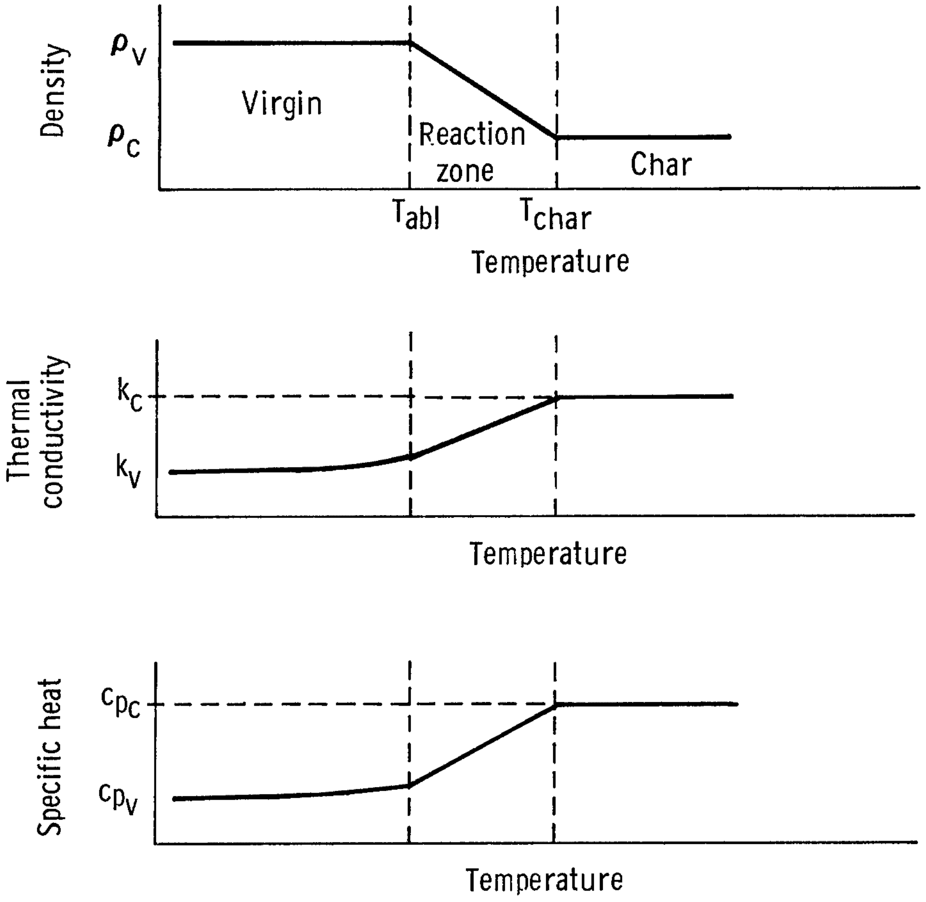


Figure 4. - Charring material property variation used as input to STAB II.

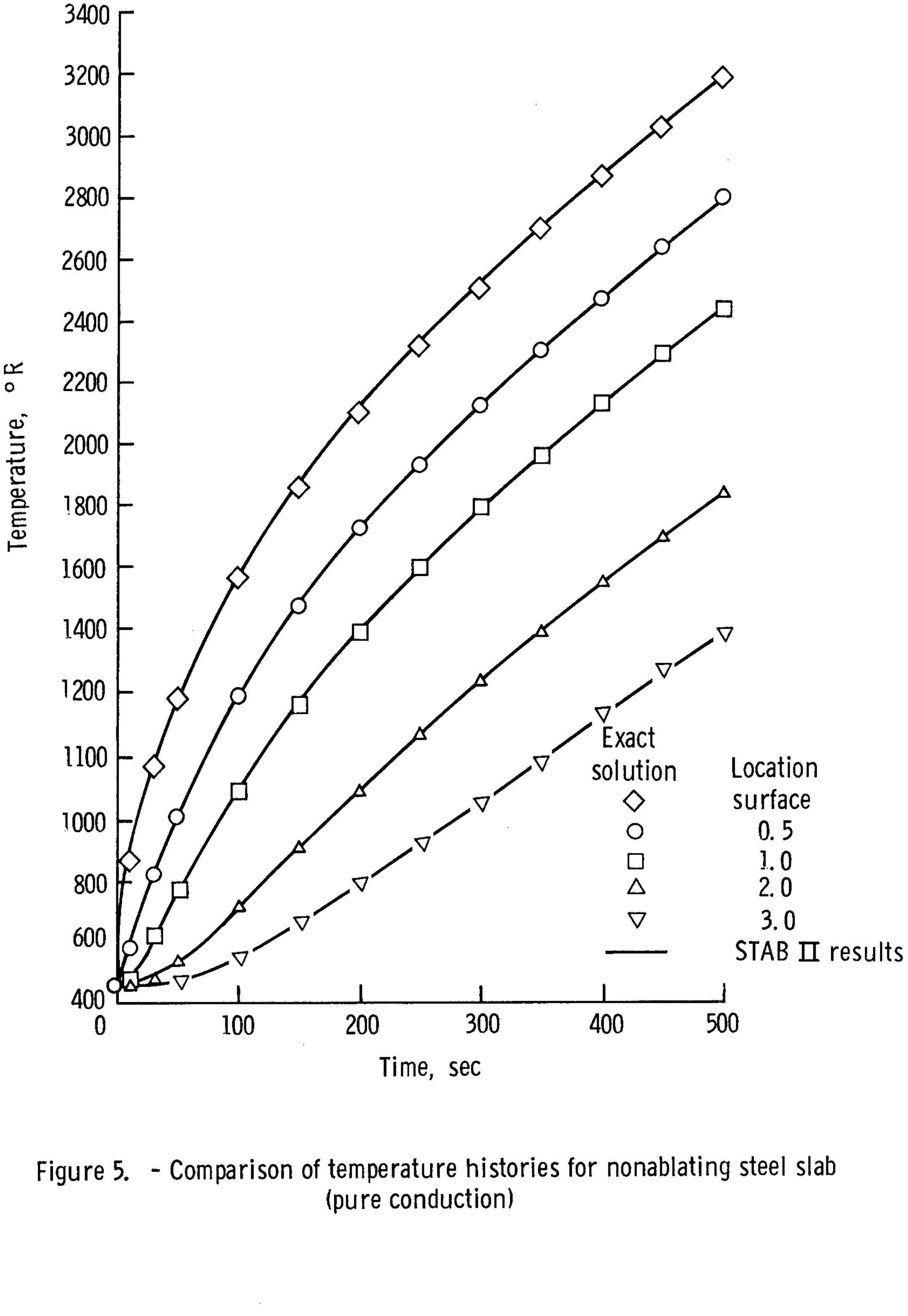


Figure 5. - Comparison of temperature histories for nonablating steel slab (pure conduction)

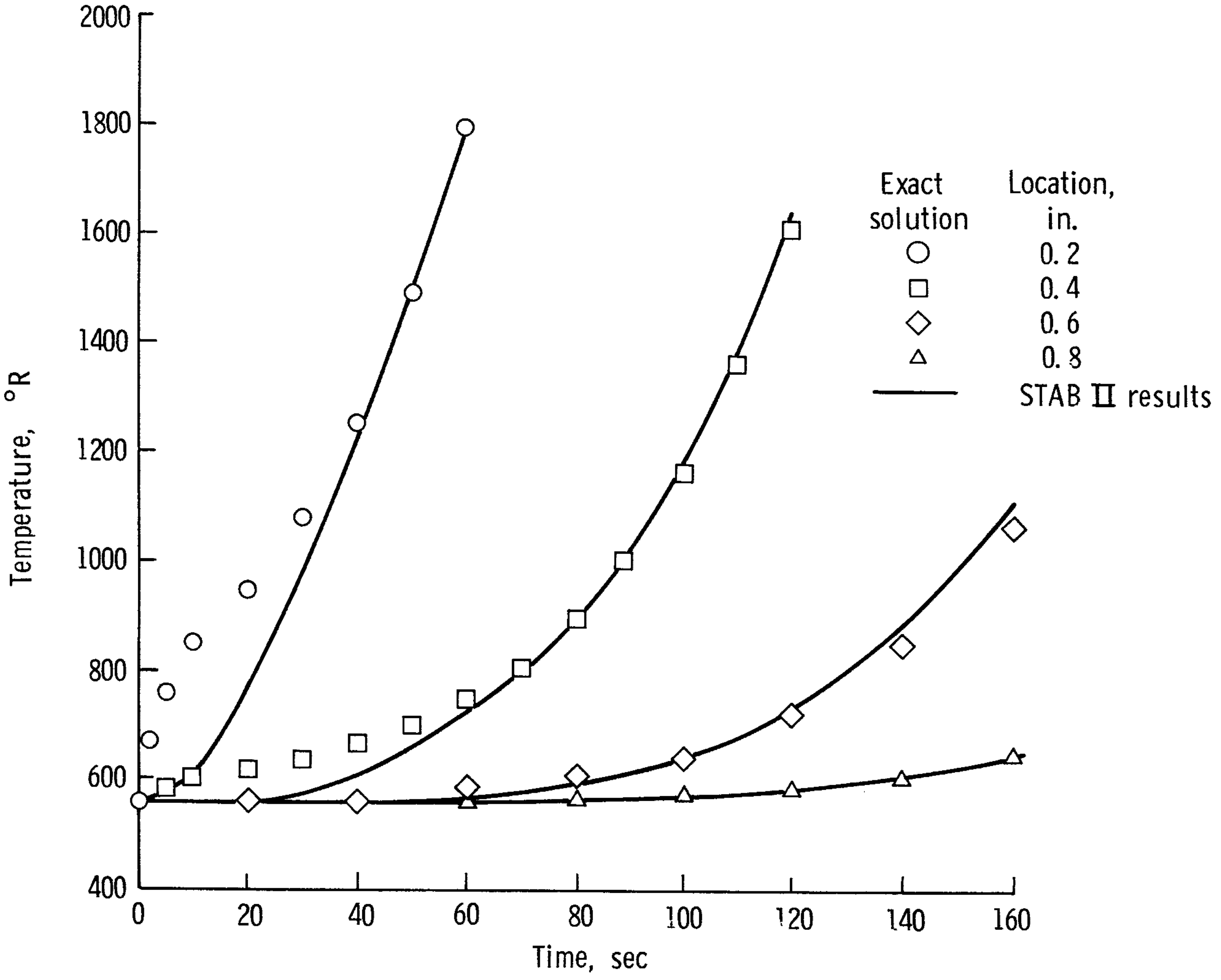


Figure 6. - Comparison of temperature histories for moving boundary model.

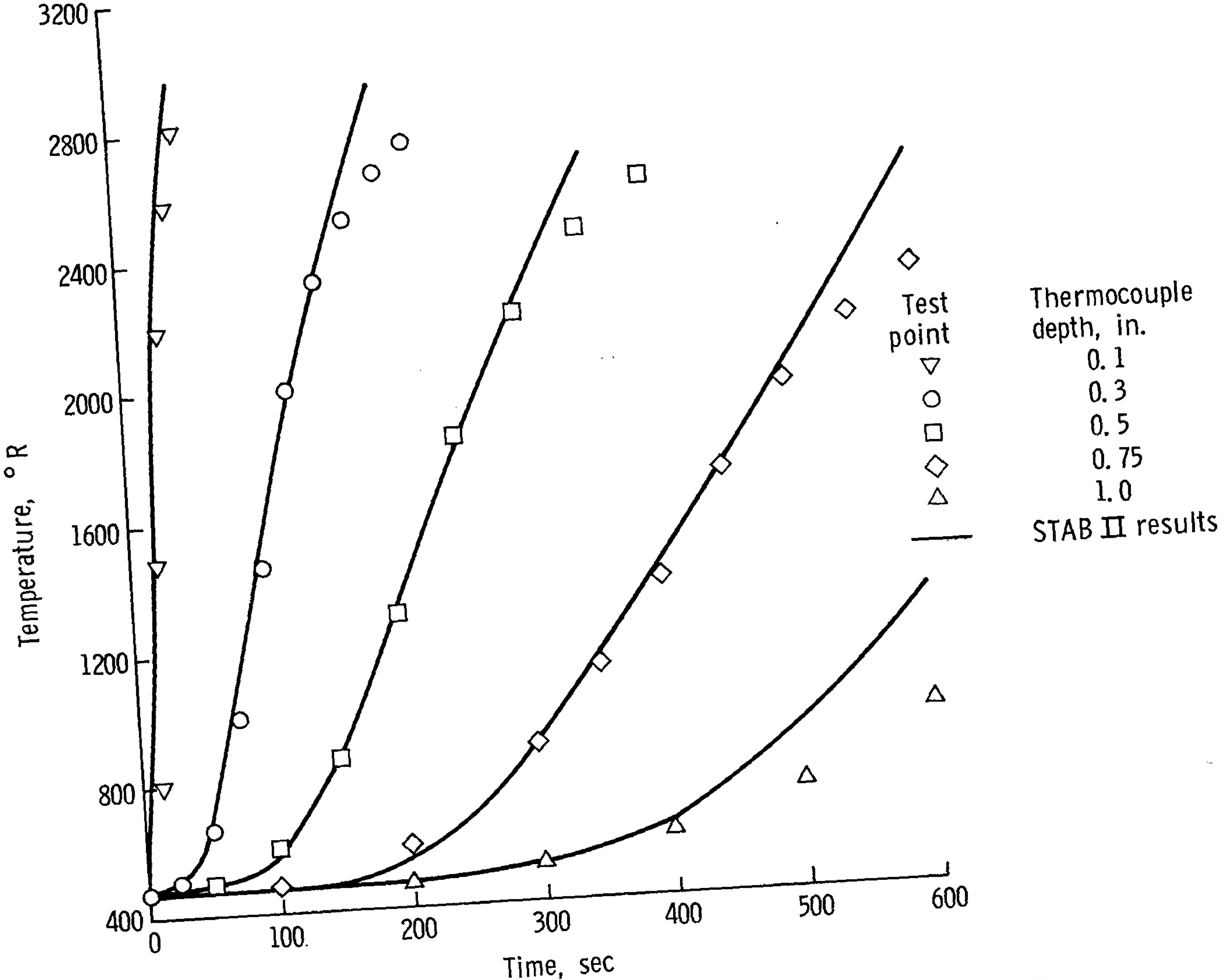


Figure 7. - Comparison of temperature histories for typical charring ablator.

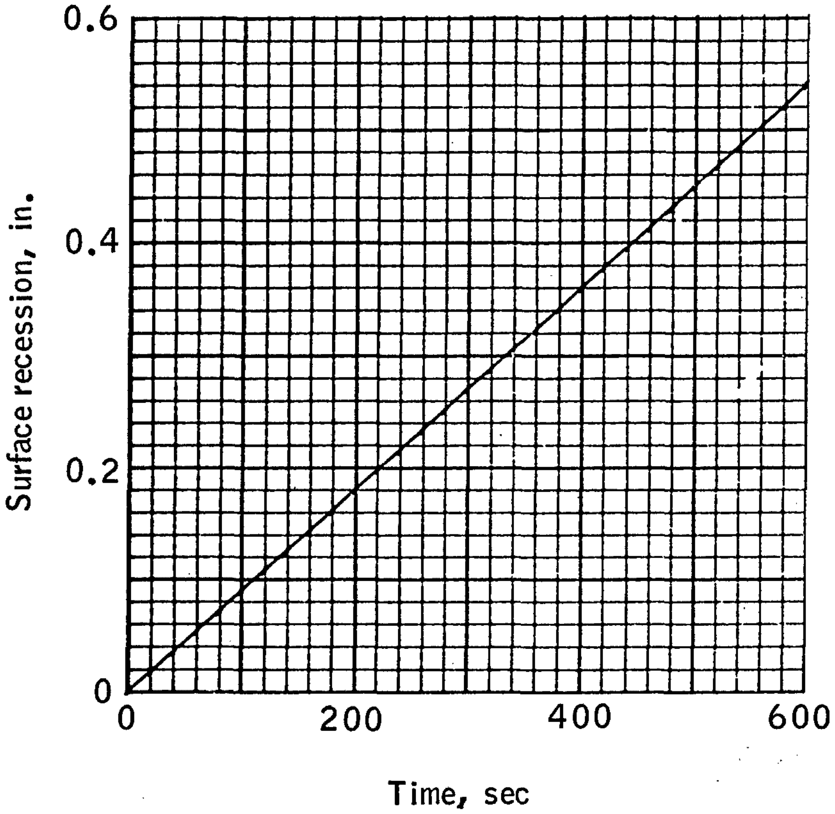


Figure 8. - Plot program surface recession curve from typical charring ablator test case.

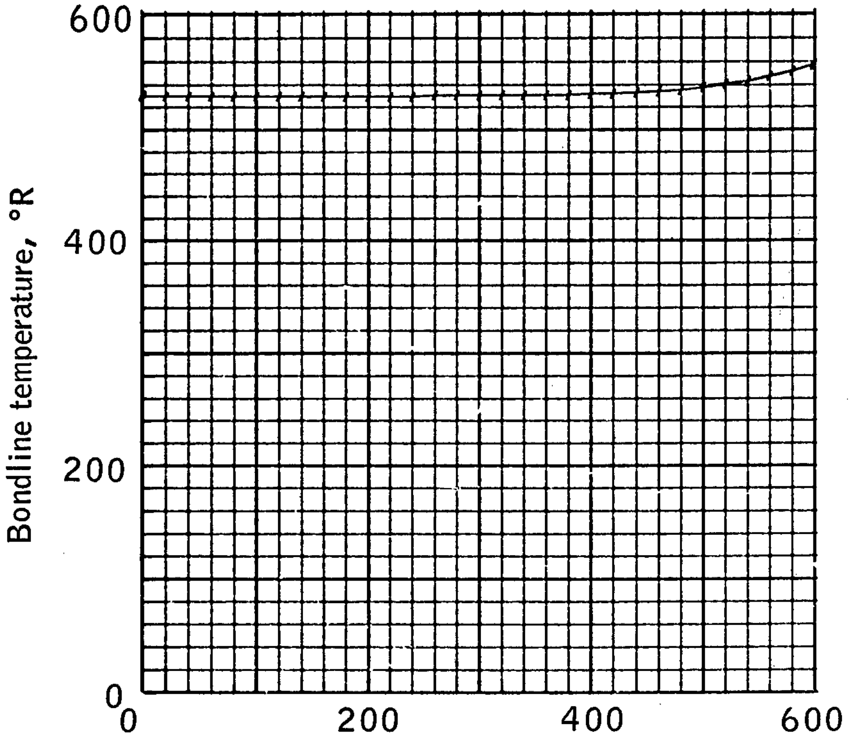


Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.

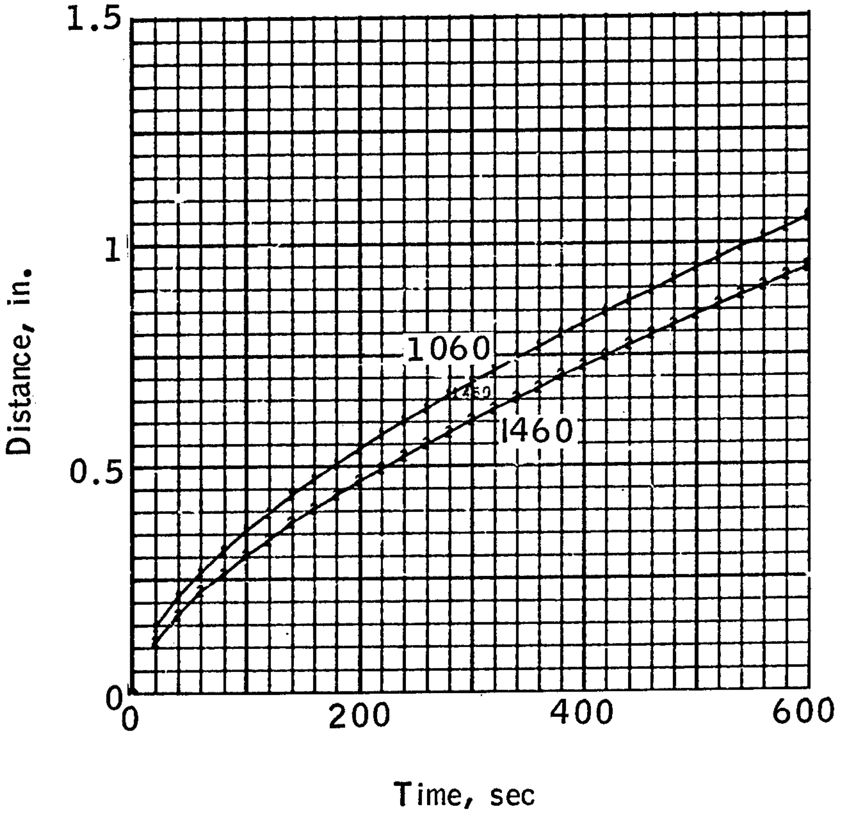


Figure 10. -Plot program 1060°R and 1460°R isotherm curves from typical charring ablator test case.

NASA-Langley, 1965 S-91