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USER'S MANUAL
AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
VERSION 3

Volume I - Program Description and Sample Problems

April 1970

Air Force Rocket Propulsion Laboratory
Director of Laboratories
Edwards, California 93523
Air Force Systems Command
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Project Officer, Robert J. Schoner/RPMCH

FOREWORD

This report is one of two computer program user's manuals prepared by Aerotherm Corporation under USAF Contract F04611-70-C-0012. Included herein is Volume I of the manual for Version 3 of the Aerotherm Charring Material Ablation code. This volume describes the problems solved by the code and presents an input (card format) user's guide and sample problems. The report was first published as Aerotherm Report No. UM-70-14. The work was administered under the direction of the Air Force Rocket Propulsion Laboratory, Motor Component Development Branch with Mr. R. J. Schoner as project officer.

Mr. M. R. Wool was program manager and principal investigator. Significant additional assistance was also provided by Dr. C. B. Moyer.

This technical report has been reviewed and is approved.

R. J. Schoner
Project Engineer, AFRPL

ABSTRACT

This two-volume report describes a Fortran IV computer code which computes the transient thermal and ablation response of a charring insulation material structure. The program is for one-dimensional bodies, but can treat a variety of shapes, including planes, cylinders, spheres, and more general thermal "stream tube" bodies. The program can treat complex systems including a main ablating material, several charring back-up materials, and a multiple non-charring material back-up structure.

An unusual feature of the code is the very general heated surface boundary condition, which can account for

- Simple specified temperature and recession rate
- Specified heat flux with no recession
- General thermochemical erosion model incorporating complete chemical erosion computations, both equilibrium and non-equilibrium, for any material exposed to any environment

The code has seen extensive use for thermal performance studies of ablating heat shields, rocket nozzles, and spacecraft structures.

Volume I of this report contains descriptions of the problem treated, the equations solved, the input information required of the program user, and the program output information. It also provides a card-by-card user's input guide and a number of sample problem input and output listings. Volume II of the report contains supplemental information on the specific Fortran IV codings. It includes program listings, flow charts, and definitions of Fortran variable names.

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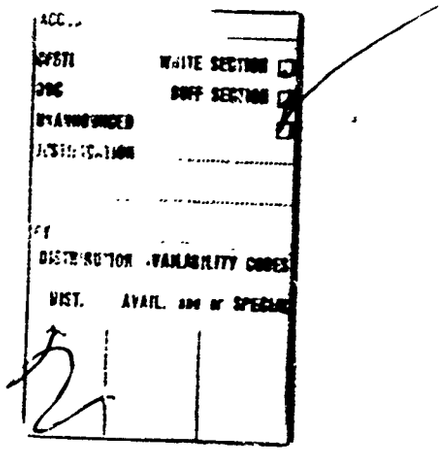

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LIST OF SYMBOLS

GENERAL

A	area	ft^2
A	coefficient in Equation (8) for T_w	$Btu/ft^2 sec\ F$
A_{BW}	area of back wall of ablating material	ft^2
A_s	area of surface of ablating material	ft^2
a	radius exponent giving variation of area with radius, $A \sim r^a$	---
B	coefficient in Equation (8) for T_w	$Btu/ft^2 sec$
B_i	pre-exponential factor, Equation (2)	sec^{-1}
B'	$\dot{m}/\rho_e u_e C_M = (\dot{m}_g + \dot{m}_c)/\rho_e u_e C_M$	---
B'_f	dimensionless ablative mass flow rate of failing (melting or mechanically removed) material, $\dot{m}_f/\rho_e u_e C_M$	---
B'_g	dimensionless pyrolysis gas rate $\dot{m}_g/\rho_e u_e C_M$	---
b	constant in burning rate equation, Section 2.4.3.4	various
C_H	Stanton number corrected for transpiration (blowing) $C_H/C_{H_o} = \zeta/(e^\zeta - 1)$ and for radius ratio effects	---
C_{H_o}	Stanton number not corrected for transpiration (blowing) or for radius ratio effects, i.e., as input	---
C_{H_1}	Stanton number corrected for radius ratio effects but not for blowing	---
C_M	mass transfer Stanton number	---
C_p	specific heat	$Btu/lb\ ^oF$
E_a	activation energy, Equation (2)	Btu/lb mol
F	view factor	---
F_i	empirical function of temperature	---
$f_1(x), f_2(x)$	functions of plastic mass fraction x, discussed in Section 2.1	---
H	recovery enthalpy	Btu/lb
h	enthalpy (sensible plus chemical)	Btu/lb
h^T	enthalpy of formation at temperature T	Btu/lb

h_c	convective transfer coefficient	Btu/ft^{2}sec$^{\circ}$F
h_g	pyrolysis gas enthalpy	Btu/lb
$\bar{h}$	defined as $(\rho_p h_p - \rho_c h_c)/(\rho_p - \rho_c)$	Btu/lb
K	proportionality constant in Equation (21)	---
K_i	mass fraction of species i in a mixture	---
k	thermal conductivity	Btu/ft-$^{\circ}$F-sec
$\dot{m}$	mass flow rate per unit area from surface	lb/ft^{2}sec
$\dot{m}_g$	mass flow rate of pyrolysis gases out of surface per unit surface area	lb/ft^{2}sec
$\dot{m}_{g_x}$	local in-depth mass flow rate of pyrolysis gases through node or control volume	lb/sec
n	burning rate exponent, Equation (17)	---
p_c	chamber pressure	lb/ft^2
q_{chem}	chemical energy rate term defined by Equation (11)	Btu/ft^{2}sec
q_{cond}	rate of energy conduction into the ablating material	Btu/ft^{2}sec
$q_{rad\ in}$	rate of radiant energy input to the ablating surface	Btu/ft^{2}sec
$q_{rad\ out}$	rate of radiant energy emission from the ablating surface, equal to $F\sigma\varepsilon T_w^4$	Btu/ft^{2}sec
q_{sen}	convective flux term defined by Equation (10)	Btu/ft^{2}sec
R	universal gas constant	Btu/lb mol $^{\circ}$R
r	radius	ft
r*	throat radius	ft
$\dot{r}$	propellant burning rate	ft/sec
r_c, r_p	char and pyrolysis density criteria	---
r_s	radius of heated surface	ft
S	distance from original location of receding surface to current surface location	ft
$\dot{S}$	rate of change of S	ft/sec
T	temperature	$^{\circ}$R
T'	"new" temperature computed during a computational cycle	$^{\circ}$R
T_w	wall (surface) temperature	$^{\circ}$R

u_e	velocity of gases at edge of boundary layer	ft/sec
x	coordinate normal to ablating surface, fixed to receding surface, also virgin plastic mass fraction defined by Equation (5)	ft, ---
y	coordinate normal to ablating surface, origin fixed in space relative to back wall	ft
Z_i	diffusion driving force = $\dfrac{K_i}{F_i \sum_j \frac{K_j}{F_j}}$	---
Z_i^*	modified Z_i discussed in Reference 2	---
GREEK		
α	thermal diffusivity $k/\rho C_p$	ft^2/sec
Γ	volume fraction of resin in plastic, see Equation (1)	ft^3/resin/ ft^3material
δ	nodal thickness, char and pyrolysis line depths	ft
ϵ	emissivity	---
ϵ_p	volume fraction of undecomposed plastic in given volume	---
ζ	$2\lambda \dot{m}/\rho_e u_e C_{H_o}$	---
θ	time	sec
λ	blowing reduction parameter; see ζ and C_H	---
ρ	density	lb/ft^3
ρC_p	defined as $\left[\epsilon_p \rho_p C_{p_p} + (1 - \epsilon_p)\rho_c C_{p_c}\right]$	Btu/ft^3 ^oR
ρ_o	initial density	lb/ft^3 resin or lb/ft^3 reinforcement
ρ_r	residual density in charred material	lb/ft^3 resin or lb/ft^3 reinforcement
σ	Stefan-Boltzmann constant	Btu/ft^2 sec $^oR^4$
τ	char thickness	ft
ψ_i	decomposition reaction order for i^{th} component Equation (2)	---
SUBSCRIPTS		
A	denotes one pyrolyzing component of resin	
B	denotes second pyrolyzing component of resin	

C	denotes reinforcement
c	denotes char, also see h_c, p_c
e	denotes outer edge of boundary layer
f	denotes failing (removed by melting or mechanical action
g	denotes pyrolysis gas
i,j	species indexes
inj	denotes material injected into the boundary layer in gas form
n	nodal index
NL	last node of ablating material
o	see C_{H_o}
ȯ	original, initial
p	denotes virgin plastic, denotes "in absence of swell"
r	denotes recovery enthalpy; denotes residual density
s	denotes sensible enthalpy; also denotes "at heated surface"
swell	denotes "with swelling effect"
w	denotes wall (heated surface)
x	see $\dot{m}_{g_x}$
1,2	see f_1, f_2, C_{H_1}, also nodal index
1,3	denote Options 1 and 3

SECTION 1

INTRODUCTION AND GENERAL PROGRAM DESCRIPTION

1.1 PURPOSE OF THIS DOCUMENT

This report is Volume I of a two volume user's description of the Aerotherm Charring Material Thermal Response and Ablation computer program, Version 3 (CMA). It has as its chief goals the description of the preparation of the necessary input data for the program and the specification of various operational details of the program such as array sizes and tape numbers used. As supplementary information, this volume includes a very brief description of the computations performed. This description is not intended to be complete, but merely serves to give the user some feel for the calculations as well as a better understanding of the input requirements.

Users interested in a more complete description of the program itself are referred to Reference 1. An earlier version of this program is described in detail in Reference 2. This user's manual pertains specifically to what will be termed Version 3 of the CMA code. It differs from the earlier Version 2 edition described in Reference 3 chiefly in the added capability to treat charring back-up materials. Hence, an alternate designation (CMA/CBM or CBM) is used occasionally in this manual.

Volume II of this user's manual contains detailed information about Fortran IV codings. These include Definitions of Fortran variables, Flow Charts of Fortran routines, and Listings of Fortran routines.

1.2 GENERAL DESCRIPTION OF THE CMA PROGRAM

The Charring Material Thermal Response and Ablation Program, Version 3, is an implicit, finite-difference computational procedure for computing the one-dimensional transient transport of thermal energy in a three-dimensional isotropic material which can ablate from a front surface and which can decompose in-depth. Decomposition reactions are based on a three component model. The program permits up to eight different back-up materials of arbitrary thickness, five of which may char. The back wall of the composite material may transfer energy by convection and radiation.

The ablating-surface boundary condition may take one of three forms:

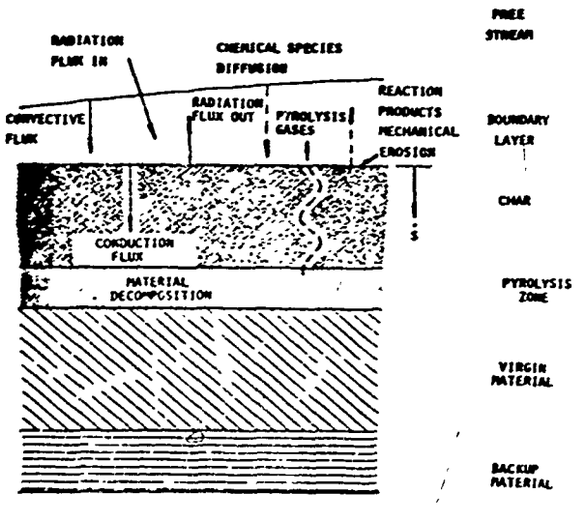
Option 1 - General convection-radiation heating with coupled mass transfer, using a transfer coefficient approach, including the effects of unequal heat and mass transfer coefficients (non-unity Lewis number) and unequal mass diffusion coefficients. Surface thermochemistry computations need not presume chemical equilibrium at the surface, but can account for kinetic effects, and can also consider thin layer melting or failing.

Option 2 - Specified surface temperature and surface recession rate.

Option 3 - Specified radiation view factor and incident radiation flux, as functions of time, for a stationary surface.

Any combination of options may be used for a single computation. Option 3 is appropriate to cooldown after termination of convective heat input and is often useful in conjunction with Options 1 and 2.

The following sketch illustrates the general physical problem treated by the CMA code.



As the material is heated, the original virgin material (or rather one or more components of the original composite virgin material) pyrolyzes and yields a pyrolysis gas, which percolates away from the pyrolysis zone, and a porous residue, which for most materials of interest is a carbonaceous char, possibly reinforced with refractory fibers or cloth.

Superimposed on this basic problem may be a number of even more complex events. The pyrolysis gases percolating through the char may undergo further chemical reactions among themselves, and may react with the char, either eroding it or depositing additional residue upon it ("coking"). The char itself may collapse or fragment from mechanical or thermal stresses, and the refractory reinforcements may melt or suffer mechanical damage. Finally, various constituents of the residue structure may react chemically with each other, changing the nature of the char, and various mechanical forces may remove material from the surface.

Despite these complexities, it is found that the "simple physics" described by

$$\text{virgin plastic} \rightarrow \text{char} + \text{gas}$$

underlies a wide range of problems of technical interest, and for a great many materials, such as carbon phenolic, graphite phenolic, and wood, constitute all the events of interest. Such events as coking, mechanical erosion, melting, and subsurface reactions (other than pyrolysis) are less common and generally characterize specific problems.

The CMA Code, Version 3, treats the basic pyrolysis or charring event for a main insulation material. This material may be backed-up by a number of charring back-up materials, which in turn may be backed-up by noncharring structural elements. The CMA code will treat cracking or fissuring of the char, as well as surface mechanical removal or melting of the char structure.

SECTION 2

PROGRAM FEATURES, CAPABILITIES, AND COMPUTATIONAL PROCEDURES

2.1 IN-DEPTH SOLUTION ASPECTS

The in-depth solution procedure is the controlling feature of the code and accounts for most of the computing time. This procedure is basically a transient heat conduction calculation which is coupled to a pyrolysis rate calculation (and to boundary conditions discussed in Section 2.4 below). The following subsections discuss important aspects of the in-depth solution.

2.1.1 Decompositon (Pyrolysis or Charring)

Since many decomposing char forming materials appear to behave as three independently pyrolyzing components, the program uses a three-component decomposition model for the main material and for any decomposing back-up material.

The resin filler is presumed to consist of two components which decompose separately, while the reinforcing material is the third component which can decompose. The instantaneous density of the composite is given by

$$\rho = \Gamma(\rho_A + \rho_B) + (1 - \Gamma)\rho_C \tag{1}$$

where A and B represent components of the resin, and C represents the reinforcing material, Γ is the volume fraction of resin and is an input quantity (Section 3.1.2). Separate Γ values may be entered for any decomposing back-ups. Each of the three components can decompose following the relation

$$\left.\frac{\partial \rho_i}{\partial \theta}\right)_Y = -B_i \exp^{-E_{a_i}/RT} \rho_{o_i}\left(\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}}\right) \tag{2}$$

where ρ_{r_i} is the residual or terminal density of component i, and ρ_{o_i} is the original density of component i. The values ρ_{o_i} ρ_{r_i}, B_i, ψ_i, and E_{a_i} are input parameters for i = A,B,C for the main material. A separate i = A,B,C set of pyrolysis data may be entered for each decomposing back-up.

The decomposition event is computed explicitly. That is, "old" temperatures are used in Equation (2) to compute the decomposition rates and the new nodal densities.

2.1.2 In-Depth Energy Balance

For the purpose of writing the in-depth energy balance differential equation, we introduce the x coordinate system tied to the receding surface, as shown in the following sketch. In this system, we have the energy equation of the form

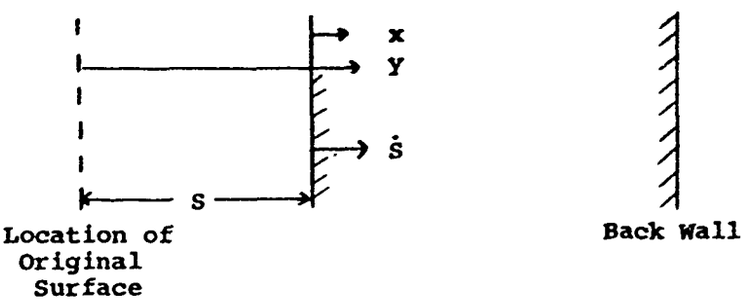
$$\rho C_p \left.\frac{\partial T}{\partial \theta}\right)_x = \frac{1}{A}\frac{\partial}{\partial x}\left(kA \left.\frac{\partial T}{\partial x}\right)_\theta + (h_g - \bar{h}) \left.\frac{\partial \rho}{\partial \theta}\right)_y + \dot{S}\ \rho C_p \left.\frac{\partial T}{\partial x}\right)_\theta + \frac{\dot{m}_g}{A}\left.\frac{\partial h_g}{\partial x}\right)_\theta \qquad (3)$$

in which the individual terms have physical meanings which may be interpreted as follows (from left to right): rate of storage of sensible energy, net rate of thermal conduction, pyrolysis energy rate, convection rate of sensible energy due to coordinate system movement, and net rate of energy convected with pyrolysis gas passing a point.

In this equation, the local specific heat and thermal conductivity are formulated from input temperature functions for both virgin plastic and char, C_{pp}, C_{pc}, k_p, and k_c (see Section 3.1.7 below). In partially pyrolyzed zones ($\rho_c < \rho < \rho_p$), the specific heat is formulated with a special mixing rule

$$C_p = xC_{pp} + (1 - x)C_{pc} \qquad (4)$$

where the weighting variable x is based on the convenient fiction that partially pyrolyzed material is a simple mixture of pure virgin plastic and pure char.



The quantity x is defined as the mass fraction of pure plastic in this imaginary mixture which yields the correct local density:

$$x = \frac{\rho_p}{\rho_p - \rho_c}\left(1 - \frac{\rho_c}{\rho}\right) \tag{5}$$

The thermal conductivity k will be weighted in the same manner unless the user provides specific information on a more complex x weighting in the input data. That is, the user may input functions of x for the following equation for the thermal conductivity of partially degraded plastic:

$$k = f_1(x)k_p + f_2(x)k_c \tag{6}$$

References 4 and 5 present an account of the rationale for the use of f-functions, along with recommended values.

The pyrolysis gas enthalpy is an input temperature dependent function (see Section 3.1.8 below). The quantity $\bar{h} \triangleq (\rho_p h_p - h_c \rho_c)/(\rho_p - \rho_c)$ is computed from temperature dependent h_p and h_c values determined from the input temperature dependent C_{pp} and C_{pc} values and input enthalpies of formation ΔH_{f_p} and ΔH_{f_c}.

Determination of the local cross-section area A will be discussed in Section 2.1.3 below.

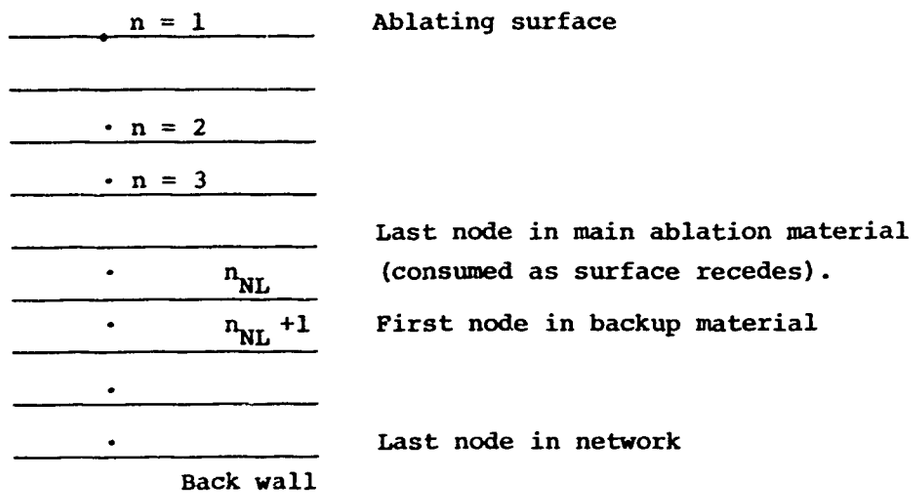
The other quantities in Equation (3), T, ρ and $\dot{S}$ are dependent quantities discovered during the solution process (except that in some boundary condition options $\dot{S}$ may be input).

2.1.3 Nodal Coordinate Layout and Body Shape Specification

The basic solution procedure of the CMA code is of the finite difference type. The following sketch illustrates a typical material section that is to be analyzed. Nodal* positions are specified by tabulating the thickness of successive nodes (see Section 3.1.5 below). The program permits a thermal contact resistance between adjacent nodes, and thus between adjacent materials (see Section 3.1.5 below). Nodes are numbered sequentially from the surface. A total of 100 nodes is permitted.

*As used here, the term node refers to a finite region in the slab wall, not to a discrete point or plane.

In harmony with the shifting x-coordinate system introduced in Section 2.1.2, nodal coordinates are tied to the heated surface. Any surface recession causes the last (deepest) node in the ablating material to shrink. If surface recession proceeds far enough, this node is dropped from the rear surface of the ablating material and the number of nodes reduced by one. Computation ceases when only one node of the main material remains.



Sketch of Nodal Network

The nodes are used for all energy balance calculations.

Since decomposition rates depend exponentially on temperature the decomposition calculations in the main material proceed on the basis of a "nodelet" network using small nodes a fraction as large* as the specified nodal layout used in energy balance calculations.**

The decomposition events are computed for each nodelet. The total density change for each node is taken as the sum of the nodelet density change rates.

The program permits the specification of a number of geometries:

1. Plane
2. Cylindrical or annular, with heated surface either inner or outer

*Usually one-tenth, although the number of nodelets per node may be selected by the user (see Section 3.1.3 below).

**The nodelet device is not used in charring back-up materials, which generally pyrolyze rather slowly.

3. Spherical or spherical shell, with heated surface either inner or outer

4. General "thermal stream tube" geometry, area varying as depth to any power

5. General "thermal stream tube" geometry, area varying arbitrarily with depth.

The distinction between these five options is indicated by the user according to the input rules given in Section 3.1.5 below.

2.1.4 Computation Procedure

2.1.4.1 General Pattern

As in all finite difference procedures, each step of the solution is made over an incremental time step $\Delta\theta$. Each computational step has three main events: internal decomposition, internal energy balance, and surface boundary energy balance. Computation of the three events gives "new" values of nodal densities, pyrolysis gas flow, nodal temperatures, and surface temperature and ablation rate. The program is then ready for the next step.

The pyrolysis event is computed for each nodelet in the main material from Equation (2), summed over the three components. Summation over all nodelets in a node gives the nodal $\partial\rho/\partial\theta$ and contribution to $\dot{m}_g$. Note that "old" known nodal temperatures (interpolated into the nodelet locations) are used in the pyrolysis calculation.

The internal energy balance equation then is computed "implicitly" for each node, using "new" temperatures in the heat conduction terms. The energy balance is linked explicitly to the decomposition events, however, since the pyrolysis gas fluxes used in the energy balance are derived from the explicit decomposition calculation. The energy balance is also linked explicitly to the surface boundary condition through the use of an "old" surface recession rate in all convection terms involving fluxes of solids. All other links to surface events are implicit.

The "implicit" formulation of the in-depth nodal energy equations yields a tri-diagonal set of equations which is solved for the unknown temperatures in two passes of direct elimination. The first pass eliminates one unknown from each equation and leaves the equation for the first node (at the heated surface) with only one unknown. In surface boundary condition Option 2, this temperature is specified and so is known. In Options 1 and 3, the first node equation is non-linear and so the first nodal temperature must be discovered by an iterative procedure. This will be discussed in Sections 2.4.2 and 2.4.3.

In any case, once this nodal temperature is determined, the second elimination pass determines the other unknown nodal temperatures and the entire in-depth calculation is ready for a new time step.

2.1.4.2 Limitations on Time Step Size

Experience shows that the implicit solution procedure of the CMA program is almost always stable regardless of time step size, and thus has an important advantage over explicit procedures for which stability considerations severely limit the allowable time step size.

However, in order to assure a smooth progression of the solution, limitations must be imposed upon the time increments. The user may specify as input (see Section 3.1.3 below) a maximum allowable time step not to be exceeded under any circumstances. Certain other limits are computed automatically and may reduce the solution time step $\Delta\theta$ below this value:

- Time steps are sized to limit the change of surface temperature during one step to approximately $50^{\circ}R$
- At the initiation of a problem, or when discontinuities are noted in the surface boundary condition option, the time step is reduced to 0.01 seconds, with subsequent values limited to twice the preceding value of the time increment.
- Time steps are limited so that recession during a time step, $\dot{S}\Delta\theta$, does not exceed the thickness of the smallest nodelet in the system.
- After all these limits have been applied, the time step is reduced so that the time remaining to the next printout time is divided into an integral number of time steps of the current size (so that no sudden reduction in time step is required in order to match a printout time).

2.2 INITIAL CONDITION

As initial conditions, the user may specify the temperature of each node and in addition may call out each node in a charring material as either virgin plastic or pure char. This allows studies of pre-charred materials and re-start problems. Section 3.1.5 below describes the necessary input rules.

2.3 BACKWALL BOUNDARY CONDITION

Heat transfer from the backwall of the system is treated with a simple temperature-potential convective transfer plus a radiative term, both

communicating with a "reservoir" at temperature T_{res}. The convective coefficient, backwall emissivity (or emittance), and T_{res} are all input constants (see Section 3.1.5 below).

2.4 ABLATING SURFACE BOUNDARY CONDITIONS

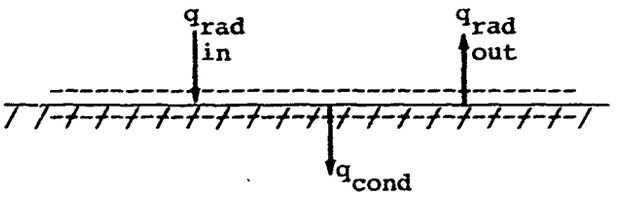
The ablating surface boundary conditions may take one of three forms at any instant, as determined by the user in the make-up of the time dependent boundary condition input table (see Section 3.1.9 below). The two simpler options will be described first, even though for historical reasons these are denoted "Option 2" and "Option 3". The general thermochemical ablation boundary condition, denoted "Option 1", is discussed last.

2.4.1 Option 2, Specified Surface Temperature and Surface Recession Rate

In this option, surface temperature and recession rate are specified by the user as input functions of time. All surface energy balance and surface thermochemical considerations are bypassed. Section 2.1.4.1 above describes how this specified temperature can be inserted into the in-depth solution procedure after the first pass of direct elimination.

2.4.2 Option 3, Specified Input Heat Flux with Zero Surface Recession Rate (Cooldown Option)

The following sketch illustrates the surface energy balance situation for this option. Equation (7) is the appropriate surface energy balance equation



$$\alpha_w q_{rad} - F_3 \sigma \varepsilon_w T_w^4 - q_{cond} = 0 \qquad (7)$$

In this equation, α_w is the surface absorptance and is assumed to equal ε_w, the surface emissivity, which is computed from input temperature dependent property tables (see Section 3.1.7 below). If the surface material is partially pyrolyzed, ε_w is computed according to the mixture rule of Equation (4). The term q_{rad} is an input time dependent heat flux specified in the boundary condition time tables (see Section 3.1.9 below). F_3 is an input view factor for

Option 3 calculations. It may depend on time (see Section 3.1.9 below). The term q_{cond} represents the rate of heat conduction into the material. It is the "mechanism" which joins the surface energy balance equation to the first nodal energy balance (since q_{cond} appears in the nodal energy balance equation) and thus to the in-depth solution procedure, as discussed in Section 2.1.4.1 above. The first pass of the elimination process for the in-depth tri-diagonal system reduction leaves the nodal energy balance equation for the first node as

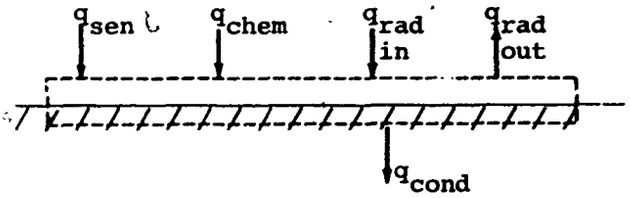
$$q_{cond} = AT_w + B \tag{8}$$

Equation (8), when substituted into the surface energy balance equation (7), yields a non-linear equation in T_w which the CMA program solves iteratively by the Newton-Raphson method.

2.4.3 Option 1, General Convective Heating and Thermochemical Erosion Option

2.4.3.1 General Description and Basic Energy Equation

In this option, events at the heated surface are determined by convective heating and by surface thermochemical interactions with the boundary layer gases. The sketch below illustrates the surface control volume and the



Sketch of Surface Energy Balance Control Volume and Energy Fluxes in Option 1

energy fluxes of interest. The surface energe balance equation employed is of the convective transfer coefficient type. In the CMA/CBM program, this energy balance equation takes the following form:

$$\underbrace{\rho_e u_e C_H (H_r - h_{ew})}_{q_{sen}} + \underbrace{\rho_e u_e C_M \left[\sum (Z^*_{ie} - Z^*_{iw}) h_i^{T_w} - B' h_w \right] + \dot{m}_c h_c + \dot{m}_g h_g}_{q_{chem}}$$

$$+ \underbrace{\alpha_w q_{rad}}_{q_{rad\ in}} - \underbrace{F\sigma\epsilon_w T_w^4}_{q_{rad\ out}} - q_{cond} = 0 \tag{9}$$

The last three terms in Equation (9) are the same as in the Option 3 boundary condition previously discussed in Section 2.4.2 above. The other terms in this equation require some further comments.

Before commencing a term by term discussion of Equation (9), however, it will be useful to describe the general nature of this transfer coefficient expression. Like all such expressions, Equation (9) is an approximation, the usefulness of which depends mainly on the validity of the transfer coefficient approach. A discussion of this subject is far beyond the scope of the present document. It may be observed here that transfer coefficients have successfully correlated both data and "exact" solutions in simple heat or mass transfer problems, and in combined heat and mass transfer problems for unity (or near unity) Lewis number. Equation (9) attempts to extend the transfer coefficient approach to both non-unity Lewis number and unequal mass diffusion coefficient problems, still allowing for chemical reactions and net mass transfer effects. This approach was suggested in Reference (6). Its validity is discussed in References 1 and 7.

In Equation (9), the term q_{sen} represents the "sensible convective heat flux." Physically, this is the convective heat flux which would occur for a frozen boundary layer and a non-catalytic wall in the absence of mass transfer;* it excludes all chemical energy contributions. (The term q_{sen} is perhaps more usually written in the form

$$q_{sen} = \rho_e u_e C_H (H_{s_r} - h_{s_w}) \tag{10}$$

but, since generally it is more convenient for the user to input H_r rather than H_s, q_{sen} in Equation (9) has been written in a modified form in which H_r appears. This form has the additional advantage that the driving force for energy transfer involves only edge gas states. The derivation of the modified form from Equation (1) is given in Reference 1 and Reference 6.

The transfer coefficient $\rho_e u_e C_H$ and the recovery enthalpy H_r are time dependent variables input by the program user in appropriate time tables (see Section 3.1.9 below). The transfer coefficient is automatically modified from the input value to account for various effects, as discussed in Section 2.4.3.4 below. The quantity h_{e_w} is part of the input thermochemical data discussed below.

*More generally in the presence of chemical reaction it is the diffusive heat flux from the gas to the wall even in the presence of net mass transfer, provided the boundary layer is frozen and the wall is catalytic.

The term q_{chem} represents the net of a number of fluxes of chemical energies at the surface. The Z*-difference term represents transport of chemical energy associated with chemical reactions at the wall and in the boundary layer; it is the chemical energy parallel to the sensible convective heat flux term. The Z* driving forces for diffusive mass transfer include the effects of unequal diffusion coefficients; for equal diffusion coefficients the Z*'s reduce to the familiar mass fractions K. The $\dot{m}_c h_c$ and $\dot{m}_g h_g$ terms represent energy fluxes arriving at the surface from within the solid material and the $B'h_w$ term represents energy leaving the surface in the gross motion (blowing) of the gas adjacent to the surface.

The source of the various terms in q_{chem} can better be visualized after a slight regrouping of terms. Observing that $B' = B'_g + B'_c$, and bringing the $\dot{m}_c h_c$ term inside the brackets, we have

$$q_{chem} = \rho_e u_e C_M \sum (Z^*_{ie} - Z^*_{iw}) h_i^{T_w} - (B'_c + B'_g) h_w + B'_c h_c + \dot{m}_g h_g \qquad (11)$$

Of the quantities in this q_{chem} expression, the convective mass transfer coefficient $\rho_c u_e C_m$ is obtained from the input time dependent values of $\rho_e u_e C_H$ (after any of the adjustments described in Section 2.4.3.4 below), by multiplying $\rho_e u_c C_H$ by an input constant value C_M/C_H (see Section 3.1.10.2 below). The quantity $\dot{m}_g$ will have been determined previous to the energy balance calculations in each time step in the decomposition section of the code (see Section 2.1.4.1 above). The quantity B'_g may be found as its definition $B'_g = \dot{m}_g/\rho_e u_e C_M$. The enthalpy h_c is obtained from integrations of the input temperature dependent specific values C_{p_c} (see Section 3.1.7 below). The pyrolysis gas enthalpy is obtained from the input temperature dependent h_g table (see Section 3.1.8 below).

Remaining quantities not yet discussed are B'_c, T_w (which does not appear explicitly but which is necessary to evaluate the temperature dependent values of the quantities h_c and h_g), h_{e_w}, $\sum Z^*_{ie} h_i^{T_w}$, $\sum Z^*_{iw} h_i^{T_w}$, and h_w. The quantities T_w, $\sum Z^*_{iw} h_i^{T_w}$, and h_w are input by the user as the dependent variables in a table with three independent variables: P, B'_g, and B'_c. Similarly, the quantities $\sum Z^*_{ie} h_i^{T_w}$ and h_{e_w} are input as the dependent variables in a table with P and T as independent variables. These tables are typically generated by the thermochemistry codes described in Section 2.4.3.2 below. Further discussion of these tables is given in Section 3.1.10.3.

The code surface energy balance solution procedure may be summarized as follows:

1. Look up H_r, $\rho_e u_e C_H$, P, and q_{rad} in input functions of time tables
2. Correct or adjust $\rho_e u_e C_H$ for various effects
3. Compute $\rho_e u_e C_M = C_M/C_H(\rho_e u_e C_H)$
4. Compute $B'_g = \dot{m}_g/\rho_e u_e C_M$
5. Assume B'_c
6. With P, B'_g, B'_c, look up in input surface thermochemistry tables values of T_w, $\sum z^*_{iw} h_i^{T_w}$, h_w
7. With ρ and T_w look up in input edge gas thermochemistry table values of $\sum z^*_{ie} h_i^{T_w}$, h_{e_w}
8. With T_w, look up in input property tables values of ϵ_w, h_c, h_g
9. Obtain values of A and B in expression $q_{cond} = AT_w + B$ from in-depth nodal energy balance solution routine
10. Construct Equation (9), noting departure from zero, if any
11. Adjust B'_c guess to reduce departure from zero
12. Go to Step (6) and continue

This procedure converges on a new B'_c value in very few iterations. The same procedure is used with T_w as the independent variable and B'_c as a dependent variable in portions of the table where B'_c varies slowly or not at all with T_w (see Section 3.1.10.3 below for input rules and suggestions).

2.4.3.2 Use of Thermochemistry Codes to Generate Input Data

Section 2.4.3.1 above makes it clear that the CMA code requires some complex tabular thermochemical input if the Option 1 boundary condition is to be used. These tables are generated by any one of a number of separate computer codes. The most recent such code is designated the Equilibrium Surface Thermochemistry Code, Version 3 (EST3). It is a general open and closed system thermochemical equilibrium code specifically constructed for this purpose. It is described in Reference 8. A generally similar code which differs from EST3 only in added detail is designated ACE and is described in Reference 9. An older version of EST3 was designated EST2 and is described in Reference 10. To obtain the necessary input tables for CMA, the user selects sets of values for the pressure P, the dimensionless gas rate B'_g, and the dimensionless char

rate B'_c. He specifies the elemental composition of the environment gas, the char, and the pyrolysis gas, and he supplies some general species thermochemical data for all molecules he wishes considered in the system. Finally he specifies an unequal diffusion coefficient if he believes unequal diffusion effects will be important. The thermochemistry code then computes all the dependent quantities of interest at each table point in the P x B'_g x B'_c matrix of independent variable values, namely, T_w, $\sum z^*_{iw} h_i^{T_w}$, and h_w, and punches this information out on punched cards. Similarly, the tables of $\sum z^*_{ie} h_i^{T_w}$ and h_{e_w} values for the frozen edge gas are prepared as functions of P and T, and punched out on cards. All these cards form part of the card input deck (see Section 3.1.10.3 below).

2.4.3.3 Simpler Forms of the Surface Energy Balance Equation

As noted in Section 2.4.3.1 above, for equal diffusion coefficients the Z^*_i driving forces reduce to the simple mass fractions K_i. If in addition to equal diffusion the user specifies that $\rho_e u_e C_M = \rho_e u_e C_H$, then since $\sum K_{ie} h_i^{T_w} = h_{e_w}$ and $\sum K_{iw} h_i^{T_w} = h_w$ by definition, Equation (9) simplifies to the more familiar form

$$\rho_e u_e C_H \left(H_r - (1 + B')h_w\right) + \dot{m}_c h_c + \dot{m}_g h_g + \alpha_w q_{rad} - F_1 \sigma \varepsilon T_w^4 - q_{cond} = 0 \qquad (12)$$

In this expression h_{e_w} and $\sum z^*_{ie} h_i^{T_w}$ do not appear, hence the frozen edge gas table is not necessary and need not be included in the input (see Section 3.1.10.3 below).

If ablation and pyrolysis do not occur, Equation (12) assumes a still simpler form

$$\rho_e u_e C_H (H_r - h_w) + \alpha_w q_{rad} - F_1 \sigma \varepsilon T_w^4 - q_{cond} = 0 \qquad (13)$$

Section 3.1.10.3 below will make it clear that this equation can be handled by the CMA code through the mechanism of "non-ablating" surface thermochemistry tables. Equation (13) can be reduced to a temperature driving force, if this is desired

$$h(T_r - T_w) + \alpha_w q_{rad} - F_1 \sigma \varepsilon T_w^4 - q_{cond} = 0 \qquad (14)$$

provided that the user enters T_r instead of H_r and h instead of $\rho_e u_e C_H$ in the boundary condition time tables (see Section 3.1.9 below), and T_w instead of h_w in the surface thermochemistry tables (see Section 3.1.10.3 below).

2 4.3.4 Automatic Program Adjustments to Input Values of Time-Dependent Convective Heat Transfer Coefficient $\rho_e u_e C_H$

2.4.3.4.1 General remarks

The CMA program user may call for several automatic adjustments to be made to the values of the convective transfer coefficient input in the functions-of-time table. This section describes these adjustments and the order in which they are applied in the program.

One adjustment, pertinent to the exposed throat ablative materials in rockets, is the "radius ratio correction." This adjustment accounts for the effect of pressure decay and throat radius change on the throat transfer coefficient, provided, as will be explained below, that the trends of the effects are given by the Bartz equation (Reference 11). A refinement to this basic correction includes the additional effect of pressure on the burning rate of a solid propellant. A second refinement on the throat radius ratio correction allows in an approximate manner for the effects of char swelling.

A second correction allows for the reduction in transfer coefficients due to the transpiration or blowing effect of the pyrolysis gases and thermochemically eroded char being injected into the boundary layer.

A final modification distinguishes the convective mass transfer coefficient $\rho_e u_e C_M$ from the heat transfer coefficient $\rho_e u_e C_H$ by referring to an input constant ratio C_M/C_H.

2.4.3.4.2 Radius ratio correction, burning rate correction, and char swell correction

Radius ratio and burning rate corrections

If the user is analyzing a solid propellant rocket throat ablation problem, and calls for the throat radius ratio correction according to the input procedures described in Section 3.1.10.3 below, the program, will, at every time step, automatically reduce the input time table value of C_H to account for the effects of the increase in throat radius resulting from ablation. The correction is derived by noting that for a solid rocket motor

$$p_c \propto \left(\frac{1}{r^*}\right)^{2/(1-n)} \tag{15}$$

where p_c - chamber pressure

r^* - nozzle throat radius

n - burning rate exponent of the solid propellant when the burning rate $\dot{r}$, is represented by $\dot{r} = bp_c^n$

From the simplified Bartz equation

$$h_c \propto \frac{p_c^{0.8}}{r^{*0.2}} \tag{16}$$

where h_c is the convective heat transfer coefficient. Combining these two equations gives

$$h_c \propto \left(\frac{1}{r^*}\right)^{\frac{1.8-0.2n}{1-n}} \tag{17}$$

For n = 0, this equation reduces to

$$h_c \propto \left(\frac{1}{r^*}\right)^{1.8} \tag{18}$$

and would represent the correction in the convective heat transfer coefficient for a constant mass flow rate. This is usually termed the radius ratio correction.

The CMA program refers the time table values of C_H to the initial condition. This, if C_{H_o} represents the input heat transfer coefficient at a given time, the program will reduce the input value according to

$$C_{H_1} = C_{H_o}\left(\frac{r_1^*}{r^*}\right)^{\frac{1.8-0.2n}{1-n}} \tag{19}$$

if the radius ratio correction has been called for.

Char swell correction

It has been determined empirically that certain phenolic materials swell or thicken during or following charring. The amount of swell has in some cases (References 12 and 13) appeared to be roughly proportional to the thickness of the charred material:

$$S_{swell} = K\tau_{char} \tag{20}$$

where K is a proportionality constant.

The char thickness (τ_c) is here defined as the char depth below the original surface (δ_c)* minus the surface recession predicted in the absence of swelling (S_p)

$$S_{swell} = K(\delta_c - S_p) \tag{21}$$

Therefore, if swell occurs, the correct recession would be given by:

$$S = S_p - S_{swell} = S_p - K(\delta_c - S_p) \tag{22}$$

or

$$S = S_p + (S_p - \delta_c)K \tag{23}$$

Furthermore, surface recession rate would be given by:

$$\dot{S} = (1 + K)\dot{S}_p - K\dot{\delta}_c \tag{24}$$

For a given value of K, these terms are computed in the CMA code and output in an auxiliary output block. In addition, if adjustments in heat transfer coefficient by a radius ratio correction are being computed as is often the case with prediction of rocket nozzle throat response, the corrected (after swell) value of recession is utilized in the radius ratio correction calculation. Otherwise this char swell formulation is not used in the thermal response calculations.

2.4.3.4.3 Blowing rate correction

The CMA program will automatically reduce the transfer coefficient to account for the familiar blowing effect according to the equation

$$C_H = C_{H_1} \frac{\zeta}{e^{\zeta} - 1} \tag{25}$$

where $\zeta \triangleq \dfrac{2\lambda \dot{m}_{inj}}{\rho_e u_e C_{H_1}}$

*The distance δ_c is defined as the distance between the original location of the heated surface and the present location of a line of density $\rho_c + r_c(\rho_p - \rho_c)$, where r_c is a user-selected input constant (see Section 3.1.6 below).

and $\dot{m}_{inj}$ = amount of material injected into the boundary layer, as discussed below

λ = an input number, discussed below

$\rho_e u_e C_{H_1}$ = transfer coefficient as input and reduced, if required, by the radius ratio and/or burning rate effect discussed in the section immediately above.

Further details of this correction scheme will be discussed below.

Values for λ

With $\lambda = 0.5$, this scheme gives the "classical" blowing correction often expressed as (References 14 and 15)

$$\frac{C_H}{C_{H_1}} = \frac{\ell n(1 + \dot{m}_{inj}/\rho_e u_e C_H)}{\dot{m}_{inj}/\rho_e u_e C_H} \tag{27}$$

which is useful for a wide range of problems.

Other values of λ allow the user to fit blowing correction curves of C_H/C_{H_1} versus B'_{inj} or B'_{inj1} to account for special effects, in the few cases where these are known with confidence, such as molecular weight effects* or variable property effects. In view of the uncertainties, it is recommended that $\lambda = 0.5$ be used for laminar flow. A value $\lambda = 0.4$ appears to correlate constant properties turbulent data somewhat better. The parameter λ may be made a function of time, if desired, to simulate transition effects. A value of $\lambda = 0$ suppresses the blowing correction.

Options for $\dot{m}_{inj}$

The symbol $\dot{m}_{inj}$ represents the rate of mass injected into the boundary layer which is effective in changing velocity profiles and reducing diffusion events. The CMA program allows three general choices for $\dot{m}_{inj}$:

1. All mass transfer is effective in reducing blowing

   $$\dot{m}_{inj} = \dot{m}_c + \dot{m}_g$$

2. If part of $\dot{m}_c$ represents failing species, and this failing component $\dot{m}_{fail}$ appears on the surface thermochemistry cards (an ACE output option), then these fail rates can, at the option of the user (see Section 3.1.10.3 below) be read in,

*These are known to be important in some simple injection problems but with many chemical reactions taking place the situation is somewhat obscure.

stored, and deducted as appropriate when computing injection rates for the blowing correction

$$\dot{m}_{inj} = \dot{m}_c - \dot{m}_f + \dot{m}_g$$

3. It can be assumed that the pyrolysis gas is injected into the boundary layer through cracks and fissures rather than evenly over the heated surface; in this case the gas injection presumably plays no role in the blowing reduction, in which case

$$\dot{m}_{inj} = \dot{m}_c$$

or

$$\dot{m}_{inj} = \dot{m}_c - \dot{m}_f$$

if Option 2 above is being used. This fissure model is discussed in more detail in Section 2.4.3.5 below.

The CMA program automatically computes the injection rate $\dot{m}_{inj}$ according to the first option above unless the fail option has been invoked according to the input rules discussed in Section 3.1.10.3 below and unless the fissure model has been called for as described in the same section.

Blowing correction applied to C_{H_1}

Note that the blowing correction is applied to the value of C_H after it has been adjusted to account for the radius ratio (including burning rate and char swell) effect.

2.4.3.4.4 Computation of convective mass transfer coefficient $\rho_e u_e C_M$

After $\rho_e u_e C_H$ has been computed from the input time dependent value $\rho_e u_e C_{H_o}$ and corrected, if called for, for radius ratio and mass transfer effects, a mass transfer coefficient $\rho_e u_e C_M$ is computed by multiplying $\rho_e u_e C_M$ by an input constant ratio C_M/C_H. See Section 3.1.10.3 below.

2.4.3.4.5 Possible future additional corrections

The automatic adjustments to input values of $\rho_e u_e C_{H_o}$ presently included in the CMA program include the largest and most important corrections the user is likely to desire. A small temperature correction might occasionally be of interest but has not yet been added to the program. A molecular weight effect in the blowing correction must for the present be accounted for by adjusting λ; this probably will yield adequate accuracy until more is known about

(1) the desired molecular weight effect, and (2) the molecular weight of the pyrolysis gas component of the injected material.

2.4.3.5 Fissure Model Option for Surface Energy Balance

Equation (9), which is repeated here for reference, includes the energy efforts associated with injecting the pyrolysis

$$\rho_e u_e C_H (H_r - h_{e_w}) + \rho_e u_e C_M \sum (Z^*_{ie} - Z^*_{iw}) h_i^{T_w} - B' h_w + \dot{m}_c h_c + \dot{m}_g h_g$$

$$+ \alpha_w q_{rad} - F\sigma\varepsilon_w T_w^4 - q_{cond} = 0 \qquad (28)$$

gas rate $\dot{m}_g$ into the surface from below with enthalpy h_g and "blowing" a corresponding flux away from the surface with enthalpy h_w (included in the $B'h_w$ term). However, some ablative materials crack or fissure during heating and sometimes it is desired to explore the effects of assuming that the pyrolysis gas follows these fissures to the surface and is blown out through the boundary layer without participating to any great degree with the boundary layer events. Specifically, in the "fissure model", the $\dot{m}_g h_g$ injection energy term in the surface energy balance is matched by an equal $m_g h_g$ outflow term as the gas passes across the surface without interacting. By the same token, the blowing term $B'h_w$ now becomes $(B' - B'_g)h_w$, since the B'_g blowing effect has been isolated and identified with enthalpy h_g rather than h_w.

Thus, the "fissure model" surface energy balance equation is

$$\rho_e u_e C_H (H_r - h_{e_w}) + \rho_e u_e C_M \sum (Z^*_{ie} - Z^*_{iw}) h_i^{T_w} - B'_c h_w + \dot{m}_c h_c$$

$$+ \alpha_w q_{rad} - F\sigma\varepsilon_w T_w^4 - q_{cond} = 0 \qquad (29)$$

Suitable programming has been implemented in the current CMA code to allow utilization of this model with only minimal adjustment of imput data.

The user may call for this surface energy balance type by punching the fissure model flag in the lead card for the surface thermochemistry tables (see Section 3.1.10.3 below).*

When using this model, the user generally makes two other modifications to the usual input. First to harmonize the in-depth calculations with the idea of the pyrolysis gas rising up cracks and fissures, pyrolysis gas thermal pick-up in the char is suppressed by artifically "flattening" the gas enthalpy-temperature relationship (see Section 3.1.8 below) for temperatures above the pyrolysis temperature (i.e., $C_{p_g} = 0$ in this temperature range). Second, the surface thermochemistry tables are prepared for $B'_g = 0$ so as to exclude any surface thermochemical effects of the pyrolysis gases. Since the interpolation routine requires two B'_g values for a given pressure, the $B'_g = 0$ table is duplicated and the duplicate is assigned a second, artifical B'_g value.

2.4.3.6 Accounting For Condensed Phase Removal (Melting or "Failing")

The surface energy balance Equation (9) does not show an energy term corresponding to condensed phase removal (as in thin layer melting or failing) but failing is detected by the ACE surface state program and the associated energy effect is automatically accounted for in the surface thermochemistry tables. The ACE User's Manual, Reference 13, describes the melting or failing features of that code and provides detailed instructions for implementing them. The EST3 code cannot account for failing.

*This flag also causes B'_g not to be included in the blowing reduction calculation for the transfer coefficients (see Section 2.4.3.4 above).

SECTION 3

USER'S GUIDE

This part of this report provides

- Detailed user oriented input instructions for the CMA code
- An explanation of the program output
- Miscellaneous specific information

3.1 INPUT FORMAT

The input to the Charring-Material Thermal Response and Ablation Program, Version 3, can conveniently be divided into ten parts. All ten portions of the deck must be present for most runs. These individual parts will be described in the following subsections.

3.1.1 Title and Heading Information

The first three cards of the data deck are used to transmit title and heading information to the output. The first 72 columns of each of these cards may be used for the title, the alphameric information in columns 61 through 72 of the third card being used as a page heading on all pages after the first.

3.1.2 Internal-Decomposition Kinetic Data

These three cards supply the constants used in Equation (2).* They are supplied according to the following format.

Column	Format	Data	Units
1	I1	Alphabetic character A, B, or C referring to the material components. These must be on the first, second and third cards of this set in order	
11-20	F10.5	Initial density of component i, ρ_{o_i}	lb/ft^3
21-30	F10.5	Residual density of component i, ρ_{r_i}	lb/ft^2
31-40	F10.3	Pre-exponential factor, B_i, of Equation (2)	sec^{-1}
41-50	F10.5	Density factor exponent, ψ_i	---

*Reference 4 cites relevant data for many materials of interest.

Column	Format	Data	Units
51-60	E10.3	Activation energy factor ($E_{a_i}/^{o}R$)	^{o}R
61-70	F10.5	Minimum temperature of reaction zone	^{o}R
71-79	---	Not read	---
80	---	(Third card only) Number (0 to 5) of decomposing (pyrolyzing) back-up materials in this problem	---

In this table, the minimum temperature of the reaction zone is included only as a means of reducing computational time. Thus, if a nodal temperature is below this value, the program will bypass the fairly complex density-calculation procedure. Also for the case of a non-decomposing reinforcing material, the value of this temperature can be set to a ridiculously high value, thus assuring no decomposition.

3.1.3 Output Interval Specification and General Program Constants

Two cards are used to provide the program with the values of certain general constants, to establish the time intervals for which output will be obtained, and to specify thermocouple and isotherm output, if desired. (If thermocouples and/or isotherms are called for, additional cards are needed, as described.)

First Card

Column	Format	Data	Units
1-2	I2	Number of nodelets per node (blank implies 10)	---
3-5	I3	Total number of nodes (maximum of 100)	---
6	I1	A non-zero punch in this column will cause thermocouple and isotherm output, normally listed with regular output, to also be punched as cards	---
7-8	I2	Number of thermocouples for which output is desired. (The depths of these thermocouples are specified on additional cards of this group.) Punches here will cause thermocouple temperatures as a function of time to be output at the end of the regular program output.	---
9-10	I2	Number of isotherms for which output is desired. (The temperatures of these isotherms are specified on additional cards of this group.) Punches here will cause isotherm depths as a function of time to be output at the end of the regular program listing.	---

First Card (concluded)

Column	Format	Data	Units
11-20	F10.5	Initial value of time	sec
21-30	F10.5	Final value of time	sec
31-40	F10.5	Initial output time interval	sec
41-50	F10.5	Second output time interval	sec
51-60	F10.5	Third output time interval	sec
61-70	F10.5	Maximum time step permitted under any circumstances. If unpunched, this limit will be set equal to 5.0 seconds	sec
71-80	F10.5	Blowing-rate parameter, λ	---

Second Card

Column	Format	Data	Units
1-10	F10.5	Time of transition from initial to second output time interval	sec
11-20	F10.5	Time of transition from second to third output time interval	sec
21-30	F10.5	Minimum thickness of last ablator node. When because of surface recession, the last node of the ablation material shrinks below this value, it is combined with the adjacent ablator node. A value equal to the second node's thickness is usually appropriate	in
31-40 41-50 51-60	F10.5 F10.5 F10.5	Heat of formation of the virgin plastic, the char, and the pyrolysis gas, respectively. These are evaluated at the datum temperature given in columns 71-80	Btu/lb
61-70	F10.5	Volume fraction or mass fraction of the virgin plastic which is occupied by resin. If mass fraction, it is input as a negative number	---
71-80	F10.5	Datum temperature for heats of formation given in columns 31-50. For Option 1 computations, this must be the same temperature as used in the EST program for generating the surface thermochemistry data deck.	^{o}R

Additional Cards as Required

Column	Format	Data	Units
1-80	8(F10.5)	If thermocouple and/or isotherm output have been called for, these cards specify thermocouple depths in inches below the original surface and isotherm temperatures in degrees Rankine. Isotherm temperatures must begin on a new card. The total number of thermocouples and isotherms may not exceed 20. If no thermocouples or isotherms are called for, these card(s) are omitted.	in and/or ^{o}R

3.1.4 Back-Up Material Decomposition Data (Optional)

If the problem includes decomposing (pyrolyzing) back-up materials, a four card set of pyrolysis data must be included for each such decomposing back-up material. Each four card set has two subgroups:

- First Subgroup:
  Back-Up Material Decomposition Kinetic Data (3 Cards)
  Three cards in the format of the three kinetic data cards for the main material, except that column 80 of Card 3 is not read. Groups 4a (three cards) and 4b (one card) are placed together as a four-card unit. There will be one such four-card unit for each decomposing back-up material.
- Second Subgroup:
  Enthalpies of Formation, Resin Volume, Or mass Fraction, En Enthalpy Reference Temperature (1 Card)
  This card follows the same format as the second card of Section 3.1.3 except that general data on that card not pertinent to the back-up material is not needed and is not read:

Column	Format	Data	Units
1-30	ad lib	Not read	---
31-40 41-50	F10.5 F10.5	Heats of formation of virgin plastic and char, respectively, evaluated at the datum temperature given in columns 71-80	Btu/lb
51-60	ad lib	Not read	---
61-70	F10.5	Volume fraction or mass fraction of the virgin plastic back-up which is occupied by resin. If mass fraction, it is input as a negative number	---
71-80	F10.5	Datum temperature for heats of formation.	^{o}R

3.1.5 Nodal Data

A set of cards equal in number to the number of nodes is used to provide certain information with regard to the initial state of the nodes, their thickness, and the contact resistances between them. In addition, the first card of this set is used to specify the geometric nature of the exposed surface, that is whether it is a flat plate or an internal or external radius. The format for these cards is shown in the following table.

Column	Format	Data	Units
1-2	I2	Material number, 1 for main material virgin plastic, 2 for main material char, 0 for main material pyrolysis zone (can not be input), 22-31 for charring back-up materials (see discussion below), and 3-10 for non-charring back-up materials	---
3-12	E10.0	Initial temperature of the node	^{o}R
13-22	E10.0	Initial cross-sectional area of the node in any units or normalized on any convenient reference such as the surface area. This data is required only for "general" geometries; for planar, cylindrical, and spherical geometries, and for shapes for which the area varies as a power of the radius the specification of individual nodal areas is not required and these columns should be left blank	Arbitrary
23-32	E10.0	Initial thickness of the node (For suggestions on the selection of nodal thicknesses, see Appendix A.)	in
33-42	E10.0	First card only. 0 for planar surface; positive value of internal radius or negative of value of external radius for all non-planar axisymmetric geometries (including spheres and shapes with $A \sim r^a$)	in
		Second card only. Exponent on radius giving nodal cross-sectional area variation for spherical and other "regular" geometries. Sphere requires 2.0. No entry needed for planar and cylindrical geometries. Must be blank is "general" geometry option is used	in
43-52	E10.0	Contact resistance between this node and the next node.	$ft^2sec\text{-}^{o}R/Btu$
53-80	38X	NOT USED	

The number of nodes may not exceed 100. Note that for a restart calculation, the nodes that make up the precharred depth in the main material are called out as material 2.

In the list of nodes, any decomposing back-up material nodes will appear between the last node of the main ablating material and the first node of non-charring back-up (if any). Material numbers of the charring back-ups must be assigned as follows:

	Virgin	Char
1st charring back-up	22	23
2nd charring back-up	24	25
3rd charring back-up	26	27
4th charring back-up	28	29
5th charring back-up	30	31

The rules here differ from those for non-charring back-ups in that one charring back-up must be distinguished from another if it has a different location. For example, the fourth back-up may happen to be identical to the first, but it still receives a different material number.

3.1.6 Back Wall Heat Transfer Conditions; Char and Pyrolysis Zone Criteria

Heat transfer at the back wall is characterized by a convective heat transfer coefficient, an emissivity, and the temperature of a "reservoir" to which heat transfer takes place from the back wall. This card allows the specification of these three quantities. Blanks serve to specify an insulated back wall.

Two additional entries define char edge density and pyrolysis zone edge density according to the following definitions:

$$\rho_{\substack{\text{char} \\ \text{edge}}} = \rho_c + r_c(\rho_p - \rho_c)$$

$$\rho_{\substack{\text{pyrolysis} \\ \text{edge}}} = \rho_c + r_p(\rho_p - \rho_c)$$

The user inputs values for r_c and r_p. Typical values are $r_c = 0.02$ (defining the char edge as occurring where the density is $\rho_c + 0.02(\rho_p - \rho_c)$) and $r_p = 0.98$. If no entries are made for r_c and r_p, 0.02 and 0.98 will be assumed.

For char swell corrections, a value of r_c = 0.5 is suggested (see Section 2.4.3.4 above).

Column	Format	Data	Units
1-10	F10.5	Back wall convective coefficient	Btu/sec-ft^2 ^oR
11-20	F10.5	Back wall emissivity	---
21-30	F10.5	Reservoir temperature	^oR
31-40	F10.5	Char zone criterion r_c	---
41-50	F10.5	Pyrolysis zone criterion r_p	---
60	I1	One punch calls for output of thermal conductivity in place of enthalpy in standard output block	

3.1.7 Material Property Tables and f-Function Tables

In these tables are presented the requisite thermodynamic data for the main material virgin plastic (material no. 1), the main material char (material no. 2), any charring back-up materials, and the various non-charring back-up materials (materials 3 through 10, as required) specified in the nodal data table. These data are input as functions of temperature according to the following format.

Column	Format	Data	Units
1-2	I2	Flag, nominally zero, +1 marks terminal card of last material property table, -1 marks terminal card of other intermediate material property tables.	---
3-12	F10.5	Temperature (independent variable)	^oR
13-22	F10.5	Specific heat	Btu/lb-^oR
23-32	F10.8	Thermal conductivity	Btu/ft-sec-^oR
33-42	F10.5	Emissivity	---

Separate tables must appear for the main material virgin plastic and the main material char, in that order. If the main material does not char, a "char" table must still be included. If charring back-up materials have been included in the problem, then paired tables must be given for the virgin plastic and char properties of all such back-ups, with the table pairs appearing in the same order with which such back-ups appear in the nodal list (see Section 3.1.5 above. If a charring back-up is duplicated, duplicate tables must be included

in the proper order. Tables for decomposing back-ups follow the two tables for the main charring material and precede any tables for non-charring back-ups.

Any necessary property tables for non-charring back-up materials follow these charring material tables. Preceding each such table, a single lead card" is used to specify the back-up material identification number and density. These data are given in the first ten columns with the following format.

Column	Format	Data	Units
1-2	I2	Material identification number (ranging from 3-10, inclusive)	---
3-10	F8.4	Material density	lb/ft^3

If the emissivity for materials 1 and 2 is input as zero, it is automatically presumed to be 1.0 for any Option 3 computations. (The user may desire to input a zero emissivity for radiation equilibrium problems under Option 1.)

The number of temperature points in each table may not exceed 30 or may not be less than 2. The tables must be ordered on either ascending or descending temperatures.

For all charring materials, material properties for partially degraded or charred material are formed from weighted averages of the plastic and char properties for the relevant nodal temperatures according to the mixture rules presented in Section 2.1.2 above. If the user wishes to employ the so called "f-functions" for this purpose (see Equation (11) of Section 2.1.2 above, the $f_1(x)$ and $f_2(x)$ values are input along with the other material properties tables described in this section. Each f-function table follows the following special rules:

- An f-function table is flagged by a lead card of the following format

Column	Format	Data	Units
1-2	I2	Identification flag which must be between 3 and 10 and which must not duplicate the identification number of a previously read non-charring back-up property table	---
3-10	F8.4	Must be blank or zero	---

Column	Format	Data	Units
11-16	6I1	Material assignment numbers for the following f-function table. If this table is assigned to the surface material, column 11 must be blank. If the same f-function table is to be assigned to one or more charring back-up materials, these assignments follow in columns 12-16 in any order with imbedded or following blanks being ignored. Note that for the material assignments in columns 11-16 of the lead card, the surface material is designated as zero (or blank) and the charring back-up materials are designated 1 through 5 in the same order as they appear in the nodal data cards. If column 11 is not blank, the f-function table will not be used for the surface material.	---

- The actual f-function table follows the lead card and has the following format

Column	Format	Data	Units
1-2	I2	Flag, as above, for last card of table	---
3-12	F10.5	x (independent variable)	---
13-22	F10.5	$f_1(x)$	---
23-32	F10.5	$f_2(x)$	---

- The f-function tables may be distributed anywhere among the non-charring back-up properties tables.
- If any charring material, main or back-up, is not assigned an f-function table, the thermal conductivity of partially charred substance for this charring material will follow the simple linear form of Equation (14).

3.1.8 Pyrolysis Gas Enthalpy Table

This table specifies the variation of pyrolysis gas enthalpy with temperature. These values are added to the heat of formation of the pyrolysis gas as specified on the program constant cards (see Section 3.1.3 above). This table is presented on card pairs, the first of which presents a set of temperature (up to 8), the second containing the corresponding enthalpy values. The first column of the temperature card is used as a flag, nominally blank but containing an integer to mark the last pair of cards. The format for this card pair is given as (I1, F9.5, 7F10.5/8F10.5), implying a basic field length of

ten columns for both temperature and enthalpy, with the exception of the first temperature which is restricted to columns 2 through 10. The temperatures should be given in ascending sequence with the exception of the last card pair which may have from one to eight entries). The total number of temperature points in the table may not exceed 30 and may not be less than 2.

Note that no pressure dependence of pyrolysis gas enthalpy may be accounted for. Also note that only one pyrolysis gas is allowed, and hence the gas given off by any charring back-ups must be the same as the pyrolysis gas of the main material, as would be the case, for example, for carbon phenolic backed by silica phenolic.

3.1.9 Surface Time-Dependent Boundary Conditions

The table of time-dependent boundary conditions is used to specify alternative sets of time-varying dependent variables for the various options. The table must be ordered with the time values increasing.

The table may be thought of as consisting of a number of sub-tables each sub-table representing one option. The switch from one option to another requires a repeated time entry, the first card representing the last entry of the earlier table and the second card representing the start of the next table.

The total number of time values in the table is limited to 30. Each sub-table must have at least 2 entries, hence the number of sub-tables cannot exceed 16. (The most common problem has only 2, representing an Option 1 or Option 2 calculation followed by cooldown, Option 3.)

The format for the time-tables is as follows:

Column	Format	Data	Units
1	I1	Flag, nominally blank, punched to indicate the last card of the time table. In any Option 1 calculations are to be done, this flag must be a one (which calls for reading the surface equilibrium tables). If no Option 1 calculations are to be done, this flag must be a two.	---
2-10	F9.5	Time (independent variable)	sec
11-20	F10.5	Option 1: Recovery enthalpy, relative to the same chemical base state as used with the heats of formation.	Btu/lb
		Option 2: Surface temperature	^{o}R
		Option 3: Radiation view factor	---

Columns	Format		Data	Units
21-30	F10.5	Option 1:	Radiant energy flux to the surface	Btu/ft^2-sec
		Option 2:	Surface-recession rate	mils/sec
		Option 3:	Radiant energy flux to the surface	Btu/ft^2-sec
31-40	F10.5	Option 1:	Heat-transfer coefficient	lb/ft^2-sec
		Option 2:	Blank	
		Option 3:	Must be blank	
41-50	F10.5	Option 1:	Pressure	atm
51-60	F10.5	Option 1:	Blowing reduction parameter (if a function of time; blank entries will be filled by constant value entered in column 71-80 of the first card of Section 3.1.3 above).	

3.1.10 Surface Thermochemistry Data (Option 1 Only)

3.1.10.1 Introduction

As discussed in Section 2.4.3 above, problems involving use of the surface thermochemistry option (Option 1) require the input of an arry of surface mass and energy data particular to the option and the material being analyzed. These data include the specification of the ratio of mass transfer coefficient to heat transfer coefficient, the radiation view factor, and surface thermochemical data. The cards containing this input are described below. Problems not involving Option 1 calculations do not need the surface thermochemistry data deck.

3.1.10.2 Ratio of Mass to Heat Transfer Coefficient, View Factor, Surface Option Flags

A single card serves to specify the ratio of the convective mass transfer coefficient to the convective heat transfer coefficient (C_M/C_H), the surface radiation view factor, and a number of control flags. (The view factor on this card will only be used for Option 1 computations. For Option 3 (cool-down) computations, a separate Option 3 view factor is input as a function of time in the functions-of-time tables. In Option 1 problems with "radiation equilibrium", the radiant energy flux to the surface may be input as zero, requiring then that the Option 1 view factor be input as zero.)

Column	Format	Data	Units
1-10	F10.0	C_M/C_H	---
11-20	F10.0	Option 1 view factor	---
21-29	F9.0	Burning rate exponent n used in throat problems to adjust input convective transfer coefficient $\rho_e u_e C_{H_o}$ according to $$\frac{C_{H_1}}{C_{H_o}} = \left(\frac{r_{s_o}}{r_s}\right)^{\frac{.68 \cdot .42n}{1-n}} \quad (30)$$ C_{H_1} is then adjusted to account for blowing effects. Applies to inner radius heating problems (nozzles) only. See Section 2.4.3.4 above.	---
30	I1	One punch calls for radius ratio correction on input convection transfer coefficient $\rho_e u_e C_{H_o}$ according to Equation (30) above. Note: Input of n > 0 calls for Equation (30) and will override blank in this column. Applies to inner radius heating problems (nozzles) only.	---
31-39	9X	Blank	---
40	I1	One-punch calls for reuse of previously input surface tables. No more input is read. Note: Ratio of C_M/C_H (columns 1-10) must be the same for this calculation as for previous one if this option is to be used.	---
50	I1	One-punch reads B'_f in "new format" surface thermochemistry tables (as discussed below) and uses $B' - B'_f$ in blowing correction to $\rho_e u_e C_{H_o}$ or $B' - B'_g - B'_f$ if fissure model is being used, see column 60 below), no punch reads "old format" surface tables or ignores B'_f in "new format" tables and uses B' in blowing correction to $\rho_e u_e C_H$ (or $B' - B'_g$ in fissure model).	---
51-59	9X	Blank	
60	I1	One-punch invokes "fissure model": exludes B'_g from blowing correction on $\rho_e u_e C_{H_o}$ and from surface energy balance; see Section 2.4.3.5 above.	---
61-70	F10.0	Char swell proportionality constant K in Equation (21), section 2.4.3.4.2	---

3.1.10.3 Surface Thermochemistry Table

3.1.10.3.1 Introduction

This table supplies the necessary input data for the surface energy balance computations in Option 1. (This energy balance is discussed in Section 2.4.3 above.)

Most commonly the deck of cards which make up the surface thermochemistry table is generated by the Equilibrium Surface Thermochemistry (EST) program or the Aerotherm Chemical Equilibrium (ACE) program. The user's manual for these programs (References 8 and 9) describe this table in complete detail. On occasion, the user may desire to construct his own surface thermochemistry table, and so the following sections include brief descriptions of the organization and format of these tables. The main emphasis, however, will be on the communication between thermochemistry programs and the Charring Material Ablation program, since this is of the most general interest.

3.1.10.3.2 Edge enthalpy data

Equation (9) of Section 2.4.3 shows that if diffusion coefficients are not equal or if the ratio C_M/C_H is not unity, then the surface energy balance requires data about the edge gases of the boundary layer. These data are provided in a special "edge table". The independent variables for this table are pressure and temperature. Dependent variables are h_{e_w} and the sum $\Sigma Z^*_{ie} h_i^{T_w}$.

The edge enthalpy data are entered on the cards as follows:

Column	Format	Data	Units
1-8	F8.5	Pressure	atm
9-24	16X	Blank	---
25-33	F9.4	Temperature	^oK (^oR if negative, in which case enthalpies below are Btu/lb)
34-38	F5.3	Unequal diffusion exponent	---
39-47	F9.3	Summation $\sum Z^*_{ie} h_i^{T_w}$	cal/gr (Btu/lb if temperature is entered with minus sign)
48-56	F9.3	h_{e_w}	cal/gr (Btu/lb if temperature is entered with minus sign)
57-58	I2	-1 (flag signifying that this card is part of the edge gas table)	---

Column	Format	Data	Units
59-66	2A4	Unused, but may contain alphameric information	---
67-78	2A6	Problem identification (not read)	---
79-80	2X	UNUSED	---

Note that although the EST and ACE programs will provide a data deck using ^{o}K and cal/gr, in those rare cases in which a user wishes to supply his own deck and prefers to work in ^{o}R and Btu/lb, he may do so simply by introducing a minus sign as a flag in front of the temperature entries.

The table length is limited to 5 pressure sets (it may have only 1 pressure set) with noc more than 30 nor less than 3 temperature entries in each set. The series of temperature values may be different for each pressure set. The table has been organized as a series of sections, each representing one pressure and each preceding the corresponding pressure group of the surface thermochemistry deck as described below. The temperature entries within each section must be ordered, either ascending or descending. Similarly, the pressures must be ordered either ascending or descending. (Deck generated by the EST and ACE programs will have been automatically ordered properly.) The sketch shown on the following page demonstrates the thermochemical data tables make-up.

3.1.10.3.3 Surface thermochemistry table

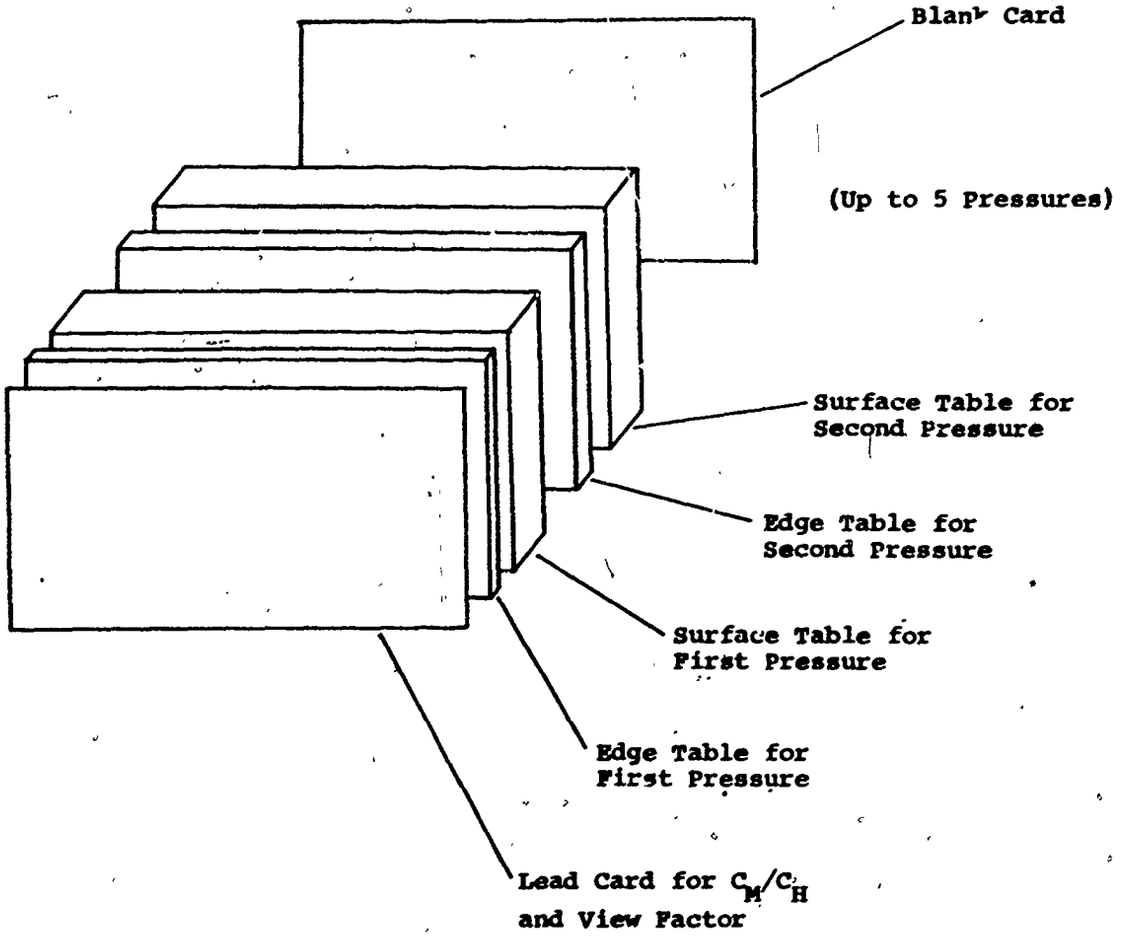
This table is comprised of a series of sections of up to 29 cards each. The sections represent <u>one</u> pressure and <u>one</u> pyrolyses gas rate. Each section consists of two subsections. The first contains the ablating cases; here the char ablation rate is the third independent variable and the surface temperature is a dependent variable. The second subsection represents surface temperatures too low for ablation; in this subsection surface temperature is the independent variable.

Thus one table has three independent variables: pressure, pyrolysis gas rate, and either surface temperature or ablation rate, depending on whether the surface temperature is high enough for ablation.

The table has either two or three dependent variables, according to whether the surface temperature is high enough for ablation. Two dependent variables always present are the summation $\sum z^{*}_{iw} h_i^{T_w}$ and h_w, the enthalpy of the wall gases. The third dependent variable is the surface temperature, but it is dependent only in those cases for which the surface temperature is high enough for ablation. (Otherwise, the surface temperature functions as an independent variable.)

SKETCH OF SURFACE THERMOCHEMICAL TABLE MAKE-UP

The following sketch illustrates the make-up of the surface thermochemistry table for CMA input.



The EST and ACE programs generate separate groups for each pressure, one at a time. These groups must be ordered on pressure (either ascending or descending) by the user to make up the surface thermochemistry deck. With each pressure group the pyrolysis gas rates B'_g will be ordered in descending order. Within each gas rate section, non-zero char rate entries will be grouped ahead of the zero char rate entries. The non-zero char rate entries will not be ordered in any particular way on the char rates; any necessary ordering is made automatically by the Charring Material Ablation program as it reads the data. The zero char rate entries are ordered with descending temperatures.*

(Users providing their own thermochemistry decks must ensure that the pressures and gas rates are ordered, but the ordering may be either ascending or descending in each case. Within each gas rate section, non-zero char rate entries must precede the zero char rate entries but need not be ordered. Char rates may not be duplicated in a given table. Zero char rate entries follow and must be ordered with descending temperatures. These cards are identified as zero char rate cards by a flag in columns 57-58, as described in the format specification below.)

The number of pressure groups may not exceed 5 (and may be only 1); the number of pyrolysis gas rates in each pressure group may not exceed 20 and may not be less than 2. The sequence of gas rate values must be the same in the different pressure sections. Within each gas rate group the number of char rate entries, including the zero char rate (independent surface temperature) cards, may not exceed 30 and may not be less than 2. The series of char values may be unique for each section.

(The ^{o}R-Btu/lb option described for the edge tables in Section 3.1.10.3.2 may be used for these tables also.)

The card format for the surface thermochemistry data is as follows:

Column	Format	Data	Unit
1-8	F8.5	Pressure	atm
9-16	F8.5	Gas rate $\dot{m}_g/\rho_e u_e C_M = B'_g$	---
17-24	F8.5	Char rate $\dot{m}_c/\rho_e u_e C_M = B'_c$	---
25-33	F9.4	Surface temperature	^{o}K (^{o}R if negative in which case enthalpies below are Btu/lb)

*Limitations in the EST and ACE chemistry routines sometimes require that these "zero char rates" not be zero, but some small number, for example, 0.0001. This causes no difficulty in CMA.

Column	Format	Data	Units
34-38	F5.3	Unequal diffusion exponent	---
39-47	F9.3	Summation $\sum z^*_{iw} h_i^{T_w}$	cal/gr (Btu/lb if temperature is entered with minus sign)
48-56	F9.3	Enthalpy of wall gases h_w	cal/gr (Btu/lb if temperature is entered with minus sign)
57-58	I2	0 for assigned-temperature entries in the thermochemistry program (no ablation); > 0 for standard surface thermochemistry with ablation (temperature is dependent)	---
59-60	2X	Blank	---
61-66	A6	Chemical symbol of surface species (EST program prints such symbols arranged alphabetically and truncated from right end if necessary.)	---
67-78	2A6	Problem identification (not read)	---
79-80	I2	UNUSED	---

The ACE program can account, as one of its options, for mechanical removal or failing of candidate surface species at defined temperatures. The energy associated with this failing can be (and is) accounted for by the ACE-CMA program combination; this is accomplished by ACE by suitably modifying the h_w output term on the punched card thermochemistry table (thus h_w does not represent the enthalpy of the wall gases if failing is occurring).

The actual value of the dimensionless failing rate $B'_f = \dot{m}_f/\rho_e u_e C_M$ may or may not appear on the punched surface thermochemistry card tables, depending on whether or not the ACE user has called for the appropriate card output format. This "new format" differs from that cited above in columns 61-80:

Alternate Card Format - Surface Tables

Column	Format	Data	Units
1-60	As described above		
61-68	2A4	Chemical symbol of surface species	---
69-78	E10.3	$B'_f = \dot{m}_f/\rho_e u_e C_M$	---
79-80	2X	Blank	---

The CMA user may call for the CMA program to read these B'_f entries and to allow for them in the blowing correction to C_{H_o} by punching a one in column 50 in the lead card for the surface thermochemistry tables, as described in Section 3.1.10.2 above.

3.1.10.3.4 Termination card

The surface thermochemistry data deck must be terminated by a single blank card. Output decks of the EST and ACE programs may not have such a card, in which case the user must supply it.

3.2 PROGRAM OUTPUT

3.2.1 Input Data (Except Surface Thermochemistry Tables)

Program output begins with an output of the input title and heading information, internal decomposition kinetic data, output interval specifications and general program constants, nodal data, material property tables, pyrolysis gas enthalpy table, and time dependent boundary conditions table.

All this output is fully labeled and is printed exactly as input by the user. Examples of these outputs are included in Section 4.

3.2.2 Surface Thermochemistry Tables

3.2.2.1 Edge Enthalpy Table

If there is an edge enthalpy table, it is output exactly as input.

3.2.2.2 Surface Thermochemistry Table

This table is output re-ordered with increasing char rates in each section and with a new computed term in place of the input enthalpy terms. For each entry in the surface equilibrium tables the program computes the quantity*

$$\left[\sum_i (Z^*_{ie} - Z^*_{iw})h_i^{T_w} - B'h_w + \frac{\dot{m}_c h_c}{\rho_e u_e C_M} + \frac{\dot{m}_g h_g}{\rho_e u_e C_M}\right] = \frac{q_{chem}}{\rho_e u_e C_M} = \underset{\text{prod}}{\text{chem}}$$

and then outputs it as the dependent variable of interest in the output surface equilibrium table. This term occurs directly in the surface energy balance, Equation (9) of Section 2.4.3 above. In the output, this quantity is labeled CHEM PROD. It has the units (Btu/ft^2-sec)/(lb/ft^2-sec) = Btu/lb and can be thought of as the chemical energy release per pound of $\rho_e u_e C_M$, where $\rho_e u_e C_M$ can be thought of as the "scrubbing flux" or "Reynolds flux."

*If edge tables are omitted, only the last three terms are included.

In the output table, the quantity $\rho_e u_e C_M$ is abbreviated to CM.

3.2.3 Regular Output

3.2.3.1 Introduction

At each output interval, as specified by the user, the program prints out the current values of ablation rates, nodal temperatures and densities, and other supplementary information, as described below. Samples of the regular output are given in Section 4.

3.2.3.2 General Information

The first line of output shows the current values of a number of miscellaneous quantities:

Heading	
TIME STEP	Total number of computational cycles (steps) required to reach the indicated value of output time. Note that the initial time is numbered as 1.
SURF ITER	Number of iterations required for the surface energy balance during the previous cycle.
PROB OPTN	Current problem option (1, 2, or 3)
SURFACE RAD (IN)	Current value of surface radius for axisymmetric geometries; current location of surface for planar geometries, measured from original location.
H WALL	Option 1: Enthalpy of frozen edge gases at the wall temperature. Option 2: Blank Option 3: Enthalpy of pyrolysis gases at the wall temperature
H EDGE	The input edge enthalpy as determined by linear interpolation in the functions-of-time table.
HEAT COEFF	The current value of the convective heat transfer coefficient $\rho_e u_e C_H$ as linearly interpolated in the functions-of-time table and corrected for the effect of transpiration (blowing) according to $C_H/C_{H_1} = \zeta/(e^{\zeta} - 1)$ where $\zeta = 2\lambda\dot{m}/C_{H_1}$ and C_{H_1} is the heat transfer coefficient before being corrected for blowing; as well as for any radius ratio effect.
CH/CHO	The ratio C_H/C_{H_1}, indicates the amount of blowing correction.

3.2.3.3 Ablation Rates

The output labels are interpreted as follows:

Heading	Data
B PRIME	The parameter $B' = \dot{m}/\rho_e u_e C_M$
B PRIME G	Parameter B' based on gas flow alone: $\dot{m}_g/\rho_e u_e C_M$
M DOT CHAR	Current char removal rate $\dot{m}_c$, lb/ft^2sec
M DOT GAS	Current pyrolysis gas flow rate at the surface $\dot{m}_g$, lb/ft^2sec.
M CHAR	Total char removal up to current time, based on a unit area of the original surface, lb/ft^2.
M GAS	Total pyrolysis gas generation up to current time, based on a unit area of the original surface, lb/ft^2.

3.2.3.4 Recessions and Recession Rates

A single output line gives the current locations, as measured from the original location of the surface, of the ablating surface, the char line [defined as the line of density $\rho_c + r_c(\rho_p - \rho_c)$], and the pyrolysis line [defined as the line of density $\rho_c + r_p(\rho_p - \rho_c)$], as well as the current rates of movement of these lines. The values r_c and r_p are also printed for convenience.

3.2.3.5 Surface Energy Flux Terms

Two lines of output give the current values of the surface energy flux terms in Equation (9) of Section 2.4.3, based on one square foot of the present surface, and the integrated values of these terms based on one square foot of the original surface.

The headings and data are related as follows:

Heading	Data
CONVECTED IN	$q_{sen} = \rho_e u_e C_H (H_r - h_{e_w})$*
RADIATED IN	$q_{rad_{in}} = \alpha_w q_{rad}$
RADIATED OUT	$q_{rad_{out}} = \sigma \epsilon T_w^4$
CHEMICAL GENERATION	q_{chem}
CONDUCTION AWAY	q_{cond}

*If edge tables are omitted, h_{e_w} is set to zero for output purposes.

3.2.3.6 Interior Energy Terms

Two lines of output show terms which describe how the input energy of q_{cond} is "accommodated" or "partitioned" in the solid material. Part of it is consumed in decomposing the plastic, part is consumed in sensible enthalpy changes of the solid, and part is "picked-up" by the pyrolysis gases as they pass through the char.

These terms are given by the energy equation (3) of Section 2.1.2 when these terms are integrated over the total extent of the ablating material. The headings and the terms are related as follows.

The pyrolysis gas pick-up represents the energy picked up by all the pyrolysis gas during its passage through the char layer. The decomposition absorption is simply the energy absorbed in isothermally decomposing the virgin plastic. The loss at the rear face is the energy passing out the back wall of the ablation material (not the back up materials). Two terms give the total rate of storage in solid materials. This quantity could in fact be represented by only one term

$$\int \overline{\rho C_p} \left(\frac{\partial T}{\partial \theta}\right)_y \frac{A\,dx}{A_s}$$

but it is more useful to divide into the two parts as indicated. For problems with a steady state temperature profile (in x), the "Storage in Solid" term

$$\int \rho C \left(\frac{\partial T}{\partial \theta}\right)_x \frac{A\,dx}{A_s}$$

goes to zero. In general, the relative sizes of the "Storage in Solid" term and the "Convection with Solids" term indicate the nearness of the approach to a steady state.

Heading	Data
PYROL GAS PICK UP	$-\int \dot{m}_g \left(\frac{\partial h_g}{\partial x}\right)_\theta \frac{dx}{A_s} = (\dot{m}_g h_g)_w + \int h_g \left(\frac{\partial \rho}{\partial \theta}\right)_y \frac{A\,dx}{A_s}$
DECOMP ABSORPTION	$-\int (h_g - \bar{h}) \left(\frac{\partial \rho}{\partial \theta}\right)_y \frac{A\,dx}{A_s}$
CONVECTION WITH SOLIDS	$-\int \dot{s}\overline{\rho C_p} \left(\frac{\partial T}{\partial x}\right)_\theta \frac{A\,dx}{A_s}$

STORAGE IN SOLID $$\int \overline{\rho C_p} \left(\frac{\partial T}{\partial \theta}\right)_x \frac{A\, dx}{A_s}$$

LOSS AT REAR FACE $$-k \frac{A_{BW}}{A_s} \left[\left(\frac{\partial T}{\partial x}\right)_\theta\right]_{BW}$$

The second line of output gives time-integrated total values of these energy rate terms, based on one square foot of the original surface.

3.2.3.7 Nodal Data

This output gives the current temperature, density and enthalpy* of all the nodes, as well as material number specifications, where material number 1 designates main material virgin plastic, defined as having a density equal to or greater than (ρ_p - 0.1 lb/ft^3), material number 2 designates main material char, defined as having a density equal to or less than (ρ_c + 0.01 lb/ft^3), material number 0 designates reacting char-plastic mixture with intermediate density, numbers 21-31 designate charring back-up material numbers according to the table of Section 3.1.6, and material numbers 3-10 designate non-charring back-up materials.

3.2.3.8 Char Swell Information

If the user has called for char swell corrections (Sections 2.4.3.4 and 3.1.10.2), two lines indicate the net surface recession and current surface recession rate as affected by the char swell effect.

3.2.4 Thermocouple and Isotherm Output

3.2.4.1 Listed Output

If thermocouple and/or isotherm output have been called for, this data will be listed at the end of the regular output, giving thermocouple temperatures in degrees Rankine and isotherm locations in inches from the location of the original surface.

In both cases the output data are determined by a curve fitting routine which extrapolates beyond the physical boundaries of the system, so that the user must himself detect when thermocouples have ablated away and lost their meaning and when isotherms are fictitiously found outside the material boundaries.

*Nodal thermal conductivity may be output instead of enthalpy. The relevant flag punch for conductivity is in column 60 of the "back wall conditions card" described in Section 3.1.6 above.

3.2.4.2 Punched Output

If punched output of thermocouple and isotherm data is called for as described in Section 3.1.3 above, the data will be punched on cards in the order: time, surface temperature, thermocouple temperatures (in the input order), isotherm depths (in the input order). The format is (8F10.4/10X7F10.4).

3.3 DUMPS

3.3.1 Introduction

To prevent the execution of computations that are wasteful or probably erroneous, the program provides two emergency stops with dumps of diagnostic information.

3.3.2 Too-Small-Time-Step Dump

One such dump occurs if the program selects a time step as small as 10^{-6} seconds. Computation ceases and the program prints out in a single line values of the current time (which will, of course, not in general correspond to a regular output time), the time increment $\Delta\theta$, the previous time increment for comparison, the amount of problem time from the previous time-table double entry (shift of option) or discontinuity, change in surface temperature during last computation step, the critical recession distance parameter (equal to one-fifth of the thickness of the first node or one-tenth of the minimum allowable last node thickness, whichever is smaller ($\Delta\theta$ is restricted so that recession during the computation step will not exceed this amount), and the surface recession rate (ft/sec) computed most recently.

Once this data has been output, the program sets the problem time equal to the final time, thus forcing an output of all the current values of the standard output quantities, followed by a termination of computation.

3.3.3 Too-Many-Surface-Iterations Dump

The program allows 51 iterations to find an acceptable surface energy balance. If a balance has not been obtained after 51 iterations, the program writes the diagnostic message "Iteration Stop" and a block of diagnostic data. Since stops of this kind are complex in nature, and generally involve the surface thermochemistry tables data deck, the dump data must usually be communicated to the program authors for analysis.

3.3.4 Unacceptable-Surface-Thermochemistry-Table Stop

A series of checks built into the input routine serve to detect common errors in the make-up of the surface thermochemistry tables. Discovery of an error stops the reading process and the program prints out a single line:

Bad Surface Equilibrium Table of Type -

Five error types are detected as follows:

Type	
0	Current section of independent temperature entries (no ablation) is not in descending order in temperature
1	Char rate in no-ablation subsection has been set greater than a char rate in the ablation subsection. Although the "zero-char-rate" can differ from zero, they must not exceed an actual ablation rate entry.
2	Edge table has been omitted even though the diffusion coefficients are not equal (unequal diffusion exponent $\neq 0$).
3	Edge table has been omitted even though $C_M/C_H \neq 1$.
4	Inconsistent unequal diffusion exponent (this must be uniform for all tables).
5	Have called for radius ratio and/or burning rate exponent correction to C_{H_o} although this is not an internal radius geometry.

3.3.5 Sense Switch Diagnostic Dumps

Sense switch calls built into the Charring Material Ablation Code provide diagnostic dumps of certain data during program execution. Usually such dumps are of interest only to the program authors, although for reference these dumps are summarized here:

Sense Switches	Dump when On
1	Writes another version of each surface thermochemistry table immediately after the regular output of this table; presents final forms of energy terms as actually used in surface energy balance computations; useful for analysis of sufrace energy balance failures
3	Dumps nodal numbers of decomposing back-ups, after regular output of input data, for checking purposes; also dumps at each standard output time various density and pyrolysis rates for nodes in charring back-up materials

4	Supplies standard output for each time step, regardless of formal output time specifications
5	Outputs diagnostic heat conduction quantities in charring back-ups each time step, only used for detailed analysis

3.4 MISCELLANEOUS

3.4.1 Running Time

Computation time depends, of course, on the problem being computed, but typical computations for charring materials run roughly in real time on the IBM 7090/7094. Appendix B presents a method for estimating run times.

3.4.2 Tape Requirements

Internal program assignments are as follows:

Tape Unit 3: Scratch used during execution

Tape Unit 5: Input

Tape Unit 6: Output

Tape Unit 7: Punch

3.4.3 Fortran Deck Make-Up

The Charring Material Ablation program source deck is in Fortran IV (or Fortran 63).

The program consists of the following units:

1. Main Program
   Drives INPØUT and CBM routines
2. Subroutine CBM
   Computes all time dependent results
3. Subroutine* INPØUT
   Reads in all input data and outputs same data in front of standard computed output
4. Subroutine LCØUNT
   Counts lines, turns and numbers pages
5. Subroutine LØØK
   Table look-up with linear interpolation
6. Subroutine SLØPQ
   Quadratic curve fit and slope finder
7. Subroutine ØGLE
   Table look-up with cubic curve fit

8. Subroutine ØRDERD

   Ordering routine

9. Subroutine ØRDERI

   Integer Array Ordering Routine

10. Subroutine SEQUA

    Orders according to results of ØRDERD

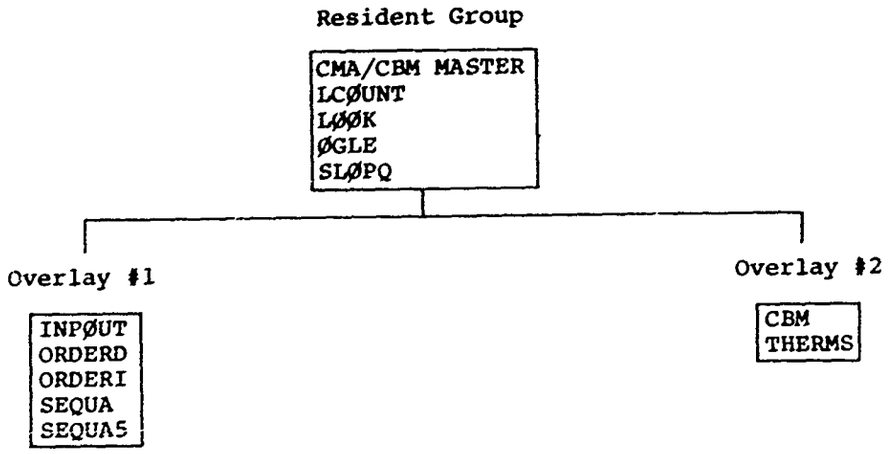
11. Subroutine SEQUA5

    Orders up to 5 Dependent Variable Arrays according to results of ORDERD

3.4.4 Storage Requirements

With "standard" dimensions on subscripted variables, the Charring Material Ablation program generally fits within the 32,000 words of CDC and Univac equipment. The program will not fit the 32,000 words of the IBM 7090/7094 machine by several thousand words. Simple dimension cutting is usually adequate to effect a fit in most cases. In others, a special overlay version of the code exists, although only minor improvements can be realized in this way since most storage requirements are for data.

The first level overlay structure has the following form:



3.4.5 Stacking of Jobs

A series of data decks representing different problems may be stacked for sequential computation.

SECTION 4

SAMPLE PROBLEMS

This section presents input listings and selected output page listings for four sample problems illustrating various features of the CMA Version 3 code. The following table summarizes the essential features of each problem. As it happens, these examples are all from rocket nozzle technology, although the CMA code is equally useful for ablating exterior heat shield analysis, various combustion problems, and, of course, simple transient heat conduction studies.

CMA/CBM SAMPLE PROBLEMS

Sample Problem	Description	Comment
No. 1	Transient thermal response at the throat location of a carbon phenolic nozzle exposed to an aluminized solid propellant. Nodal network includes steel shell back-up. Heat transfer coefficient is corrected for radius change and burning rate as a function of time.	This problem shows the effect of burning rate correction on the convective heat transfer coefficient. In addition, the input of f-functions is demonstrated although only a linear variation is used. Finally, since no decomposing back up materials are present, this problem shows that the CMA/CBM code will do all problems that the CMA, Version 2 code could do.
No. 2	Identical surface boundary conditions as Sample Problem No. 1, but the nodal network contains seven silica phenolic nodes which decompose when sufficiently heated.	This problem demonstrates the input and output for the CMA/CBM solution of a nodal system containing a decomposing back-up material. Also the temperatures of three thermocouples and the depths of two isotherms are computed and output, and the nodal thermal conductivity is output instead of enthalpy.
No. 3	Identical surface boundary conditions and nodal network as Sample Problem No. 2, but the radius in this problem is corrected for char swell.	The effect of char swell on the predicted recession is demonstrated in this problem.
No. 4	Identical to Sample Problem No. 2, except that the "fissure" model is utilized to describe pyrolysis gas terms. (This requires a change in the surface thermochemistry model and the pyrolysis gas enthalpy table.)	The effect of "fissure" model on the prediction is demonstrated.

```
CHAR/CHM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
  THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE. P=29 ATM
  HEAT TRANSFER COEFFICIENT CORRECTED FOR BURNING RATE EXP. SAMPLE NO. 1
A              20.25        0.0  1.400+04        3.00  1.960+04     1000.0
B              40.75      32.40  4.480+09        3.00  3.680+04      600.
C              94.50      94.50       0.0         0.0       0.0    90000.
   141 1 2      0.0      120.0       0.5         2.0       5.0      1.0      0.3750
       2.0      10.0       0.04    -376.5         0.0       0.0     -0.345    536.
     1.0    1.08        1.4
   531.     1000.
 1     530.0                0.020 1.15
 1     530.0                0.040
 1     530.0                0.040
 1     530.0                0.440
 1     530.0                0.060
 1     530.0                0.100
 1     530.0                0.100
 1     530.0                0.100
 1     530.0                0.1
 1     530.0                0.1
 1     530.0                0.150
 1     530.0                0.150
 1     530.0                0.2
 1     530.0                0.2
 1     530.0                0.250
 1     530.0                0.250
       0.0       0.0      530.0
       530.0     0.210  1.880-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
       800.0     0.360  2.130-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      1160.0     0.360  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      1500.0     0.472  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      2000.0     0.484  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      3000.0     0.493  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      4000.0     0.498  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      5000.0     0.500  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
-1    6000.0     0.500  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
       530.0     0.210  2.470-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      1000.0     0.430  2.530-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      1500.0     0.472  2.580-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      2000.0     0.484  7.240-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      3000.0     0.493  7.190-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      4000.0     0.498  1.340-03      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      5000.0     0.500  2.000-03      0.630        MX4926 (CHAR  +60 DEG LAYUP)
-1    6000.      0.500   .750-03      0.630        MX4926 (CHAR  +60 DEG LAYUP)
  4 496.00
       500.0     0.110    0.00694
-1    5300.0     0.110    0.00694
 4     0.0
         0.0       0.0        1.0
+1       1.00      1.0        0.0
 9    900.0    1800.0    2700.0    3600.0    4500.0    5400.0    6300.0
    -1786.0    -918.2     195.6    2289.0    3600.0    4596.0    6152.0
       0.0     1947.0     904.0    0.8588      29.2
      10.0     1947.0     904.0    0.9233      29.2
     80.000    1947.0     904.0    0.7238      29.2
     80.000     .05         0.
1    120.       .05         0.
     0.602       1.0      0.625
    29.20                 3500.0  0.0  914.106  914.106-1
    29.20                 3000.0  0.0  671.985  671.985-1
    29.20                 2500.0  0.0  434.119  434.119-1
    29.20                 2000.0  0.0  202.668  202.668-1
    29.20                 1500.0  0.0  -20.763  -20.763-1
    29.20                 1000.0  0.0 -231.356 -231.356-1
    29.20                  500.0  0.0 -405.022 -405.022-1
29.20000 0.50000  .350003438.72130.     2054.193 2054.193  1  C*        0.
29.20000 0.50000   .700003299.27410.     1697.988 1697.988  1  C*        0.
29.20000 0.50000 9.50003239.24700.     1557.984 1557.984  1  C*        0.
29.20000 0.50000 0.100003165.21060.     1463.180 1463.180  1  C*        0.
29.20000 0.50000 0.050003069.66700.     1228.521 1228.521  1  C*        0.
29.20000 0.50000 0.000102938.28580.     1025.668 1025.668  1  C*        0.
29.20000 0.50000 0.000102500.00000.      685.109  685.109  0  C*        0.
29.20000 0.50000 0.000102000.00000.      298.892  298.892  0  C*        0.
29.20000 0.50000 0.000101500.00000.     -250.818 -250.818  0  AL203*    0.
29.20000 0.50000 0.000101000.00000.     -933.780 -933.780  0  AL203*    0.
29.20000 0.50000 0.00010 500.00000.    -1305.336-1305.336  0  AL203*    0.
29.20000 0.20000 0.350003439.01650.     1818.079 1818.079  1  C*        0.
29.20000 0.20000 0.200003243.19548.     1342.244 1342.244  1  C*        0.
29.20000 0.20000 0.150003136.66150.     1142.947 1142.947  1  C*        0.
29.20000 0.20000 0.100002981.30280.      907.434  907.434  1  C*        0.
29.20000 0.20000 0.050002716.33590.      602.753  602.753  1  C*        0.
29.20000 0.20000 0.030002525.79420.      435.126  435.126  1  C*        0.
29.20000 0.20000 0.010002116.21660.      145.414  145.414  1  C*        0.
29.20000 0.20000 0.007501952.70850.       42.720   42.720  1  C*        0.
29.20000 0.20000 0.005001788.38790.     -494.248 -494.248  1  C*        0.
29.20000 0.20000 0.000101252.80290.     -552.718 -552.718  1  C*        0.
29.20000 0.20000 0.000101000.00000.    -1012.490-1012.490  0  AL203*    0.
29.20000 0.20000 0.00010 500.00000.    -1353.107-1353.107  0  AL203*    0.
29.20000 0.10000 0.350003443.87986.     1718.127 1718.127  1  C*        0.
29.20000 0.10000 0.200003209.53360.     1182.973 1182.973  1  C*        0.
29.20000 0.10000 0.150003067.38830.      949.646  949.646  1  C*        0.
29.20000 0.10000 0.100002830.58750.      656.888  656.888  1  C*        0.
29.20000 0.10000 0.050002470.40020.      138.870  138.870  1  C*        0.
29.20000 0.10000 0.040002372.99160.     -528.689 -528.689  1  C*        0.
29.20000 0.10000 0.030002254.70890.     -629.431 -629.431  1  C*        0.
29.20000 0.10000 0.010002111.71570.     -799.809 -799.809  1  C*        0.
```

INPUT, SAMPLE PROBLEM 1

29.20000	0.10000	0.000101095.31170.	-884.688	-884.688	1	C* 0.
29.20000	0.10000	0.000101000.00000.	-1045.958	-1045.958	0	AL203* 0.
29.20000	0.10000	0.00010 500.00000.	-1374.827	-1374.827	0	AL203* 0.
29.20000	0.06000	0.350001446.34560.	1674.303	1674.303	1	C* 0.
29.20000	0.06000	0.200001191.95550.	1111.021	1111.021	1	C* 0.
29.20000	0.06000	0.150001028.23220.	859.936	859.936	1	C* 0.
29.20000	0.06000	0.100002731.58620.	531.322	531.322	1	C* 0.
29.20000	0.06000	0.080002506.35480.	344.891	344.891	1	C* 0.
29.20000	0.06000	0.070002314.54540.	211.524	211.524	1	C* 0.
29.20000	0.06000	0.065002151.65580.	109.606	109.606	1	C* 0.
29.20000	0.06000	0.060001325.71120.	-461.918	-461.918	1	C* 0.
29.20000	0.06000	0.050001241.34840.	-583.801	-583.801	1	C* 0.
29.20000	0.06000	0.030001151.88170.	-758.859	-758.859	1	C* 0.
29.20000	0.06000	0.000101018.34140.	-1033.389	-1033.389	1	C* 0.
29.20000	0.06000	0.000101000.00000.	-1061.054	-1061.054	0	AL203* 0.
29.20000	0.06000	0.00010 500.00000.	-1384.661	-1384.661	0	AL203* 0.
29.20000	0.03500	0.350003448.08240.	1645.678	1645.678	1	C* 0.
29.20000	0.03500	0.200003179.22710.	1063.164	1063.164	1	C* 0.
29.20000	0.03500	0.150002998.68670.	799.242	799.242	1	C* 0.
29.20000	0.03500	0.100002646.98070.	440.337	440.337	1	C* 0.
29.20000	0.03500	0.080002326.98750.	206.774	206.774	1	C* 0.
29.20000	0.03500	0.075002166.44010.	106.992	106.992	1	C* 0.
29.20000	0.03500	0.070001337.17750.	-452.619	-452.619	1	C* 0.
29.20000	0.03500	0.060001245.53300.	-578.878	-578.878	1	C* 0.
29.20000	0.03500	0.050001194.91830.	-670.321	-670.321	1	C* 0.
29.20000	0.03500	0.00010 899.26350.	-1195.571	-1195.571	1	C* 0.
29.20000	0.03500	0.00010 500.00000.	-1391.193	-1391.193	0	C* 0.
29.20000	0.02000	0.350003449.20720.	1628.023	1628.023	1	C* 0.
29.20000	0.02000	0.200003178.86300.	1033.320	1033.320	1	C* 0.
29.20000	0.02000	0.150002978.39280.	760.889	760.889	1	C* 0.
29.20000	0.02000	0.100002582.78380.	378.825	378.825	1	C* 0.
29.20000	0.02000	0.080002129.85570.	78.164	78.164	1	C* 0.
29.20000	0.02000	0.075001328.44640.	-465.197	-465.197	1	C* 0.
29.20000	0.02000	0.070001275.99870.	-533.272	-533.272	1	C* 0.
29.20000	0.02000	0.060001215.23460.	-632.586	-632.586	1	C* 0.
29.20000	0.02000	0.050001170.94980.	-718.460	-718.460	1	C* 0.
29.20000	0.02000	0.00010 685.98190.	-1350.252	-1350.252	1	C* 0.
29.20000	0.02000	0.00010 500.00000.	-1395.265	-1395.265	0	AL203* 0.
29.20000	0.00010	0.350003450.80590.	1604.023	1604.023	1	C* 0.
29.20000	0.00010	0.200003158.75570.	992.289	992.289	1	C* 0.
29.20000	0.00010	0.150002948.10120.	787.221	787.221	1	C* 0.
29.20000	0.00010	0.100002472.02610.	284.658	284.658	1	C* 0.
29.20000	0.00010	0.080002306.33350.	175.096	175.096	1	C* 0.
29.20000	0.00010	0.075002119.58270.	62.729	62.729	1	C* 0.
29.20000	0.00010	0.045001914.41420.	-56.221	-56.221	1	C* 0.
29.20000	0.00010	0.042501338.25080.	-466.518	-466.518	1	C* 0.
29.20000	0.00010	0.040001299.59480.	-503.670	-503.670	1	C* 0.
29.20000	0.00010	0.040001181.20180.	-698.086	-698.086	1	C* 0.
29.20000	0.00010	0.035001140.60580.	-780.959	-780.959	1	C* 0.
29.20000	0.00010	0.00010 600.47750.	-1384.243	-1384.243	1	C* 0.
29.20000	0.00010	0.00010 500.00000.	-1400.855	-1400.855	0	AL203* 0.

INPUT, SAMPLE PROBLEM 1 (CONCLUDED)

CHAR OR ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CANNON MATERIALIC AT A 60 DEGREE LAYUP ANGLE, P=20 ATM
HEAT TRANSFER COEFFICIENT CORRECTED FOR BURNING RATE EXP. SAMPL NO. 1

---REACTION KINETIC EQUATION---

$$\frac{d(RHO)}{dTIME} = GAMMA\,(BARE)\,(-EA/T)\,RHO0A\left(\frac{RHOA-RHORA}{RHO0A}\right)^{**PSIA} + GAMMA\,(BO*EXP(-EB/T)\,RHO0B\left(\frac{RHOB-RHORB}{RHO0B}\right)^{**PSIB} + (1-GAMMA)\,(BC*EXP(-EC/T)\,RHO0C\left(\frac{RHOC-RHORC}{RHO0C}\right)^{**PSIC}$$

---REACTION KINETIC CONSTANTS---

REACTION	RHO0 (LB/CU FT)	RHOR	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	90.75	.00	.1400+05	3.00	.1540+05	1000.
B	60.75	32.40	.4460+10	3.00	.3680+05	600.
C	94.50	94.50	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION, GAMMA = .381 (MASS FRACTION = .345)

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00

OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME

MAXIMUM TIME STEP <1.00 SECOND>

---NODAL DATA---

NODE NO.	MATL NO.	TEMPERATURE (DEG.RANKINE)	RELATIVE AREA	THICKNESS (INCHES)	NODE DEPTH (INCHES)	CONT.RESISTANCE (SQFT-S-DEG/BTU)
1	1	530.00	.1150+01	.02000	.000000*	-.0000
2	1	530.00	.1190+01	.04000	.040000	-.0000
3	1	530.00	.1230+01	.04000	.080000	-.0000
4	1	530.00	.1270+01	.04000	.120000	-.0000
5	1	530.00	.1320+01	.06000	.170000	-.0000
6	1	530.00	.1400+01	.10000	.250000	-.0000
7	1	530.00	.1500+01	.10000	.350000	-.0000
8	1	530.00	.1600+01	.10000	.450000	-.0000
9	1	530.00	.1700+01	.10000	.550000	-.0000
10	1	530.00	.1800+01	.10000	.650000	-.0000
11	1	530.00	.1925+01	.15000	.775000	-.0000
12	1	530.00	.2075+01	.15000	.925000	-.0000
13	1	530.00	.2250+01	.20000	1.100000	-.0000
14	1	530.00	.2450+01	.20000	1.300000	-.0000
15	3	530.00	.2675+01	.25000	1.525000	-.0000
16	3	530.00	.2925+01	.25000	1.775000	-.0000

*INITIAL INTERNAL RADIUS 1.150 AREA PROP.TO RADIUS**1.00
MINIMUM THICKNESS OF LAST ABLATOR NODE (INCHES) .0400
THERE ARE 10 NODELETS ASSIGNED TO EACH ABLATING NODE

BACK WALL CONVECTION COEF BTU/FTSQ-SEC-DEG R	BACK WALL EMISSIVITY	RESERVOIR TEMPERATURE
.0000	.000	530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS---
(BTU/LB)

PLASTIC	CHAR	GAS
-376.50	.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---

MATERIAL NO. 1 VIRGIN PLASTIC | MATERIAL NO. 2 CHAR | MATERIAL NOS. 3 THROUGH 10 BACK-UP

DECOMPOSING BACK-UP VIRGIN MATERIALS 22,24,26,28,30, CHAR MATERIALS 23,25,27,29,31

MATERIAL NO. 1 DENSITY = 89.362 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.3100	.0001880	-1.71	.6300
800.00	.3600	.0002130	75.24	.6300
1160.00	.3600	.0002470	204.84	.6300
1500.00	.4720	.0002470	346.28	.6300
2000.00	.4840	.0002470	585.28	.6300
3000.00	.4930	.0002470	1073.78	.6300
4000.00	.4980	.0002470	1569.28	.6300
5000.00	.5000	.0002470	2068.28	.6300
6000.00	.5000	.0002470	2568.28	.6300

OUTPUT, SAMPLE PROBLEM 1

MATERIAL NO. 2 DENSITY = 70.864 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0002670	-1.92	.6300
1000.00	.4300	.0002530	148.48	.6300
1500.00	.4720	.0002580	373.98	.6300
2000.00	.4840	.0003240	612.98	.6300
3000.00	.4930	.0007190	1101.48	.6300
4000.00	.4980	.0013400	1596.98	.6300
5000.00	.5000	.0020000	2095.98	.6300
6000.00	.5000	.0027500	2595.98	.6300

MATERIAL NO. 3 DENSITY = 486.000 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)
500.00	.1100	.0069400
5000.00	.1100	.0069400

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(X)*KP + F2(X)*KC

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)		900.00	1800.00	2700.00	3600.00	4500.00
ENTHALPY (BTU/LB)		-1782.00	-930.20	195.60	2289.00	3600.00
TEMPERATURE (DEG R)		5400.00	6300.00			
ENTHALPY (BTU/LB)		4696.00	6152.00			

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	29.20000	.375
10.00	1	1947.00	904.00	.7238	29.20000	.375
60.00	1	1947.00	904.00	.7238	29.20000	.375

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
60.00	3	.05	.00
120.00	3	.05	.00

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BHP*M DOT/CHO. BRP IN TABLE

---SURFACE EQUILIBRIUM DATA---

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .602
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSURE MODEL NOT USED FOR GAS TERMS
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (R INITIAL/R CURRENT)**EX,
WHERE EX = (1.0-.2N)/(1.-N) AND N IS THE BURNING RATE EXPONENT,
IN THIS PROBLEM N HAS BEEN SET EQUAL TO .62500
NO CHAR SWELL CORRECTION ON SURFACE RECESSION

* = 29.2000 ATM

TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL	TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL	TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL
6300.00	1645.39	3600.00	344.89	900.00	-729.04
5400.00	1209.57	2700.00	-37.37		
4500.00	781.41	1800.00	-416.44		

M-DOT-GAS/CM = .5000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1984.61		5525.40	.0500	489.73	C*
1800.00	.0001	1639.89		5497.38	.1000	144.96	C*
2700.00	.0001	737.70		5038.64	.1500	-136.89	C*
3600.00	.0001	702.38		5938.69	.2000	-429.43	C*
4500.00	.0001	731.68		6175.30	.3500	-1341.58	C*
5288.91	.0001	667.30	C*				

M-DOT-GAS/CM = .2000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1837.53		4546.43	.0300	627.29	C*
1800.00	.0001	1584.73		4885.80	.0500	523.48	C*
2255.05	.0031	892.01	C*	5366.34	.1000	228.91	C*
2319.10	.0050	817.04	C*	5645.99	.1500	-67.65	C*
3514.88	.0075	661.57	C*	5837.59	.2000	-378.87	C*
3809.19	.0100	677.63	C*	6190.23	.3500	-1343.84	C*

M-DOT-GAS/CM = .1000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1815.18		3906.72	.0500	569.08	C*
1800.00	.0001	1561.78		5095.06	.1000	291.35	C*
1971.56	.0001	1332.83	C*	5521.30	.1500	-26.02	C*
2040.69	.0100	1222.21	C*	5777.16	.2000	-349.21	C*
2186.48	.0300	998.02	C*	6198.98	.3500	-1345.93	C*

M-DOT-GAS/CM = .0600 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1806.23		4166.18	.0700	499.60	C*
1800.00	.0001	1852.48		4511.44	.0800	444.09	C*
1833.01	.0001	1515.29	C*	4916.71	.1000	320.94	C*
2073.39	.0300	1167.30	C*	5450.82	.1500	-4.01	C*
2234.43	.0588	941.07	C*	5745.52	.2000	-334.63	C*
2386.28	.0600	793.57	C*	6203.42	.3500	-1347.[illegible]	C*
3872.98	.0850	528.85	C*				

M-DOT-GAS/CM = .0350 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP ([illegible] R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1800.64		4488.58	.0800	466.24	C*
1618.67	.0001	1702.88	C*	4764.57	.1000	361.78	C*
2150.85	.0500	1052.68	C*	5397.49	.1500	12.05	C*
2241.96	.0600	936.26	C*	5722.61	.2000	-324.27	C*
2406.92	.0700	786.01	C*	6206.55	.3500	-1348.12	C*
3899.59	.0750	499.60	C*				

M-DOT-GAS/CM = .0200 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1797.29		3833.74	.0800	490.84	C*
1234.77	.0001	1628.56	C*	4649.01	.1000	355.63	C*
2107.71	.0500	1114.58	C*	5361.11	.1500	23.06	C*
2187.42	.0600	1004.81	C*	5707.55	.2000	-317.56	C*
2296.80	.0700	881.02	C*	6208.57	.3500	-1348.75	C*
2391.20	.0750	801.56	C*				

M-DOT-GAS/CM = .0001 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1792.84		3815.25	.0875	472.54	C*
1080.86	.0001	1820.09	C*	4151.40	.0925	429.21	C*
2053.09	.0500	1193.91	C*	4449.65	.1000	376.57	C*
2126.17	.0600	1068.47	C*	5306.58	.1500	38.46	C*
2339.26	.0800	847.43	C*	5685.76	.2000	-307.97	C*
2394.45	.0825	805.10	C*	6211.45	.3500	-1349.69	C*
3445.95	.0850	517.23	C*				

----OUTPUT----

.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
1	0	1	1.1500	.00	1943.00	.8588	.00000

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS	M CHAR (LB/ORIG SQ FT)	M GAS
.00000	.00000	.000000	.0000A0	.000000	.000000

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.0000000/ .0000000	.0000000/ .0000A00	.0000000/ .0000000

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	1	530.00	89.362	-378.21	9	1	530.00	89.362	-378.21
2	1	530.00	89.362	-378.21	10	1	530.00	89.362	-378.21
3	1	530.00	89.362	-378.21	11	1	530.00	89.362	-378.21
4	1	530.00	89.362	-378.21	12	1	530.00	89.362	-378.21
5	1	530.00	89.362	-378.21	13	1	530.00	89.362	-378.21
6	1	530.00	89.362	-378.21	14	1	530.00	89.362	-378.21
7	1	530.00	89.362	-378.21	15	2	530.00	486.000	.00
8	1	530.00	89.362	-378.21	16	2	530.00	486.000	.00

OUTPUT. SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM PAGE 7
SAMPLE NO. 1

.5000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CM/CMO
85	3	1	1.1527	1194.19	1967.00	.7951	.94285

---ABLATION RATES---

B PRIME	H PRIME O	M DOT CHAR (LM/SQ FT-SEC)	M DOT GAS (LM/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.269338	.15324	.055591	.073367	.015750	.020237

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.00286377/ .0094137	.0124550/-.0440915	.05562187/ .0918892

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.599+03	.570+03	.252+03	.693+02	.986+03
TOTAL	.467+03	.285+03	.841+02	.105+03	.753+03

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.388+03	.527+02	.142+03	.405+03	-.863-05
TOTAL	.162+03	.736+02	.371+03	.476+03	-.264-05

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5368.01	71.478	2263.29	9	1	530.00	89.362	-378.21
2	0	2681.34	81.788	353.00	10	1	530.00	89.362	-378.21
3	1	764.33	89.362	-311.43	11	1	530.00	89.362	-378.21
4	1	561.27	89.362	-369.30	12	1	530.00	89.362	-378.21
5	1	531.96	89.362	-377.65	13	1	530.00	89.362	-378.21
6	1	530.04	89.362	-378.20	14	1	530.00	89.362	-378.21
7	1	530.00	89.362	-378.21	15	1	530.00	486.000	.00
8	1	530.00	89.362	-378.21	16	1	530.00	486.000	.00

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM PAGE 8
SAMPLE NO. 1

1.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CM/CMO
89	4	1	1.1507	1217.95	1947.06	.7924	.94214

---ABLATION RATES---

B PRIME	B PRIME O	M DOT CHAR (LM/SQ FT-SEC)	M DOT GAS (LM/SQ FT-SEC)	M CHAR / M/ORIG SQ FT)	M GAS / M/ORIG SQ FT)
.264732	.11462	.063301	.054617	.039838	.092867

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.00672311/ .0107193	.0156046/ .0172408	.07666397/ .0275006

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.578+03	.570+03	.261+03	.298+02	.916+03
TOTAL	.730+03	.971+03	.218+03	.117+03	.120+04

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.250+03	.553+02	.725+03	.921+03	-.842-05
TOTAL	.321+03	.108+03	.970+03	.672+03	-.695-05

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5417.40	71.294	2292.89	9	1	530.00	89.362	-378.21
2	0	2981.27	74.832	988.80	10	1	530.00	89.362	-378.21
3	0	1226.87	88.859	-135.29	11	1	530.00	89.362	-378.21
4	1	691.99	89.362	-332.04	12	1	530.00	89.362	-378.21
5	1	552.71	89.362	-371.74	13	1	530.00	89.362	-378.21
6	1	531.21	89.362	-377.87	14	1	530.00	89.362	-378.21
7	1	530.05	89.362	-378.20	15	1	530.00	486.000	.00
8	1	530.00	89.362	-378.21	16	1	530.00	486.000	.00

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 14
SAMPLE NO. 1

10.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
125	3	1	1.2461	1347.70	1947.00	.4743	.93775

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS	M CHAR (LB/ORIG SQ FT)	M GAS
.29705	.11990	.050584	.0342+0	.591677	.499702

---RECESSIONS/RECESSION RATES---

SURFACE (IN)	/ (IN/SEC)	CHAR (-02)		PYROLYSIS (.98)	
.0960598/	.0085658	.1814950/	.0004+75	.3300085/	.0177243

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.284+03	.570+03	.317+0?	-.628+02	.474+03
TOTAL	.437+04	.592+04	.385+0?	-.286+03	.696+04

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT HEAR FACE
RATE	.199+03	.233+02	.145+0?	.186+03	-.314-05
TOTAL	.256+04	.432+03	.151+0?	.236+04	-.824-04

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5686.67	71.003	2435.47	9	1	535.72	89.362	-376.58
2	0	5859.10	71.017	2121.33	10	1	531.04	89.362	-377.91
3	0	4378.80	71.124	1778.87	11	1	530.11	89.362	-378.18
4	0	3616.50	71.382	1392.77	12	1	530.01	89.362	-378.21
5	0	2351.63	74.640	645.95	13	1	530.00	89.362	-378.21
6	0	1106.05	80.198	-171.50	14	1	530.00	89.362	-378.21
7	1	665.50	89.362	-339.59	15	1	530.00	486.000	.00
8	1	559.20	89.362	-369.89	16	1	530.00	486.000	.00

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 16
SAMPLE NO. 1

20.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
146	3	1	1.3250	1383.62	1947.00	.3595	.93513

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS	M CHAR (LB/ORIG SQ FT)	M GAS
.31252	.11892	.041901	.0257+0	1.113484	.811107

---RECESSIONS/RECESSION RATES---

SURFACE (IN)	/ (IN/SEC)	CHAR (.02)		PYROLYSIS (.98)	
.1749902/	.0070954	.3454744/	.0115171	.5032318/	.0128019

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.203+03	.570+03	.334+0?	-.689+02	.369+03
TOTAL	.701+04	.123+05	.670+0?	-.106+04	.115+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT HEAR FACE
RATE	.154+03	.166+02	.123+0?	.751+02	.141-02
TOTAL	.444+04	.616+03	.308+0?	.339+04	.397-02

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5761.03	70.980	2473.30	9	1	584.69	89.362	-362.62
2	0	5286.01	70.972	2237.02	10	1	546.05	89.362	-373.64
3	0	4792.04	70.982	1988.95	11	1	533.12	89.362	-377.32
4	0	4268.10	71.028	1726.24	12	1	530.47	89.362	-378.08
5	0	3535.86	71.245	1356.57	13	1	530.04	89.362	-378.20
6	0	2005.72	77.230	454.82	15	1	530.00	486.000	.00
7	0	1065.23	88.904	-198.22	16	1	530.00	486.000	.00
8	1	706.13	89.362	-328.01					

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
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SAMPLE NO. 1

30.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
164	3	1	1.1900	1399.80	1947.00	.2896	.93294

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.32419	.12328	.035027	.021433	1.567173	1.088958

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.2399879/ .0059314	.4525759/ .0112430	.6436105/ .0121794

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.158+03	.570+03	.342+03	-.634+02	.323+03
TOTAL	.911+04	.198+05	.187+05	-.183+04	.156+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.134+03	.120+02	.184+03	.725+02	.238-01
TOTAL	.613+04	.789+03	.441+04	.424+04	.113+00

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5794.50	70.949	2498.89	9	1	684.54	89.362	-334.17
2	0	5385.56	70.928	2286.99	10	1	586.48	89.362	-362.11
3	0	4989.14	70.906	2073.33	11	1	544.80	89.362	-373.99
4	0	4510.93	70.977	1848.83	12	1	533.08	89.362	-377.33
5	0	3902.40	71.060	1543.22	13	1	530.50	89.362	-378.07
6	0	2780.10	71.827	967.87	15	1	530.03	486.000	.00
7	0	1557.40	83.339	109.12	16	1	530.01	486.000	.00
8	0	936.56	89.292	-250.98					

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SAMPLE NO. 1

60.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
205	3	1	1.5370	1436.40	1947.00	.1631	.92413

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.37163	.15313	.024081	.016896	2.673523	1.806242

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.3870228/ .0040779	.7232865/ .0077472	.9480117/ .0103161

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.935+02	.570+03	.360+03	-.573+02	.246+03
TOTAL	.137+05	.408+05	.241+05	-.415+04	.262+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.107+03	.899+01	.751+03	.531+02	.128+01
TOTAL	.106+05	.119+04	.776+04	.653+04	.172+02

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	5870.15	70.926	2529.33	8	1	1867.59	77.337	386.25
2	0	5565.48	70.907	2377.52	9	1	1211.15	86.148	-129.90
3	0	5255.18	70.915	2222.17	10	1	860.88	89.362	-279.34
4	0	4935.38	70.925	2062.05	11	1	655.89	89.362	-342.33
5	0	4517.22	70.944	1852.45	12	1	563.06	89.362	-368.79
6	0	3799.82	71.010	1493.77	15	1	533.62	486.000	.00
7	0	2882.48	71.380	1030.14	16	1	532.65	486.000	.00

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

65.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
245	3	3	1.5371	3125.69	.00	.0000	.00000

---ABLATION RATES---

B PRIME	B PRIME G	H DOT CHAR (LB/SQ FT-SEC)	H DOT GAS (LB/SQ FT-SEC)	H CHAR (LB/ORIG SQ FT)	H GAS (LB/ORIG SQ FT)
.00000	.00000	.000090	.013143	2.673845	1.911224

---RECESSIONS/RECESSION RATES---

	SURFACE (IN)	/ (IN/SEC)	CHAR (.02) (IN)	/ (IN/SEC)	PYROLYSIS (.98) (IN)	/ (IN/SEC)
	.3870633	/ .0000000	.7646316	/ .0050814	.9943477	/ .0080042

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.446+01	.000	-.446+01
TOTAL	.137+05	.408+05	.242+05	-.415+04	.261+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.543+02	.636+01	-.000	-.662+02	.172+01
TOTAL	.111+05	.124+04	.776+04	.591+04	.271+02

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	4142.01	70.911	1666.53	8	1	2141.41	73.163	420.69
2	0	4134.12	70.904	1662.79	9	1	1392.33	85.521	-6.11
3	0	4091.28	70.910	1641.25	10	1	966.09	89.284	-240.20
4	0	4014.87	70.919	1602.89	11	1	700.52	89.362	-329.61
5	0	3878.55	70.933	1534.89	12	1	574.91	89.362	-365.41
6	0	3561.22	70.977	1376.46	15	1	535.66	486.000	.00
7	0	2985.65	71.148	1086.67	16	1	534.31	486.000	.00

90.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
293	3	3	1.5371	527.79	.00	.0000	.00000

---ABLATION RATES---

B PRIME	B PRIME G	H DOT CHAR (LB/SQ FT-SEC)	H DOT GAS (LB/SQ FT-SEC)	H CHAR (LB/ORIG SQ FT)	H GAS (LB/ORIG SQ FT)
.00000	.00000	.000000	.004813	2.673845	2.173855

---RECESSIONS/RECESSION RATES---

	SURFACE (IN)	/ (IN/SEC)	CHAR (.02) (IN)	/ (IN/SEC)	PYROLYSIS (.98) (IN)	/ (IN/SEC)
	.3870633	/ .0000000	.8166857	/ .0008198	1.1258767	/ .0031283

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.963-00	.000	-.963-00
TOTAL	.137+05	.408+05	.243+05	-.415+04	.260+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.853+01	.153+01	-.000	-.161+02	.525+01
TOTAL	.119+05	.135+04	.776+04	.488+04	.142+03

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	2823.47	70.905	1014.12	8	1	2130.98	71.409	662.05
2	0	2821.63	70.901	1013.32	9	1	1750.48	74.978	386.56
3	0	2807.09	70.906	1006.08	10	1	1364.46	84.918	-6.53
4	0	2780.71	70.912	993.03	11	1	973.36	89.097	-234.53
5	0	2734.48	70.923	970.15	12	1	673.59	89.362	-337.29
6	0	2628.52	70.950	917.63	15	1	558.48	486.000	.00
7	0	2423.19	71.032	815.08	16	1	554.16	486.030	.00

OUTPUT. SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
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SAMPLE NO. 1

- - - - - - - - - - - - - - - - 110.0000 SECONDS - - - - - - - - - - - - - - - -

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H BODY (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
307	3	1	1.5371	-95.48	.00	.0000	.00000

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.00000	.00000	.000000	.002753	2.673845	2.269376

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.38706133/ .0000000	.8277693/ .0003719	1.18004478/ .0026041

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT-SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.589-04	.000	-.589-00
TOTAL	.137+05	.408+05	.243+05	-.415+04	.260+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT-SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLID	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.356+01	.867-01	-.000	-.121+02	.734+01
TOTAL	.120+05	.137+04	.776+04	.453+04	.315+03

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	2496.96	70.904	854.65	8	0	1998.20	71.322	599.56
2	0	2496.18	70.901	854.35	9	0	1728.12	73.468	413.81
3	0	2486.59	70.905	849.54	10	0	1434.05	82.024	80.08
4	0	2468.50	70.911	840.54	11	0	1095.82	88.090	-173.38
5	0	2435.68	70.921	824.24	12	0	746.97	89.362	-316.37
6	0	2358.93	70.946	786.05	13	0	591.35	486.000	.00
7	0	2210.33	71.019	711.46	14	0	585.13	486.000	.00

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SAMPLE NO. 1

- - - - - - - - - - - - - - - - 120.0000 SECONDS - - - - - - - - - - - - - - - -

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H BODY (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
319	3	3	1.5371	-185.91	.00	.0000	.00000

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.00000	.00000	.000000	.002150	2.673845	2.301115

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.38706133/ .0000000	.8309254/ .0002737	1.20086679/ .0017627

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT-SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.492-04	.000	-.492-00
TOTAL	.137+05	.408+05	.243+05	-.415+04	.260+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT-SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLID	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.252+01	.510-00	-.000	-.113+02	.781+01
TOTAL	.121+05	.138+04	.776+04	.437+04	.417+03

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	ENTHALPY (BTU/LB)
1	0	2386.66	70.903	800.77	8	0	1942.28	71.304	573.35
2	0	2386.09	70.900	800.57	9	0	1704.10	73.196	409.31
3	0	2377.73	70.905	796.37	10	0	1440.49	81.166	100.58
4	0	2361.82	70.911	788.44	11	0	1125.64	87.545	-153.09
5	0	2332.82	70.920	774.01	12	0	774.20	89.362	-308.61
6	0	2264.58	70.945	739.99	13	0	610.38	486.000	.00
7	0	2131.11	71.016	672.85	14	0	603.69	486.000	.00

OUTPUT, SAMPLE PROBLEM 1 (CONCLUDED)

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CMA/CBM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
  THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
  SILICA PHENOLIC DECOMPOSING BACK-UP MATL WITH F-FUNCTIONS SAMPLE NO. 2
A                20.25          0.0  1.480+04         3.00  1.540+04     1000.0
B                60.75        32.40  4.480+09         3.00  3.680+04      600.
C                94.50         94.50       0.0          0.0       0.0   90000.0          1
   191 3 2         0.0        120.0       0.5          2.0       5.0       1.0       0.3750
       2.0        10.0         0.04     -376.5          0.0       0.0      -0.345      536.
     1.0     1.08         1.4
   531.      1000.
A                20.250         0.0  0.140+05         3.0  0.154+05      1000.
B                60.750        40.50  0.448+10         3.0  0.368+05      600.0
C                129.00        129.0       0.0          0.0       0.0     90000.
                                       -4887.0     -5280.0       0.0      -0.315      536.0
 1     530.0                  0.020 1.15
 1     530.0                  0.040
 1     530.0                  0.040
 1     530.0                  0.040
 1     530.0                  0.060
 1     530.0                  0.100
 1     530.0                  0.100
 1     530.0                  0.100
 1     530.0                  0.150
 1     530.0                  0.150
22     530.0                  0.020
22     530.0                  0.040
22     530.0                  0.040
22     530.0                  0.100
22     530.0                  0.100
22     530.0                  0.100
22     530.0                  0.200
 3     530.0                  0.250
 3     530.0                  0.250
       0.0       0.0     530.0                          1
       530.0     6.210  1.880-04      0.630        MX4926 :VIRGIN,60 DEG LAYUP)
       800.0     8.360  2.130-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      1160.0     8.360  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      1500.0     8.472  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      2000.0     8.484  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      3000.0     8.493  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      4000.0     8.498  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
      5000.0     8.500  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
-1    6000.0     8.500  2.470-04      0.630        MX4926 (VIRGIN,60 DEG LAYUP)
       530.0     0.210  2.470-04      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      1000.0     0.430  2.530-04      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      1500.0     0.472  2.580-04      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      2000.0     0.484  3.240-04      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      3000.0     0.493  7.190-04      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      4000.0     0.498  1.340-03      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
      5000.0     0.500  2.000-03      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
-1    6000.      0.500  2.750-03      0.630        MX4926 (CHAR  ,60 DEG LAYUP)
       530.0     0.260 0.0001070
       800.0     0.275  0.000109
      1160.0     0.310  0.000110
      1500.0     0.472  0.000110
      2000.0     0.484  0.000110
      3000.0     0.493  0.000110
      4000.0     0.493  0.000110
-1    5000.0     0.500 0.0001100
       530.0     0.210  0.000318
      1000.0     0.430  0.000330
      1500.0     0.472  0.000335
      2000.0     0.484  0.000356
      3000.0     0.493  0.000383
      3500.0     0.495  0.000395
      4000.0     0.498  0.000427
-1    5000.0     0.500  0.000582
 3  486.00
       500.0     0.110   0.00694
-1    5000.0     0.110   0.00694
 4     0.0
         0.0       0.0       1.0
-1       1.0       1.0       0.0
 5    0.001
         0.0       0.0       1.0
        0.35       0.4       1.0
       0.600       0.4       0.0
        0.90       0.4       0.0
+1     1.00       1.0       0.0
 6    900.0    1800.0    2700.0    3600.0    4500.0    5400.0    6300.0
   -1782.0    -930.2     195.6    2289.0    3600.0    4696.0    6152.0
       0.0    1947.0     904.0    0.8588      29.2
      10.0    1947.0     904.0    0.7238      29.2
     60.000   1947.0     904.0    0.7238      29.2
     60.000    .05         0.
1  120.       .05         0.
     0.607      1.0     0.625
   29.20                  3500.0   0.0  914.106  914.106-1
   29.20                  3000.0   0.0  671.985  671.985-1
   29.20                  2500.0   0.0  434.119  434.1191
   29.20                  2000.0   0.0  202.668  202.668-1
   29.20                  1500.0   0.0  -20.763  -20.763-1
   29.20                  1000.0   0.0 -231.356 -231.356-1
   29.20                   500.0   0.0 -485.022 -485.022-1
29.20000 0.50000 0.350003430.72130.     2854.193 2854.193 1  C*       0.
29.20000 0.50000 0.200003299.77410.     1697.988 1697.988 1  C*       0.
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INPUT, SAMPLE PROBLEM 2

```
29.20000 0.50000 0.150003239.24700.   1557.984 1557.984 1  C*        0.
29.20000 0.40000 0.100003165.21060.   1403.100 1403.100 1  C*        0.
29.20000 0.50000 0.050003069.66700.   1228.521 1228.521 1  C*        0.
29.20000 0.50000 0.300102934.28580.   1025.668 1025.668 1  C*        0.
29.20000 0.50000 0.000102500.00000.    685.109  685.109 0  C         0.
29.20000 0.50000 0.000102000.00000.    298.892  298.892 0  C*        0.
29.20000 0.90000 0.000101500.00000.   -250.818 -250.818 0  AL203*    0.
29.20000 0.50000 0.000101000.00000.   -933.780 -933.780 0  AL203*    0.
29.20000 0.50000 0.00010 500.00000.  -1305.336-1305.336 0  AL203*    0.
29.20000 0.20000 0.350003439.01650.   1818.079 1818.079 1  C*        0.
29.20000 0.20000 0.200003241.10580.   1342.244 1342.244 1  C*        0.
29.20000 0.20000 0.150003136.66150.   1142.947 1142.947 1  C*        0.
29.20000 0.20000 0.100002981.30290.    907.434  907.434 1  C*        0.
29.20000 0.20000 0.050002714.33590.    602.753  602.753 1  C*        0.
29.20000 0.20000 0.030002525.79420.    435.126  435.126 1  C*        0.
29.20000 0.20000 0.010002116.21660.    145.414  145.414 1  C*        0.
29.20000 0.20000 0.007501952.70850.     42.720   42.720 1  C*        0.
29.20000 0.20000 0.005001288.38790.   -494.248 -494.248 1  C*        0.
29.20000 0.20000 0.000101252.80290.   -552.718 -552.718 1  C*        0.
29.20000 0.20000 0.000101000.00000.  -1012.490-1012.490 0  AL203*    0.
29.20000 0.20000 0.00010 500.00000.  -1353.107-1353.107 0  AL203*    0.
29.20000 0.10000 0.350003443.87980.   1718.127 1718.127 1  C*        0.
29.20000 0.10000 0.200003209.53360.   1182.973 1182.973 1  C*        0.
29.20000 0.10000 0.150003067.38830.    949.646  949.646 1  C*        0.
29.20000 0.10000 0.100002830.58750.    656.888  656.888 1  C*        0.
29.20000 0.10000 0.050002170.49020.    138.870  138.870 1  C*        0.
29.20000 0.10000 0.040001272.99140.   -528.689 -528.689 1  C*        0.
29.20000 0.10000 0.030101214.70890.   -629.431 -629.431 1  C*        0.
29.20000 0.10000 0.010001133.71570.   -799.809 -799.809 1  C*        0.
29.20000 0.10000 0.000101095.31170.   -884.688 -884.688 1  C*        0.
29.20000 0.10000 0.000101000.00000.  -1045.958-1045.958 0  AL203*    0.
29.20000 0.10000 0.00010 500.00000.  -1374.827-1374.827 0  AL203*    0.
29.20000 0.06000 0.350003446.24560.   1674.303 1674.303 1  C*        0.
29.20000 0.06000 0.200003191.95550.   1111.021 1111.021 1  C*        0.
29.20000 0.06000 0.150003102A.23220.    859.936  859.936 1  C*        0.
29.20000 0.06000 0.100002731.50620.    531.322  531.322 1  C*        0.
29.20000 0.06000 0.080002506.35480.    344.891  344.891 1  C*        0.
29.20000 0.06000 0.070002314.54540.    211.524  211.524 1  C*        0.
29.20000 0.06000 0.065002151.65580.    109.606  109.606 1  C*        0.
29.20000 0.06000 0.040001325.71120.   -461.918 -461.918 1  C*        0.
29.20000 0.06000 0.050001241.34840.   -583.801 -583.801 1  C*        0.
29.20000 0.06000 0.030001151.88170.   -758.859 -758.859 1  C*        0.
29.20000 0.06000 0.000101018.34140.  -1033.389-1033.389 1  C*        0.
29.20000 0.04000 0.000101000.00000.  -1061.054-1061.054 0  AL203*    0.
29.20000 0.06000 0.00010 500.00000.  -1384.661-1384.661 0  AL203*    0.
29.20000 0.03500 0.350003448.08240.   1645.678 1645.678 1  C*        0.
29.20000 0.03500 0.200003179.22710.   1063.164 1063.164 1  C*        0.
29.20000 0.03500 0.150002998.60670.    799.242  799.242 1  C*        0.
29.20000 0.03500 0.100002646.98070.    440.337  440.337 1  C*        0.
29.20000 0.03500 0.080002326.98750.    206.774  206.774 1  C*        0.
29.20000 0.03500 0.075002166.44010.    106.992  106.992 1  C*        0.
29.20000 0.03500 0.070001137.17750.   -452.619 -452.619 1  C*        0.
29.20000 0.03500 0.060001245.53300.   -578.870 -578.870 1  C*        0.
29.20000 0.03500 0.050001136.91430.   -670.321 -670.321 1  C*        0.
29.20000 0.03500 0.00010 A99.26150.  -1195.571-1195.571 1  C*        0.
29.20000 0.03500 0.00010 500.00000.  -1391.193-1391.193 0  C*        0.
29.20000 0.02000 0.350003449.20720.   1628.023 1628.023 1  C*        0.
29.20000 0.02000 0.200003170.86300.   1033.320 1033.320 1  C*        0.
29.20000 0.02000 0.150002978.39280.    760.809  760.809 1  C*        0.
29.20000 0.02000 0.100002582.78380.    378.825  378.825 1  C*        0.
29.20000 0.02000 0.080002129.85570.     78.164   78.164 1  C*        0.
29.20000 0.02000 0.075001328.44640.   -465.197 -465.197 1  C*        0.
29.20000 0.02000 0.070001275.99870.   -533.272 -533.272 1  C*        0.
29.20000 0.02000 0.060001215.23460.   -632.586 -632.586 1  C*        0.
29.20000 0.02000 0.050001170.94980.   -718.460 -718.460 1  C*        0.
29.20000 0.02000 0.00010 685.98190.  -1350.252-1350.252 1  C*        0.
29.20000 0.02000 0.00010 500.00000.  -1395.765-1395.265 0  AL203*    0.
29.20000 0.00010 0.350003450.88590.   1604.023 1604.023 1  C*        0.
29.20000 0.00010 0.200003158.75570.    992.289  992.289 1  C*        0.
29.20000 0.00010 0.150002948.10120.    787.221  787.221 1  C*        0.
29.20000 0.00010 0.100002472.02610.    284.658  284.658 1  C*        0.
29.20000 0.00010 0.092502306.33350.    175.096  175.096 1  C*        0.
29.20000 0.00010 0.087502119.58270.     62.729   62.729 1  C*        0.
29.20000 0.00010 0.085001914.41820.    -56.221  -56.221 1  C*        0.
29.20000 0.00010 0.082501330.25040.   -466.518 -466.518 1  C*        0.
29.20000 0.00010 0.080001299.59080.   -503.670 -503.670 1  C*        0.
29.20000 0.00010 0.060001181.20300.   -698.006 -698.006 1  C*        0.
29.20000 0.00010 0.050001140.60500.   -780.959 -780.959 1  C*        0.
29.20000 0.00010 0.00010 600.47750.  -1384.243-1384.243 1  C*        0.
29.20000 0.00010 0.00010 500.00000.  -1400.855-1400.855 0  AL203*    0.
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INPUT, SAMPLE PROBLEM 2 (CONCLUDED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 1

CMA/COM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE. P=29 ATM
SILICA PHENOLIC DECOMPOSING BACK-UP MATL WITH F-FUNCTIONS SAMPLE NO. 2

---REACTION KINETIC EQUATION---

DRHO/DTIME = GAMMA (BA*EXP(-EA/T))RHOOA((RHOA-RHORA)/RHOOA)**PSIA)
+ GAMMA (BB*EXP(-EB/T))RHOOB((RHOB-RHORB)/RHOOB)**PSIB)
+(1-GAMMA)(BC*EXP(-EC/T))RHOOC((RHOC-RHORC)/RHOOC)**PSIC)

---REACTION KINETIC CONSTANTS---

REACTION	RHOO (LB/CU FT)	RHOR	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400E+05	3.00	.1540E+05	1000.
B	68.75	48.50	.4480E+14	3.00	.3680E+05	880.
C	94.50	94.50	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION= GAMMA = .381MASS FRACTION = .345

---DECOMPOSING BACK-UP KINETICS---

DECOMPOSING BACK-UP NO. 1

REACTION	RHOO (LB/CU FT)	RHOR	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400E+05	3.00	.1540E+05	1000.
B	68.75	48.50	.4480E+14	3.00	.3680E+05	880.
C	129.00	129.00	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION= GAMMA = .423MASS FRACTION = .315

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00

OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME

MAXIMUM TIME STEP =1.00 SECONDS

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 2
SAMPLE NO. 2

---NODAL DATA---

NODE NO.	MATL NO.	TEMPERATURE (DEG.RANKINE)	RELATIVE AREA	THICKNESS (INCHES)	NODAL DEPTH (INCHES)*	CONT.RESISTANCE (SQFT-S-DEG/BTU)
1	1	530.00	.1150E+01	.02000	.000000*	-.0000
2	1	530.00	.1190E+01	.04000	.040000	-.0000
3	1	530.00	.1230E+01	.04000	.080000	-.0000
4	1	530.00	.1270E+01	.04000	.120000	-.0000
5	1	530.00	.1320E+01	.05000	.170000	-.0000
6	1	530.00	.1400E+01	.10000	.250000	-.0000
7	1	530.00	.1500E+01	.10000	.350000	-.0000
8	1	530.00	.1600E+01	.10000	.450000	-.0000
9	1	530.00	.1725E+01	.15000	.575000	-.0000
10	1	530.00	.1875E+01	.15000	.725000	-.0000
11	22	530.00	.1960E+01	.02000	.810000	-.0000
12	22	530.00	.1990E+01	.04000	.840000	-.0000
13	22	530.00	.2030E+01	.04000	.880000	-.0000
14	22	530.00	.2100E+01	.10000	.950000	-.0000
15	22	530.00	.2200E+01	.10000	1.050000	-.0000
16	22	530.00	.2300E+01	.10000	1.150000	-.0000
17	22	530.00	.2450E+01	.20000	1.300000	-.0000
18	3	530.00	.2675E+01	.25000	1.525000	-.0000
19	3	530.00	.2925E+01	.25000	1.775000	-.0000

*INITIAL INTERNAL RADIUS 1.150 AREA PROP.TO RADIUS**1.00
MINIMUM THICKNESS OF LAST ABLATOR NODE (INCHES) .0400
THERE ARE 10 NODELETS ASSIGNED TO EACH ABLATING NODE

BACK WALL CONVECTION COEF BTU/FTSQ-SEC-DEG R	BACK WALL EMISSIVITY	RESERVOIR TEMPERATURE
.0000	.000	530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS-->
(BTU/LB)

PLASTIC	CHAR	GAS
-376.50	.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

DECOMPOSING BACK-UP NO. 1

PLASTIC	CHAR	GAS
-4807.00	-5280.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---

MATERIAL NO. 1 VIRGIN PLASTIC	MATERIAL NO. 2 CHAR	MATERIAL NOS. 3 THROUGH 10 BACK-UP

DECOMPOSING BACK-UP VIRGIN MATERIALS 22,24,26,28,30, CHAR MATERIALS 23,25,27,29,

OUTPUT, SAMPLE PROBLEM 2

MATERIAL NO. 1 — DENSITY = 89.362 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0001880	-1.71	.6300
800.00	.3600	.0002130	75.24	.6300
1100.00	.3600	.0002470	204.84	.6300
1500.00	.4720	.0002470	346.28	.6300
2000.00	.4840	.0002470	585.28	.6300
3000.00	.4930	.0002470	1073.28	.6300
4000.00	.4980	.0002470	1569.28	.6300
5000.00	.5000	.0002470	2068.28	.6300
6000.00	.5000	.0002470	2568.28	.6300

MATERIAL NO. 2 — DENSITY = 70.664 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0002470	-1.92	.6300
1000.00	.4300	.0002530	148.48	.6300
1500.00	.4720	.0002580	373.98	.6300
2000.00	.4840	.0002860	612.96	.6300
3000.00	.4930	.0007190	1101.48	.6300
4000.00	.4980	.0013400	1594.98	.6300
5000.00	.5000	.0020000	2095.98	.6300
6000.00	.5000	.0027580	2595.98	.6300

MATERIAL NO.22 — DENSITY = 108.708 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2600	.0001070	-1.62
800.00	.2750	.0001090	70.62
1100.00	.3100	.0001100	175.92
1500.00	.4720	.0001100	308.86
2000.00	.4840	.0001100	547.86
3000.00	.4930	.0001100	1036.36
4000.00	.4980	.0001100	1529.36
5000.00	.5000	.0001100	2025.86

MATERIAL NO.23 — DENSITY = 91.586 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2100	.0003180	-1.92
1000.00	.4300	.0003300	148.48
1500.00	.4720	.0003350	373.98
2000.00	.4840	.0003560	612.98
3000.00	.4930	.0003830	1101.48
3500.00	.4950	.0003950	1348.48
4000.00	.4980	.0004270	1596.73
5000.00	.5000	.0005820	2095.73

MATERIAL NO. 3 — DENSITY = 486.000 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)
540.00	.1100	.0069400
5000.00	.1100	.0069400

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(A)*KP + F2(A)*KC

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
1.0000	1.0000	.0000

F-FUNCTION TABLE NO. 2 ASSIGNED TO DECOMPOSING BACK-UP NO. 1

X	F1(X)	F2(X)
.0000	.0000	1.0000
.3500	.0000	1.0000
.6000	.4000	.0000
.9000	.4000	.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)		900.00	1800.00	2700.00	3600.00	4500.00
ENTHALPY	(BTU/LB)	-1782.00	-930.20	195.60	2289.00	3600.00
TEMPERATURE (DEG R)		5400.00	6300.00			
ENTHALPY	(BTU/LB)	4696.00	6152.00			

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	29.20000	.375
10.00	1	1947.00	904.00	.7236	29.20000	.375
60.00	1	1947.00	904.00	.7236	29.20000	.375

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
60.00	3	.05	.00
120.00	3	.05	.00

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BXP*M DOT/CHO. BXP IN TABLE

OUTPUT, SAMPLE PROBLEM 2 (CONTINUED)

---SURFACE EQUILIBRIUM DATA>--

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .002
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSURE MODEL NOT USED FOR GAS TERMS
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (H INITIAL/H CURRENT)**EX,
WHERE EX = (1.8-.2N)/(1.-N) AND N IS THE BURNING RATE EXPONENT.
IN THIS PROBLEM N HAS BEEN SET EQUAL TO .62500
NO CHAR SWELL CORRECTION ON SURFACE RECESSION

P = 29.2000 ATM

TEMPERATURE (DEG R)	EDGE ENTH AT I=WALL	TEMPERATURE (DEG R)	EDGE ENTH AT I=WALL	TEMPERATURE (DEG R)	EDGE ENTH AT I=WALL
6380.00	1645.39	3600.00	364.80	900.00	-729.04
5400.00	1209.57	2700.00	-37.37		
4500.00	781.41	1800.00	-416.44		

H-DOT=BAS/CM = .0008 PRESSURE = 29.2000 ATM

TEMP (DEG R)	H-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	H-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1906.61		5525.00	.0500	489.73	C*
1800.00	.0001	1639.89		5097.30	.1000	144.96	C*
2746.08	.0001	737.78		5010.04	.1500	-136.89	C*
3600.00	.0001	702.58		5030.69	.2000	-420.43	C*
4500.00	.0001	731.68		6175.30	.3500	-1341.50	C*
5288.91	.0001	667.30	C*				

H-DOT=BAS/CM = .2000 PRESSURE = 29.2000 ATM

TEMP (DEG R)	H-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	H-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1837.53		4546.63	.0300	627.29	C*
1800.00	.0001	1584.73		4485.80	.0500	523.48	C*
2255.05	.0001	842.01	C*	5166.34	.1000	228.91	C*
2319.10	.0050	817.04	C*	5645.99	.1500	-67.65	C*
3514.48	.0075	661.57	C*	5837.59	.2000	-378.07	C*
3809.19	.0100	677.63	C*	6190.23	.3500	-1343.84	C*

10.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
125	3	1	1.2461	1347.70	1947.00	.4743	.93775

---ABLATION RATES---

B PRIME	B PRIME G	H DOT CHAR (LB/SQ FT-SEC)	H DOT GAS (LB/SQ FT-SEC)	H CHAR (LB/ORIG SQ FT)	H GAS (LB/ORIG SQ FT)
.29705	.11991	.050584	.034239	.591677	.499704

---RECESSIONS/RECESSION RATES---

SURFACE (IN)	/ (IN/SEC)	CHAR (.02) (IN)	/ (IN/SEC)	PYROLYSIS (.98) (IN)	/ (IN/SEC)
.09605897	.0085658	.18149507	.0004975	.33001007	.0177266

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.284+03	.570+03	.317+03	-.628+02	.474+03
TOTAL	.437+04	.592+04	.305+04	-.286+03	.698+04

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.199+03	.233+04	.145+03	.[illegible]+03	.371-01
TOTAL	.258+04	.432+03	.159+04	.[illegible]+04	.667-01

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)
1	0	5665.67	71.003	.000493	11	22	530.42	108.708	.000107
2	0	5059.10	71.017	.002026	12	22	530.14	108.708	.000107
3	0	4378.79	71.124	.001566	13	22	530.04	108.708	.000107
4	0	3616.50	71.382	.001072	14	22	530.00	108.708	.000107
5	0	2351.63	74.640	.000410	15	22	530.00	108.708	.000107
6	0	1106.07	88.198	.000203	16	22	530.00	108.708	.000107
7	1	665.61	89.362	.000201	17	22	530.00	108.708	.000107
8	1	599.54	89.362	.000191	18	3	530.00	486.000	.006940
9	1	553.82	89.362	.000188	19	3	530.00	486.000	.006940
10	1	530.89	89.362	.000188					

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 20
SAMPLE NO. 2

30.0000 SECONDS

TIME STEP	SURF ITER	PHOB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
164	3	1	1.3900	1399.77	1967.00	.2896	.93291

---ABLATION RATES---

B PRIME	B PRIME G	M OUT CHAR (LB/SQ FT-SEC)	M OUT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.32437	.12352	.039017	.021534	1.567104	1.089242

---RECESSIONS/RECESSION RATES---

SURFACE (IN) / (IN/SEC)	CHAR (.02) (IN) / (IN/SEC)	PYROLYSIS (.98) (IN) / (IN/SEC)
.2399781/ .0059497	.0525852/ .0112474	.6440501/ .0124473

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.158+03	.576+03	.348+03	-.436+02	.323+03
TOTAL	.911+04	.190+05	.187+05	-.183+04	.156+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	-.136+03	.120+02	.101+03	.713+02	.471+01
TOTAL	.613+04	.789+03	.438+04	.424+04	.371+02

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	0	5796.44	70.949	.002582	11	22	646.41	108.708	.000108
2	0	5345.39	70.928	.002288	12	22	610.64	108.708	.000108
3	0	4958.67	70.906	.001963	13	22	578.16	108.708	.000107
4	0	4618.67	70.877	.001646	14	22	548.45	108.708	.000107
5	0	3901.97	71.080	.001265	15	22	531.64	108.708	.000107
6	0	2780.24	71.826	.000807	16	22	530.30	108.708	.000107
7	0	1558.72	83.320	.000252	17	22	530.02	108.708	.000107
8	0	941.06	89.288	.000226	18	3	530.00	486.000	.006940
9	1	733.65	89.362	.000207	19	3	530.00	486.000	.006940

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 25
SAMPLE NO. 2

60.0000 SECONDS

TIME STEP	SURF ITER	PHOB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
284	3	1	1.5402	1457.11	1967.00	.1842	.93851

---ABLATION RATES---

B PRIME	B PRIME G	M OUT CHAR (LB/SQ FT-SEC)	M OUT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.29402	.04651	.027451	.0088A7	2.698+89	1.651891

---RECESSIONS/RECESSION RATES---

SURFACE (IN) / (IN/SEC)	CHAR (.02) (IN) / (IN/SEC)	PYROLYSIS (.98) (IN) / (IN/SEC)
.3901706/ .0046485	.7681906/ .0199420	.7960916/ .0000126

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.993+02	.570+03	.370+03	-.796+02	.210+03
TOTAL	.137+05	.488+05	.242+05	-.433+04	.259+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.293+01	.201+01	.486+03	.830+02	.623+02
TOTAL	.957+04	.115+04	.704+04	.882+04	.104+04

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	0	5912.98	70.988	.002674	12	A	1728.25	102.004	.000044
2	0	5652.27	70.988	.002483	13	A	1148.98	108.376	.000099
3	0	5386.76	70.915	.002283	14	2>	810.95	108.708	.000109
4	0	5114.37	70.925	.002078	15	2>	625.07	108.708	.000108
5	0	4768.88	70.942	.001834	16	2>	559.98	108.708	.000107
6	0	4183.69	70.994	.001437	17	2>	533.65	108.708	.000107
7	0	3343.55	71.168	.000918	18	>	530.16	486.000	.006940
11	0	2964.47	92.187	.000382	19	>	530.11	486.000	.006940

OUTPUT, SAMPLE PROBLEM 2 (CONTINUED)

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 AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
                                                                PAGE 31
                                                          SAMPLE NO. 2

- - - - - - - - - - - - - - -   90.0000 SECONDS   - - - - - - - - - - - - - - -
 TIME  SURF  PROP  SURFACE     H WALL     H EDGE      HEAT COEFF       CH/CHO
 STEP  ITCN  OPTN  RAD (IN)   (BTU/LB)   (BTU/LB)   (LB/SQ FT-SEC)
  275     3     3    1.5402    1465.18        .00          .0000          .00000

                          ---ABLATION RATES---
  B PRIME   B PRIME G   H DOT CHAR   H DOT GAS      H CHAR       H GAS
                          (LB/SQ FT-SEC)          (LB/ORIG SQ FT)
   .00000     .00000       .000000      .000018     2.698857     1.656183

                    ---RECESSIONS/RECESSION RATES---
                                (IN)   /   (IN/SEC)
        SURFACE                    CHAR ( .02)              PYROLYSIS ( .98)
   .3982171/ .0000000        .7980475/ .0000000        .7980475/ .0000000

                      ---SURFACE ENERGY FLUX TERMS---
                  CURRENT RATES (BTU/SQ FT -SURFACE-SEC)
                AND INTEGRATED VALUES (BTU/ORIG SQ FT)
        CONVECTED      RADIATED      RADIATED      CHEMICAL      CONDUCTION
           IN             IN            OUT       GENERATION       AWAY
RATE       .000           .000        -.165+01        .000        -.165+01
TOTAL      .137+05        .408+05     -.244+05       -.433+04      -.257+05

                      ---INTERIOR ENERGY TERMS---
                  CURRENT RATES (BTU/SQ FT -SURFACE-SEC)
                AND INTEGRATED VALUES (BTU/ORIG SQ FT)
        PYROL GAS      DECOMP      CONVECTION      STORAGE       LOSS AT
         PICK UP      ABSORPTION    WITH SOLID     IN SOLID     REAR FACE
RATE       .821-02        .330+01        -.000       -.281+02       .172+02
TOTAL      .958+04        .117+04        .784+04     -.445+04       .293+04

NODE MAT   TEMP      DENSITY   COND(BTU/   NODE MAT   TEMP      DENSITY   COND(BTU/
           (DEG R)  (LB/CU FT)  FT SC F)              (DEG R)  (LB/CU FT)  FT SC F)
  1   0   3229.73     70.902    .000860     12   0   2770.62     91.797    .000377
  2   0   3231.68     70.900    .000861     13   0   2648.81     91.905    .000374
  3   0   3225.15     70.904    .000857     14   0   1468.84    103.076    .000044
  4   0   3218.50     70.909    .000848     15   2   681.56     108.708    .000109
  5   0   3182.52     70.916    .000830     16   2   695.61     108.708    .000108
  6   0   3115.41     70.932    .000788     17   2   563.29     108.708    .000107
  7   0   2980.94     70.945    .000708     18   1   532.57     486.000    .006940
 11   0   2840.98     91.738    .000379     19   1   532.07     486.000    .006940
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 AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
                                                                PAGE 32
                                                          SAMPLE NO. 2

 OPTIONAL OUTPUT OF THERMOCOUPLE TEMPERATURES AND/OR ISOTHERM DEPTHS
          DEPTHS MEASURED FROM ORIGINAL SURFACE
          TEMPERATURES IN DEGREES RANKINE

 EACH OUTPUT BLOCK SHOWS THE TIME IN SECONDS, THE CURRENT SURFACE TEMPERATURE,
 THE TEMPERATURES OF  3 THERMOCOUPLES, AND THE DEPTHS IN INCHES OF  2 ISOTHERMS
 WITHIN THE MAIN ABLATING MATERIAL.

 THE FIRST BLOCK SHOWS A SAMPLE TIME AND SURFACE TEMPERATURE, THE SPECIFIED
 DEPTHS OF THE THERMOCOUPLES (IF ANY) AND THE ISOTHERM TEMPERATURES.  THE
 ARRANGEMENT OF THIS BLOCK CORRESPONDS TO THE ARRANGEMENT OF THE OUTPUT DATA.

120.0000 2744.2577    1.0000    1.0000    1.4000  3531.0000 1000.0000

 OUTPUT DATA

   .0000  530.0000  530.0000  530.0000  530.0000    .0000     .0000
   .5000  5366.0062  529.9993  529.9993  529.9993    .2150     .0065
  1.0000  5417.4048  529.9993  529.9993  529.9993    .2855     .0734
  1.5000  5417.4251  529.9992  529.9992  529.9993    .3593     .1207
  2.0000  5472.8511  529.9992  529.9992  529.9993    .3880     .1405
  4.0000  5594.6941  529.9991  529.9991  529.9992    .4879     .2075
  6.0000  5638.4379  529.9991  529.9991  529.9992    .5094     .2601
  8.0000  5668.1278  529.9994  529.9991  529.9992    .5268     .3140
 10.0000  5686.0652  530.0010  529.9992  529.9991    .7745     .3521
 15.0000  5732.4111  530.0585  530.0057  529.9990    .8773     .4508
 20.0000  5761.0004  530.4914  530.0748  529.9990    .9483     .5356
 25.0000  5778.3470  532.0589  530.3934  529.9990   1.0352     .6067
 30.0000  5794.4435  536.1323  531.3669  529.9994   1.1046     .6748
 35.0000  5809.8780  544.8522  533.7271  530.0013   1.1484     .7440
 40.0000  5824.4448  561.8489  538.7209  530.0066   1.2452     .8096
 45.0000  5838.3840  589.4641  547.6947  530.0207   1.2838     .8391
 50.0000  5849.4401  628.3926  562.3136  530.0513   1.3038     .8627
 55.0000  5879.4758  668.4491  581.5158  530.1108   1.3543     .8853
 60.0000  5912.6955  710.2161  605.1079  530.2149   1.3773     .9093
 65.0000  4399.3768  780.2317  634.3748  530.3900   1.3889     .9352
 70.0000  3981.9189  901.2597  674.9311  530.6428   1.3958     .9739
 75.0000  3884.1407  1099.3228  730.5211  531.0152   1.4083     .9938
 80.0000  3481.8733  1189.3322  781.8933  531.5414   1.7284     .9948
 85.0000  3330.9929  1245.4984  793.0680  532.2345   1.9000    1.0006
 90.0000  3229.1565  1299.0890  824.8276  533.1032   1.9000    1.0137
 95.0000  3144.0102  1343.3826  856.2641  534.1536   1.9000    1.0250
100.0000  3072.8904  1382.0287  888.5304  535.3907   1.9000    1.0366
105.0000  3009.5926  1418.3042  950.1859  536.8241   1.9000    1.0494
110.0000  2943.7005  1328.0881  1049.1070  533.4880   1.9000    1.0697
115.0000  2870.0370  1442.2308  1116.9266  540.4088   1.9000    1.0950
120.0000  2744.2577  1639.4365  1160.1015  542.5938   1.9000    1.0960
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OUTPUT, SAMPLE PROBLEM 2 (CONCLUDED)

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CHA/CRM ANALYSIS AT ARLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
  THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE. P=29 ATM
  CHAR SWELL AND BURNING RATE CORRECTION ON HEAT TRANS COEF SAMPLE NO. 3
A                20.25          0.0  1.400+04        3.00  1.540+06     1000.0
B                60.75        32.40  4.480+09        3.00  3.680+06      600.
C                94.50        94.50       0.0         0.0       0.0  90000.0          1
   191 3 2         0.0        120.0       0.5         2.0       5.0      1.0     0.3750
       2.0         10.0         0.04     -376.5         0.0       0.0   -0.345      536.
     1.0     1.08        1.4
   571.     1000.
A                20.250         0.0  0.140+05        3.0  0.154+05     1000.
B                60.750       40.50  0.448+10        3.0  0.368+05      600.0
C                129.00       129.0       0.0         0.0       0.0  90000.
                                      -4807.0     -5280.0       0.0   -0.315      536.0
 1      530.0                 0.020 1.15
 1      530.0                 0.040
 1      530.0                 0.040
 1      530.0                 0.040
 1      530.0                 0.060
 1      530.0                 0.100
 1      530.0                 0.100
 1      530.0                 0.100
 1      530.0                 0.150
 1      530.0                 0.150
22      530.0                 0.020
22      530.0                 0.040
22      530.0                 0.040
22      530.0                 0.100
22      530.0                 0.100
22      530.0                 0.100
22      530.0                 0.200
 3      530.0                 0.250
 3      530.0                 0.250
        0.0         0.0      530.0                                    1
        530.0       0.210  1.880-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
        800.0       0.340  2.130-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       1160.0       0.360  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       1500.0       0.472  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       2000.0       0.484  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       3000.0       0.493  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       4000.0       0.498  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
       5000.0       0.500  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
-1     6000.0       0.500  2.470-04       0.630          MX4926 (VIRGIN.60 DEG LAYUP)
        530.0       0.210  2.470-04       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       1000.0       0.430  2.530-04       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       1500.0       0.472  2.580-04       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       2000.0       0.484  3.240-04       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       3000.0       0.493  7.190-04       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       4000.0       0.498  1.340-03       0.630          MX4926 (CHAR  .60 DEG LAYUP)
       5000.0       0.500  2.000-03       0.630          MX4926 (CHAR  .60 DEG LAYUP)
-1     6000.        0.500  2.750-03       0.630          MX4926 (CHAR  .60 DEG LAYUP)
        530.0       0.260 0.0001070
        800.0       0.275  0.000109
       1160.0       0.310  0.000110
       1500.0       0.472  0.000110
       2000.0       0.484  0.000110
       3000.0       0.493  0.000110
       4000.0       0.493  0.000110
-1     5000.0       0.500 0.0001100
        530.0       0.210  0.000314
       1000.0       0.430  0.000330
       1500.0       0.472  0.000335
       2000.0       0.484  0.000356
       3000.0       0.493  0.000383
       3500.0       0.495  0.000395
       4000.0       0.498  0.000427
-1     5000.0       0.500  0.000582
 3  480.00
        500.0       0.110  0.00694
-1     5000.0       0.110  0.00694
 4      0.0
          0.0         0.0       1.0
-1        1.0         1.0       0.0
 5    0.001
          0.0         0.0       1.0
        0.35          0.0       1.0
       0.680          0.4       1.0
        0.90          0.4       0.0
-1        1.00        1.0       0.0
 1     980.0      1800.0    2700.0     3690.0    4500.0    5400.0    6300.0
    -1782.0      -930.2     195.6     2289.0    3600.0    4696.0    6152.0
        0.0       1967.0     984.0     0.4588      29.2
       10.0       1967.0     984.0     0.7238      29.2
     60.000       1967.0     984.0     0.7238      29.2
     40.000         .05         0.
 1  120.           .05         0.
       0.607         1.0       0.625          1                          0.315
```

INPUT, SAMPLE PROBLEM 3

CHA/CHM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
CHAR SWELL AND BURNING RATE CORRECTION ON HEAT TRANS COEF SAMPLE NO. 3

---REACTION KINETIC EQUATION---

DRHO/DTIME = GAMMA (BA*EXP(-EA/T)RHOOA((RHOA-RHORA)/RHOOA)**PSIA)
+ GAMMA (BB*EXP(-EB/T)RHOOB((RHOB-RHORB)/RHOOB)**PSIB)
+(1-GAMMA)(BC*EXP(-EC/T)RHOOC((RHOC-RHORC)/RHOOC)**PSIC)

---REACTION KINETIC CONSTANTS---

REACTION	RHOO (LB/CU FT)	RHOR (LB/CU FT)	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400+05	3.00	.1540+05	1000.
B	60.75	32.40	.4480+10	3.00	.3680+05	600.
C	94.50	94.50	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION, GAMMA = .381(MASS FRACTION = .345)

---DECOMPOSING BACK-UP KINETICS---

DECOMPOSING BACK-UP NO. 1

REACTION	RHOO (LB/CU FT)	RHOR (LB/CU FT)	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400+05	3.00	.1540+05	1000.
B	60.75	40.50	.4480+10	3.00	.3680+05	600.
C	129.00	129.00	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION, GAMMA = .423(MASS FRACTION = .315)

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC) 120.00

OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME

MAXIMUM TIME STEP =1.00 SECONDS

---NODAL DATA---

NODE NO.	MATL NO.	TEMPERATURE (DEG.RANKINE)	RELATIVE AREA	THICKNESS (INCHES)	NODAL DEPTH (INCHES)	CONT.RESISTANCE (SQFT-S-DEG/BTU)
1	1	530.00	.1150+01	.02000	.000000*	-.0000
2	1	530.00	.1190+01	.04000	.040000	-.0000
3	1	530.00	.1230+01	.04000	.080000	-.0000
4	1	530.00	.1270+01	.04000	.120000	-.0000
5	1	530.00	.1320+01	.06000	.170000	-.0000
6	1	530.00	.1400+01	.10000	.250000	-.0000
7	1	530.00	.1500+01	.10000	.350000	-.0000
8	1	530.00	.1600+01	.10000	.450000	-.0000
9	1	530.00	.1725+01	.15000	.575000	-.0000
10	1	530.00	.1875+01	.15000	.725000	-.0000
11	22	530.00	.1960+01	.02000	.810000	-.0000
12	22	530.00	.1990+01	.04000	.840000	-.0000
13	22	530.00	.2030+01	.04000	.880000	-.0000
14	22	530.00	.2100+01	.10000	.950000	-.0000
15	22	530.00	.2200+01	.10000	1.050000	-.0000
16	22	530.00	.2300+01	.10000	1.150000	-.0000
17	22	530.00	.2450+01	.20000	1.300000	-.0000
18	3	530.00	.2675+01	.25000	1.525000	-.0000
19	3	530.00	.2925+01	.25000	1.775000	-.0000

*INITIAL INTERNAL RADIUS 1.150 AREA PROP.TO RADIUS**1.00
MINIMUM THICKNESS OF LAST ABLATOR NODE (INCHES) .0400
THERE ARE 10 NODELTS ASSIGNED TO EACH ABLATING NODE

BACK WALL CONVECTION COEF BTU/FTSQ-SEC-DEG R	BACK WALL EMISSIVITY	RESERVOIR TEMPERATURE
.0000	.000	530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS---
(BTU/LB)

PLASTIC	CHAR	GAS
-376.50	.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

DECOMPOSING BACK-UP NO. 1

PLASTIC	CHAR	GAS
-4807.00	-5280.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---

MATERIAL NO. 1 VIRGIN PLASTIC	MATERIAL NO. 2 CHAR	MATERIAL NOS. 3 THROUGH 10 BACK-UP

DECOMPOSING BACK-UP VIRGIN MATERIALS 22,24,26,28,30, CHAR MATERIALS 23,25,27,29,31

OUTPUT, SAMPLE PROBLEM 3

MATERIAL NO. 1 — DENSITY = 89.362 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0001880	-1.71	.6300
800.00	.3600	.0002130	75.24	.6300
1160.00	.3600	.0002470	204.84	.6300
1500.00	.4720	.0002470	346.28	.6300
2000.00	.4840	.0002470	585.28	.6300
3000.00	.4930	.0002470	1073.78	.6300
4000.00	.4980	.0002470	1569.28	.6300
5000.00	.5000	.0002470	2068.28	.6300
6000.00	.5000	.0002470	2568.28	.6300

MATERIAL NO. 2 — DENSITY = 70.866 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0002470	-1.92	.6300
1000.00	.4300	.0002530	148.48	.6300
1500.00	.4720	.0002580	373.98	.6300
2000.00	.4840	.0003240	612.98	.6300
3000.00	.4930	.0007190	1101.48	.6300
4000.00	.4980	.0013400	1596.98	.6300
5000.00	.5000	.0020000	2095.98	.6300
6000.00	.5000	.0027500	2595.98	.6300

MATERIAL NO.22 — DENSITY = 108.708 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2600	.0001070	-1.60
800.00	.2750	.0001090	70.62
1160.00	.3100	.0001100	175.92
1500.00	.4720	.0001100	308.86
2000.00	.4840	.0001100	547.86
3000.00	.4930	.0001100	1036.36
4000.00	.4930	.0001100	1529.36
5000.00	.5000	.0001100	2025.86

MATERIAL NO.23 — DENSITY = 91.586 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2100	.0003180	-1.92
1000.00	.4300	.0003300	148.48
1500.00	.4720	.0003350	373.98
2000.00	.4840	.0003560	612.98
3000.00	.4930	.0003830	1101.48
3500.00	.4950	.0003950	1348.48
4000.00	.4980	.0004270	1596.73
5000.00	.5000	.0005820	2095.73

MATERIAL NO. 3 — DENSITY = 486.000 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)
500.00	.1100	.0069400
5000.00	.1100	.0069400

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(A)*KP + F2(A)*KC

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
1.0000	1.0000	.0000

F-FUNCTION TABLE NO. 2 ASSIGNED TO DECOMPOSING BACK-UP NO. 1

X	F1(X)	F2(X)
.0000	.0000	1.0000
.3500	.0000	1.0000
.6000	.4000	.0000
.9000	.4000	.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE (DEG R)	900.00	1800.00	2700.00	3600.00	4500.00
ENTHALPY (BTU/LB)	-1782.00	-930.20	195.60	2289.00	3600.00

TEMPERATURE (DEG R)	5400.00	6300.00
ENTHALPY (BTU/LB)	4696.00	6152.00

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.8588	29.20000	.375
10.00	1	1947.00	904.00	.7238	29.20000	.375
60.00	1	1947.00	904.00	.7238	29.20000	.375

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
60.00	3	.05	.00
120.00	3	.05	.00

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BRP*M DOT/CHO, BRP IN TABLE

OUTPUT, SAMPLE PROBLEM 3 (CONTINUED)

SURFACE TABLES ARE THE SAME AS IN PREVIOUS PROBLEM

---SURFACE EQUILIBRIUM DATA>--

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .602
UNEQUAL DIFFUSION EXPONENT = -.000
NOMINAL SURFACE VIEW FACTOR = 1.00, (OPTION 1)
FISSURE MODEL NOT USED FOR GAS TERMS
HEAT TRANSFER COEFFICIENT MULTIPLIED BY (R INITIAL/R CURRENT)**EX,
WHERE EX = (1.0-.2N)/(1.-N) AND N IS THE BURNING RATE EXPONENT,
IN THIS PROBLEM N HAS BEEN SET EQUAL TO .62500
CHAR SWELL = .3100 * CHAR THICKNESS

----OUTPUT----

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
1	0	1	1.1500	.90	1947.00	.8588	.00000

---ABLATION RATES---

B PRIME	H PRIME G	M DOT CHAR (LM/SQ FT-SEC)	M DOT GAS	M CHAR (LB/ORIG SQ FT)	M GAS
.00000	.00000	.000000	.000000	.000000	.000000

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.0000000/ .0000000	.0000000/ .0000000	.0000000/ .0000000

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	1	530.00	89.362	.000188	11	22	530.00	108.708	.000107
2	1	530.00	89.362	.000188	12	22	530.00	108.708	.000107
3	1	530.00	89.362	.000188	13	22	530.00	108.708	.000107
4	1	530.00	89.362	.000188	14	22	530.00	108.708	.000107
5	1	530.00	89.362	.000188	15	22	530.00	108.708	.000107
6	1	530.00	89.362	.000188	16	22	530.00	108.708	.000107
7	1	530.00	89.362	.000188	17	22	530.00	108.708	.000107
8	1	530.00	89.362	.000188	18	3	530.00	486.000	.006940
9	1	530.00	89.362	.000188	19	3	530.00	486.000	.006940
10	1	530.00	89.362	.000188					

SURFACE RECESSION AFTER SWELL (INCHES) = .0000
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) = .0000

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
100	3	1	1.2529	1350.68	1947.00	.5088	.93881

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS	M CHAR (LB/ORIG SQ FT)	M GAS
.29262	.11293	.055045	.034594	.635517	.506903

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.10287507/ .0093212	.1865783/ .0245823	.3338688/ .0152919

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.303+03	.570+03	.318+03	-.715+02	.483+03
TOTAL	.456+06	.594+06	.308+06	-.341+05	.707+06

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.200+03	.240+02	.157+03	.101+03	.393-01
TOTAL	.259+06	.453+05	.171+06	.230+06	.705-01

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	0	5692.84	71.018	.002496	11	22	530.45	108.708	.000107
2	0	5054.55	71.056	.002017	12	22	530.15	108.708	.000107
3	0	4361.92	71.200	.001569	13	22	530.04	108.708	.000107
4	0	3587.41	71.443	.001051	14	22	530.00	108.708	.000107
5	0	2293.99	75.180	.000387	15	22	530.00	108.708	.000107
6	0	1080.66	88.401	.000240	16	22	530.00	108.708	.000107
7	1	659.24	89.362	.000200	17	22	530.00	108.708	.000107
8	1	558.01	89.362	.000191	18	3	530.00	486.000	.006940
9	1	533.62	89.362	.000188	19	3	530.00	486.000	.006940
10	1	530.91	89.362	.000188					

SURFACE RECESSION AFTER SWELL (INCHES) = .0769
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) = .0946

OUTPUT. SAMPLE PROBLEM 3 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 25
SAMPLE NO. 3

60.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
193	3	1	1.5898	1452.86	1941.00	.2203	.93713

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.30805	.06619	.032674	.000374	3.097767	1.654282

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.4398004/ .0054314	.7963537/ .0000672	.7963537/ .0000672

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.109+03	.570+03	.368+03	-.902+02	.420+03
TOTAL	.153+05	.415+05	.246+05	-.517+04	.270+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.981-00	.105+01	.426+02	.166+02	.120+03
TOTAL	.953+04	.120+04	.783+04	.649+04	.147+04

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)
1	0	5904.05	70.932	.002667	12	0	2414.97	93.874	.000367
2	0	5632.87	70.911	.002467	13	0	1445.57	106.836	.000048
3	0	5355.84	70.919	.002259	14	22	857.34	108.700	.000109
4	0	5072.56	70.929	.002046	15	22	636.42	108.708	.000108
5	0	4705.82	70.948	.001796	16	22	563.20	108.708	.000107
6	0	4082.47	70.999	.001384	17	22	534.01	108.708	.000107
7	0	3434.63	71.094	.000977	18	3	530.18	486.000	.006940
11	0	2965.44	91.946	.000382	19	3	530.12	486.000	.006940

SURFACE RECESSION AFTER SWELL (INCHES) = .3293
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) = .0071

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM
PAGE 37
SAMPLE NO. 3

120.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
299	3	3	1.5899	303.66	.00	.0000	.00000

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.00000	.00000	.000000	.000003	3.098211	1.657128

---RECESSIONS/RECESSION RATES---
(IN) / (IN/SEC)

SURFACE	CHAR (.02)	PYROLYSIS (.98)
.4398548/ .0000000	.7980205/ .0000000	.7980205/ .0000000

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.846-00	.000	-.846-00
TOTAL	.153+05	.415+05	.249+05	-.517+04	.268+05

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.644-03	.322-02	-.000	-.145+02	.131+02
TOTAL	.953+04	.121+04	.783+04	.337+04	.408+04

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/FT SC F)
1	0	2733.95	70.901	.000613	12	0	2324.12	91.715	.000365
2	0	2733.84	70.900	.000613	13	0	2222.12	91.761	.000366
3	0	2724.60	70.903	.000609	14	0	2049.77	92.805	.000357
4	0	2706.57	70.907	.000602	15	0	1293.02	104.904	.000044
5	0	2673.36	70.913	.000589	16	22	878.37	108.708	.000109
6	0	2594.73	70.925	.000558	17	22	631.64	108.708	.000108
7	0	2475.41	70.941	.000510	18	3	542.70	486.000	.006940
11	0	2398.43	91.687	.000367	19	3	541.20	486.000	.006940

SURFACE RECESSION AFTER SWELL (INCHES) = .3288
SURFACE RECESSION RATE WITH SWELL (INCHES/SEC) = .0000

OUTPUT. SAMPLE PROBLEM 3 (CONCLUDED)

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CAA/CRM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
  THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
  FISSURE MODEL APPLIED TO SAMPLE PROBLEM NO. 2              SAMPLE NO. 4
A              20.75        0.0  1.400+04       3.00  1.540+04     1000.0
B              60.75      32.40  4.480+09       3.00  3.680+04      600.
C              94.50      94.50       0.0        0.0       0.0   90000.0          1
  191 1 2        0.0      120.0       0.5        2.0       5.0       1.0     0.3750
      2.0       10.0       0.04    -376.5        0.0       0.0    -0.345      536.
    1.0     1.08        1.4
  531.     1080.
A              20.250       0.0  0.140+05       3.0  0.156+05     1000.
B              60.750     40.50  0.448+10       3.0  0.368+05      600.0
C             129.00      129.0       0.0        0.0       0.0    90000.
                                   -4807.0   -5280.0       0.0    -0.315      536.0
 1     530.0                0.020 1.15
 1     530.0                0.040
 1     530.0                0.040
 1     530.0                0.040
 1     530.0                0.060
 1     530.0                0.100
 1     530.0                0.100
 1     530.0                0.100
 1     530.0                0.150
 1     530.0                0.150
22     530.0                0.020
22     530.0                0.040
22     530.0                0.040
22     530.0                0.100
22     530.0                0.100
22     530.0                0.100
22     530.0                0.200
 1     530.0                0.250
 3     530.0                0.250
       0.0       0.0      530.0                                    1
       530.0     0.210  1.880-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
       880.0     0.360  2.130-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      1160.0     0.360  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      1500.0     0.472  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      2000.0     0.484  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      3000.0     0.493  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      4000.0     0.498  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
      5000.0     0.500  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
-1    6000.0     0.500  2.470-04      0.630        MX4926 (VIRGIN+60 DEG LAYUP)
       530.0     0.210  2.470-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      1000.0     0.430  2.530-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      1500.0     0.472  2.580-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      2000.0     0.484  3.240-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      3000.0     0.493  7.190-04      0.630        MX4926 (CHAR  +60 DEG LAYUP)
      4000.0     0.498  [illegible]   0.630        MX4926 (CHAR  +60 DEG LAYUP)
      5000.0     0.500  [illegible]   0.630        MX4926 (CHAR  +60 DEG LAYUP)
-1    6000.      0.500  [illegible]   0.630        MX4926 (CHAR  +60 DEG LAYUP)
       530.0     0.260 0.0001070
       800.0     0.275  0.000109
      1160.0     0.310  0.000110
      1500.0     0.472  0.000110
      2000.0     0.484  0.000110
      3000.0     0.493  0.000110
      4000.0     0.493  0.000110
-1    5000.0     0.500 0.0001100
       530.0     0.210  0.000338
      1000.0     0.430  0.000350
      1500.0     0.472  0.000335
      2000.0     0.484  0.000356
      3000.0     0.493  0.000383
      3500.0     0.495  0.000395
      4000.0     0.498  0.000427
-1    5000.0     0.500  0.000587
 1  486.00
       500.0     0.110   0.00694
-1    5000.0     0.110   0.00694
 4     0.0
         0.0       0.0       1.0
-1       1.0       1.0       0.0
 5    0.001
         0.0       0.0       1.0
        0.15       0.0       1.0
       0.400       0.4       0.0
        0.90       0.4       0.0
+1      1.00       1.0       0.0
1    900.0    6300.0
        0.0       0.0
        0.0    1947.0     904.0     0.8588      29.2
       10.0    1947.0     904.0     0.7238      29.2
     40.000    1947.0     904.0     0.7238      29.2
     60.000      .05         0.
1    120.       .05         0.
      0.607       1.0     0.625                                    1
    29.20                    3500.0   0.0  914.106  914.106-1
    29.20                    3000.0   0.0  671.985  671.985-1
    29.20                    2500.0   0.0  434.119  434.119-1
    29.20                    2000.0   0.0  202.668  202.668-1
    29.20                    1500.0   0.0  -20.763  -20.763-1
    29.20                    1000.0   0.0 -231.356 -231.356-1
    29.20                     500.0   0.0 -405.022 -405.022-1
29.20000 0.00020 0.350003450.86590.     1604.023 1604.023 1  C*       0.
29.20000 0.00020 0.200003158.75570.      992.289  992.289 1  C*       0.
```

INPUT, SAMPLE PROBLEM 4

```
29.20000 0.00020 0.150002948.10120.     707.221  707.221 1  C*        0.
29.20000 0.00020 0.100002472.02610.     284.658  284.658 1  C*        0.
29.20000 0.00020 0.092502306.33350.     175.096  175.096 1  C*        0.
29.20000 0.00020 0.087502119.58270.      62.729   62.729 1  C*        0.
29.20000 0.00020 0.085001914.41820.     -56.221  -56.221 1  C*        0.
29.20000 0.00020 0.082501330.25080.    -466.518 -466.518 1  C*        0.
29.20000 0.00020 0.080001299.59080.    -503.670 -503.670 1  C*        0.
29.20000 0.00020 0.060001181.20300.    -698.006 -698.006 1  C*        0.
29.20000 0.00020 0.050001140.60500.    -780.959 -780.959 1  C*        0.
29.20000 0.00020 0.00010 600.47150.   -1384.243-1384.243 1  C*        0.
29.20000 0.00020 0.00010 500.00000.   -1400.855-1400.855    AL2O30    .
29.20000 0.00010 0.350003450.80590.    1604.023 1604.023 1  C*        0.
29.20000 0.00010 0.200003158.75570.     992.289  992.289 1  C*        0.
29.20000 0.00010 0.150002948.10120.     707.221  707.221 1  C*        0.
29.20000 0.00010 0.100002472.02610.     284.658  284.658 1  C*        0.
29.20000 0.00010 0.092502306.33350.     175.096  175.096 1  C*        0.
29.20000 0.00010 0.087502119.58270.      62.729   62.729 1  C*        0.
29.20000 0.00010 0.085001914.41820.     -56.221  -56.221 1  C*        0.
29.20000 0.00010 0.082501330.25080.    -466.518 -466.518 1  C*        0.
29.20000 0.00010 0.080001299.59080.    -503.670 -503.670 1  C*        0.
29.20000 0.00010 0.060001181.20300.    -698.006 -698.006 1  C*        0.
29.20000 0.00010 0.050001140.60500.    -780.959 -780.959 1  C*        0.
29.20000 0.00010 0.00010 600.47750.   -1384.243-1384.243 1  C*        0.
29.20000 0.00010 0.00010 500.00000.   -1400.855-1400.855 0  AL2O3*    0.
```

INPUT, SAMPLE PROBLEM 4 (CONCLUDED)

CMA/CBM ANALYSIS AT ABLATIVE THROAT OF A SOLID PROPELLANT ROCKET MOTOR
THROAT SURFACE IS CARBON PHENOLIC AT A 60 DEGREE LAYUP ANGLE, P=29 ATM
FISSURE MODEL APPLIED TO SAMPLE PROBLEM NO. 2 SAMPLE NO. 4

---REACTION KINETIC EQUATION---

DRHO/DTIME = GAMMA (BA*EXP(-EA/T)RHOOA((RHOA-RHORA)/RHOOA)**PSIA)
+ GAMMA (BB*EXP(-EB/T)RHOOB((RHOB-RHORB)/RHOOB)**PSIB)
+(1-GAMMA)(BC*EXP(-EC/T)RHOOC((RHOC-RHORC)/RHOOC)**PSIC)

---REACTION KINETIC CONSTANTS---

REACTION	RHOO (LB/CU FT)	RHOR	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400+05	3.00	.1540+05	1000.
B	60.75	32.40	.4480+10	3.00	.3680+05	600.
C	94.50	94.50	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION, GAMMA = .381 (MASS FRACTION = .345)

---DECOMPOSING BACK-UP KINETICS---

DECOMPOSING BACK-UP NO. 1

REACTION	RHOO (LB/CU FT)	RHOR	B (1/SEC)	PSI	E (DEG R)	T REAC (DEG R)
A	20.25	.00	.1400+05	3.00	.1540+05	1000.
B	60.75	40.50	.4480+10	3.00	.3680+05	600.
C	129.00	29.00	.0000	.00	.0000	90000.

RESIN VOLUME FRACTION, GAMMA = .423 (MASS FRACTION = .315)

---TIME INCREMENT INFORMATION---

INITIAL TIME (SEC) .000 FINAL TIME (SEC= 120.00

OUTPUT INTERVAL = .500 SEC FROM INITIAL TIME UNTIL 2.000 SEC
OUTPUT INTERVAL = 2.000 SEC FROM 2.000 SEC UNTIL 10.000 SEC
OUTPUT INTERVAL = 5.000 SEC FROM 10.000 SEC UNTIL FINAL TIME

MAXIMUM TIME STEP =1.00 SECONDS

---NODAL DATA>--

NODE NO.	MATL NO.	TEMPERATURE (DEG.RANKINE)	RELATIVE AREA	THICKNESS (INCHES)	NODAL DEPTH (INCHES)	CONT.RESISTANCE (SQFT-S-DEG/BTU)
1	1	530.00	.1150+01	.02000	.000000*	-.0000
2	1	530.00	.1190+01	.04000	.040000	-.0000
3	1	530.00	.1230+01	.04000	.080000	-.0000
4	1	530.00	.1270+01	.04000	.120000	-.0000
5	1	530.00	.1320+01	.06000	.170000	-.0000
6	1	530.00	.1400+01	.10000	.250000	-.0000
7	1	530.00	.1500+01	.10000	.350000	-.0000
8	1	530.00	.1600+01	.10000	.450000	-.0000
9	1	530.00	.1725+01	.15000	.575000	-.0000
10	1	530.00	.1875+01	.15000	.725000	-.0000
11	22	530.00	.1960+01	.02000	.810000	-.0000
12	22	530.00	.1990+01	.04000	.840000	-.0000
13	22	530.00	.2030+01	.04000	.880000	-.0000
14	22	530.00	.2100+01	.10000	.950000	-.0000
15	22	530.00	.2200+01	.10000	1.050000	-.0000
16	22	530.00	.2300+01	.10000	1.150000	-.0000
17	22	530.00	.2450+01	.20000	1.300000	-.0000
18	3	530.00	.2675+01	.25000	1.525000	-.0000
19	3	530.00	.2925+01	.25000	1.775000	-.0000

*INITIAL INTERNAL RADIUS 1.150 AREA PROP.TO RADIUS**1.00
MINIMUM THICKNESS OF LAST ABLATOR NODE (INCHES) .0400
THERE ARE 10 NODELETS ASSIGNED TO EACH ABLATING NODE

BACK WALL CONVECTION COEF BTU/FTSQ-SEC-DEG R	BACK WALL EMISSIVITY	RESERVOIR TEMPERATURE
.0000	.000	530.00

---HEAT OF FORMATION OF MATERIAL CONSTITUENTS->-
(BTU/LB)

PLASTIC	CHAR	GAS
-376.50	.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

DECOMPOSING BACK-UP NO. 1

PLASTIC	CHAR	GAS
-4807.00	-5280.00	.00

ENTHALPY DATUM TEMPERATURE = 536.000 DEG RANKINE

---MATERIAL THERMAL PROPERTY DATA---

MATERIAL NO. 1 VIRGIN PLASTIC	MATERIAL NO. 2 CHAR	MATERIAL NOS. 3 THROUGH 10 BACK-UP

DECOMPOSING BACK-UP VIRGIN MATERIALS 22,24,26,28,30, CHAR MATERIALS 23,25,27,29,31

OUTPUT, SAMPLE PROBLEM 4

MATERIAL NO. 1 DENSITY = 89.362 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0001880	-1.71	.6300
800.00	.3600	.0002130	75.24	.6300
1160.00	.3600	.0002470	204.84	.6300
1500.00	.4720	.0002470	346.28	.6300
2000.00	.4840	.0002470	585.28	.6300
3000.00	.4930	.0002470	1073.78	.6300
4000.00	.4980	.0002470	1569.28	.6300
5000.00	.5000	.0002470	2068.28	.6300
6000.00	.5000	.0002470	2568.28	.6300

MATERIAL NO. 2 DENSITY = 70.864 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)	EMISSIVITY
530.00	.2100	.0002470	-1.92	.6300
1000.00	.4300	.0002530	148.48	.6300
1500.00	.4720	.0002580	373.98	.6300
2000.00	.4840	.0003240	612.98	.6300
3000.00	.4930	.0007190	1101.48	.6300
4000.00	.4980	.0013400	1596.98	.6300
5000.00	.5000	.0020000	2095.98	.6300
6000.00	.5000	.0027500	2595.98	.6300

MATERIAL NO.22 DENSITY = 108.708 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2600	.0001070	-1.60
800.00	.2750	.0001090	70.62
1160.00	.3100	.0001100	175.92
1500.00	.4720	.0001100	308.86
2000.00	.4840	.0001100	547.86
3000.00	.4930	.0001100	1036.36
4000.00	.4930	.0001100	1529.36
5000.00	.5000	.0001100	2025.86

MATERIAL NO.23 DENSITY = 91.516 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)	SENSIBLE ENTHALPY (BTU/LB)
530.00	.2100	.0003180	-1.92
1000.00	.4300	.0003300	148.48
1500.00	.4720	.0003350	373.98
2000.00	.4840	.0003560	612.98
3000.00	.4930	.0003830	1101.48
3500.00	.4950	.0003950	1348.48
4000.00	.4980	.0004270	1596.73
5000.00	.5000	.0005820	2095.73

MATERIAL NO. 3 DENSITY = 485.000 LB/CU FT

TEMPERATURE (DEG R)	SPECIFIC HEAT (BTU/LB-DEG)	CONDUCTIVITY (BTU/FT-SEC-DEG)
500.00	.1100	.0069400
5000.00	.1100	.0069400

TABLES OF OPTIONAL MASS-FRACTION FUNCTIONS FOR THERMAL CONDUCTIVITY
K = F1(X)*KP + F2(X)*KC

F-FUNCTION TABLE NO. 1 ASSIGNED TO MAIN MATERIAL

X	F1(X)	F2(X)
.0000	.0000	1.0000
1.0000	1.0000	.0000

F-FUNCTION TABLE NO. 2 ASSIGNED TO DECOMPOSING BACK-UP NO. 1

X	F1(X)	F2(X)
.0000	.0000	1.0000
.3500	.0000	1.0000
.6000	.4000	.0000
.9000	.4000	.0000
1.0000	1.0000	.0000

---RESIN DECOMPOSITION GAS SENSIBLE ENTHALPY---

TEMPERATURE	(DEG R)	900.00	6300.00
ENTHALPY	(BTU/LB)	.00	.00

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	BLOWING REDUCTION PARAMETER
.00	1	1947.00	904.00	.6588	29.20000	.375
10.00	1	1947.00	904.00	.7238	29.20000	.375
60.00	1	1947.00	904.00	.7238	29.20000	.375

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
60.00	3	.05	.00
120.00	3	.05	.00

CM/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BHP*. OOT/CHO, BHP IN TABLE

---SURFACE EQUILIBRIUM DATA---

OUTPUT, SAMPLE PROBLEM 4 (CONTINUED)

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .602
UNEQUAL DIFFUSION EXPONENT = .000
NOMINAL SURFACE VIEW FACTOR = 1.000 (OPTION 1)
FISSURE MODEL USED FOR SURFACE ENERGY TERMS AND BLOWING CORRECTION
HEAT-TRANSFER COEFFICIENT MULTIPLIED BY (H INITIAL/H CURRENT)**EX,
WHERE EX = (1.8-.2N)/(1.-N) AND N IS THE BURNING RATE EXPONENT.
IN THIS PROBLEM N HAS BEEN SET EQUAL TO .62500
NO CHAR SWELL CORRECTION ON SURFACE RECESSION

P = 29.2000 ATM

TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL	TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL	TEMPERATURE (DEG R)	EDGE ENTH AT T-WALL
6300.00	1645.39	3600.00	364.80	900.00	-729.04
5400.00	1209.57	2700.00	-37.37		
4500.00	781.41	1800.00	-416.44		

M-DOT-GAS/CM = .0002 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1792.76		3815.25	.0875	472.29	C*
1080.86	.0001	1820.00	C*	4151.40	.0925	428.96	C*
2053.09	.0500	1193.83	C*	4449.65	.1000	376.27	C*
2126.17	.0600	1088.40	C*	5306.58	.1500	38.13	C*
2339.26	.0800	847.37	C*	5685.76	.2000	-308.31	C*
2394.45	.0825	805.03	C*	6211.45	.3500	-1350.00	C*
3445.95	.0850	517.03	C*				

M-DOT-GAS/CM = .0001 PRESSURE = 29.2000 ATM

TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES	TEMP (DEG R)	M-DOT-CHAR/CM	CHEM.PROD (BTU/LB)	SURFACE SPECIES
900.00	.0001	1792.76		3815.25	.0875	472.29	C*
1080.86	.0001	1820.00	C*	4151.40	.0925	428.96	C*
2053.09	.0500	1193.83	C*	4449.65	.1000	376.27	C*
2126.17	.0600	1088.40	C*	5306.58	.1500	38.13	C*
2339.26	.0800	847.37	C*	5685.76	.2000	-308.31	C*
2394.45	.0825	805.03	C*	6211.45	.3500	-1350.00	C*
3445.95	.0850	517.03	C*				

OUTPUT SAMPLE PROBLEM 4 (CONTINUED)

AEROTHERM CHARRING MATERIAL THERMAL RESPONSE AND ABLATION PROGRAM

----OUTPUT----

.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
1	0	1	1.1500	.00	1947.00	.8588	.00000

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.00000	.00000	.000000	.000000	.000000	.000000

---RECESSIONS/RECESSION RATES---

SURFACE (IN)	/ (IN/SEC)	CHAR (.02) (IN)	/ (IN/SEC)	PYROLYSIS (.98) (IN)	/ (IN/SEC)
.0000000/	.0000000	.0000000/	.0000000	.0000000/	.0000000

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.000	.000	.000	.000	.000
TOTAL	.000	.000	.000	.000	.000

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	1	530.00	89.362	.000188	11	22	530.00	108.708	.000107
2	1	530.00	89.362	.000188	12	22	530.00	108.708	.000107
3	1	530.00	89.362	.000188	13	22	530.00	108.708	.000107
4	1	530.00	89.362	.000188	14	22	530.00	108.708	.000107
5	1	530.00	89.362	.000188	15	22	530.00	108.708	.000107
6	1	530.00	89.362	.000188	16	22	530.00	108.708	.000107
7	1	530.00	89.362	.000188	17	22	530.00	108.708	.000107
8	1	530.00	89.362	.000188	18	3	530.00	486.000	.006940
9	1	530.00	89.362	.000188	19	3	530.00	486.000	.006940
10	1	530.00	89.362	.000188					

10.0000 SECONDS

TIME STEP	SURF ITER	PROB OPTN	SURFACE RAD (IN)	H WALL (BTU/LB)	H EDGE (BTU/LB)	HEAT COEFF (LB/SQ FT-SEC)	CH/CHO
123	3	1	1.2719	1384.86	1947.00	.4399	.95322

---ABLATION RATES---

B PRIME	B PRIME G	M DOT CHAR (LB/SQ FT-SEC)	M DOT GAS (LB/SQ FT-SEC)	M CHAR (LB/ORIG SQ FT)	M GAS (LB/ORIG SQ FT)
.36617	.14869	.057546	.039433	.758908	.576524

---RECESSIONS/RECESSION RATES---

SURFACE (IN)	/ (IN/SEC)	CHAR (.02) (IN)	/ (IN/SEC)	PYROLYSIS (.98) (IN)	/ (IN/SEC)
.1218793/	.0097448	.1441457/	-.0000381	.3601299/	.0174075

---SURFACE ENERGY FLUX TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	CONVECTED IN	RADIATED IN	RADIATED OUT	CHEMICAL GENERATION	CONDUCTION AWAY
RATE	.247+03	.570+03	.334+03	-.123+03	.360+03
TOTAL	.394+04	.601+04	.331+04	-.116+04	.548+04

---INTERIOR ENERGY TERMS---
CURRENT RATES (BTU/SQ FT SURFACE-SEC)
AND INTEGRATED VALUES (BTU/ORIG SQ FT)

	PYROL GAS PICK UP	DECOMP ABSORPTION	CONVECTION WITH SOLIDS	STORAGE IN SOLID	LOSS AT REAR FACE
RATE	.000	.524+02	.168+03	.138+03	.691-01
TOTAL	.000	.715+03	.269+04	.267+04	.120+00

NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)	NODE	MAT	TEMP (DEG R)	DENSITY (LB/CU FT)	COND(BTU/ FT SC F)
1	0	5763.61	71.048	.002544	11	22	530.74	108.708	.000107
2	0	5280.64	71.079	.002182	12	22	530.23	108.708	.000107
3	0	4753.11	71.098	.001812	13	22	530.06	108.708	.000107
4	0	4158.50	71.226	.001415	14	22	530.00	108.708	.000107
5	0	2945.05	72.580	.000646	15	22	530.00	108.708	.000107
6	0	1095.62	86.978	.000242	16	22	530.00	108.708	.000107
7	1	660.28	89.362	.000200	17	22	530.00	108.708	.000107
8	1	557.54	89.362	.000191	18	3	530.00	486.000	.006940
9	1	532.95	89.362	.000188	19	3	530.00	486.000	.006940

OUTPUT, SAMPLE PROBLEM 4 (CONCLUDED)

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APPENDIX A

SOME SUGGESTIONS FOR SELECTING NODAL SIZES

APPENDIX A

SOME SUGGESTIONS FOR SELECTING NODAL SIZES

A.1 GENERAL REMARKS

Experience with particular problems will always be the best guide in selecting the sizes of the finite difference nodes within the heated material. Nevertheless, it is possible to set down some very rough guidelines for nodal size which require only a preliminary estimate of the overall character of the solution history rather than detailed experience with closely related problems. The following subsections describe how such preliminary estimates can be turned into moderately useful nodal size assessments.

A.2 NODAL SIZES RELATED TO TIME CONSTANT INFORMATION

Most transient problems have some identifiable time constant which can be used to select a nodal size. This time constant is either the basic resistance times capacitance time constant of the system (usually, of course, the chief resistance is found in the ablating material itself, since the outer heat transfer conductance is very high in most ablation problems) or some time constant associated with a transient boundary condition. The second case is the simpler of the two to visualize: obviously, we want the time constant of the nodal zones to not be significantly larger than the time constant of the boundary condition, θ_{cb}. The time constant of a node is simply

$$\theta_{cn} \approx \frac{\rho C_p \delta A}{kA/\delta} = \frac{\delta^2}{\alpha} \tag{A-1}$$

where ρ, C_p, and k are evaluated at the nodal temperature. Thus, the first nodal size criterion is simply

$$\frac{\delta^2}{\alpha} \approx \theta_{cb} \tag{A-2}$$

or

$$\delta \approx (\alpha \theta_{cb})^{\frac{1}{2}} \tag{A-3}$$

For problems with relatively steady boundary conditions, Equation (A-3) will not yield useful results and one must consider the "natural" time constant of the ablating material, i.e., the first case mentioned above. For a problem with negligible recession and steady boundary conditions, no single set of nodes can be appropriate for the entire problem history. If we let θ_i stand for the time around which interest centers, then the standard similarity solution for the transient temperature in a constant properties slab initially at constant temperature T_i with steady surface temperature T_o impressed at $\theta = 0$ shows that the dimensionless temperature $(T - T_i)/(T_o - T_i)$ has decayed to less than 0.1 at $x/2(\alpha\theta_i)^{\frac{1}{2}} \approx 2$. If we want 10 or so nodes distributed over this region, then

$$\delta = \frac{x}{10} \approx \frac{4(\alpha\theta_i)^{\frac{1}{2}}}{10} = 0.4(\alpha\theta_i)^{\frac{1}{2}} \qquad \text{(A-4)}$$

which naturally enough is similar to the result of Equation (A-3), even though two different time concepts are involved.

A.3 NODAL SIZES RELATED TO SURFACE RECESSION RATE INFORMATION

If (as is usual) the problem has surface recession $\dot{S}$, then some additional time step considerations must be made. If $\dot{S}$ and T_w are constant values impressed at time zero for a constant properties slab initially at T_i, the simple analysis shows that the in-depth temperature profile as measured from the heated surface ultimately attains a steady shape

$$\frac{T - T_i}{T_o - T_i} = e^{-\dot{S}x/\alpha} \qquad \text{(A-5)}$$

This profile decays to 0.1 for $\dot{S}x/\alpha \approx 3$; if we want, say, 10 nodes in this interval then

$$\delta = \frac{x}{10} = \frac{3\alpha}{10\dot{S}} = 0.3\alpha/\dot{S}$$

However, a slightly tighter criterion than this derives from a basic accuracy study of the particular finite difference equations used in CMA. This study, reported in Appendix B of Reference A-1 below, indicated that for good in-depth accuracy one should satisfy the restriction

$$\delta \approx 0.1\alpha/\dot{S} \qquad \text{(A-7)}$$

A final result of interest may be obtained by noting that the constant $\dot{S}$, constant T_w problem described here does have a transient beginning and approaches the steady state only as a limit. References A-2 and A-3 show that this limit, as measured by the closeness of approach of q_{cond} to its steady state value is reached to within a few percent at

$$\theta \approx \alpha/\dot{S}^2 \qquad \text{(A-8)}$$

It is very interesting to observe that if we consider the time given by Equation (A-8) as the "time of interest" and substitute it into the time constant result (A-4), we obtain the result

$$\delta \approx 0.4\alpha/\dot{S} \qquad \text{(A-9)}$$

which harmonizes rather remarkably with Equation (A-6), derived from steady state profile considerations.

A.4 CONSEQUENCES OF SELECTING INAPPROPRIATE NODE SIZES

The selection of node sizes much smaller than necessary generally merely increases the computing time to far above what could be achieved with more reasonable nodal sizes. In theory, extremely small nodal size could introduce excessive numerical round-off error problems, although this has never been observed in practice with the CMA program.

The choice of too large nodes usually results in a non-obvious lack of accuracy for the entire prediction, especially for the in-depth temperature profile. Important problems should be computed with two different choices of nodal sizes for a check of the accuracy attained. Gross violations of restriction (A-7) sometimes cause drastic and obvious oscillations in the in-depth predictions.

A.5 REMARKS ON NODELETS

As noted in Section 2.1.1 above, the pyrolysis events in the CMA program are computed in a grid of "nodelets" finer than the nodal grid used for the energy calculations. The number of "nodelets" per node may be selected by the user. Experience to date has not been sufficient to lay down any general rules for selecting the number of nodelets per node in various applications. Ten appears sufficient, although many problems seem to do well with fewer. The number of nodelets per node often has an appreciable effect on computation time (see Appendix B below), and for an extensive series of calculations it is worthwhile to minimize this number (by experiment) to reduce costs.

A.6 SUMMARY

The user confronted with an ablation problem outside the range of his prior experience can draw upon several rough guides to select nodal sizes. Locally throughout the material, nodal thicknesses should satisfy the basic thermal profile penetration relation

$$\delta \approx 0.4(\alpha\theta_i)^{\frac{1}{2}} \tag{A-10}$$

where θ_i is a representative real time of principal interest and α is evaluated locally throughout the material. For example, suppose the user is studying nozzle ablation during a 60 second rocket firing and specifies output every 10 seconds. The "real time of interest" to the user is evidently about 10 seconds, since the first output will occur then. The user would set θ_i equal to 10 seconds in Equation (A-10), and select α values for the char for estimating nodal spacing near the surface. Values of α for the virgin plastic would be used for estimating the nodal spacing deeper in the material.

For time varying boundary conditions with a "time constant" or time scale of θ_{cb},

$$\delta \approx (\alpha\theta_{cb})^{\frac{1}{2}} \tag{A-11}$$

if this variation is to be "followed" accurately by the in-depth solution. For example, suppose the user is analyzing heat shield ablation during a reentry for which the "heating pulse" rate rises from zero to a maximum in 60 seconds and then decays again in an additional 100 seconds. Speaking in very approximate terms, the "time constant" of such a pulse represents the time required for the pulse to rise about half way from "trough" to peak or to sink roughly half way from peak to trough. This gives time constants of 30 and 50 seconds; the user would naturally select the shorter one for use in Equation (A-11).

Finally, if recession is important, nodal sizes should also satisfy

$$\delta \lesssim 0.1\alpha/\dot{S} \tag{A-12}$$

to preserve accuracy of the solution.

Most generally users prefer to grade the nodal sizes within the general limits set by these guidelines, beginning with smaller nodes near the heated surface and expanding to rather large nodes (even violating these guidelines) in regions where the thermal pulse does not penetrate, or just begins to penetrate. It is recommended that the user make the first node half the thickness of the second node in all cases, since the program assumes the first node is in fact a half node with only half the usual number of nodelets.

REFERENCES FOR APPENDIX A

A-1. Moyer, C. B. and Rindal, R. A., "Finite Difference Solution for the In-Depth Response of Charring Materials Considering Surface Chemical and Energy Balances. Aerotherm Corporation, Mountain View, California, Aerotherm Report 66-7, Part II, March 14, 1967 (also NASA CR-1061, June 1968).

A-2. Rindal, R. A., Flood, D. T., and Kendall, R. M., "Analytical and Experimental Study of Ablation Material for Rocket-Engine Application," Vidya Division, Itek Corporation, Palo Alto, California, NASA CR-54757, May 15, 1966.

A-3. Baer, D. and Ambrosio, A., "Heat Conduction in a Semi-Infinite Slab with Sublimation at the Surface." Space Technology Laboratories, Inc., Pasadena, California, TR-59-0000-00610, February 24, 1959.

APPENDIX B

ESTIMATION OF EXECUTION TIME

APPENDIX B

ESTIMATION OF EXECUTION TIME

Estimates of computer run time can generally be made by determining the required computation time per time step and multiplying this by the estimated number of time steps needed (equal to problem time divided by time step size). The following sections will discuss this approach. A quicker estimate, adequate for some purposes, may be obtained from the simple empirical statement that most CMA problems consume computer time at a rate of about 20 to 30 percent of the real problem time. This estimate applies to charring problems of about 50 nodes with recession rates less than about 25 mils/sec.

B.1 ROUGH ESTIMATES OF COMPUTER TIME PER TIME STEP

"Typical" problems of the type cited above have been observed to require about 50,000 μsec to 100,000 μsec per time step on Univac 1108 and CDC-6600 machines, and about 500,000 μsec per time step on the IBM 7094 machines.

B.2 REFINED ESTIMATES OF COMPUTER TIME PER TIME STEP

A refined estimate of the computer time required per time step can be obtained from a count of arithmetic operations. The following table of the number of operations in each section of the Charring Material Ablation program provides a useful estimate of execution time as a function of the number of nodes, the number of nodelets per node, and so on.

The input subroutine and all other operations, such as output, not performed each time step, have not been included. Only floating arithmetic is considered.

As an example, with the average operating times for the IBM 7094 (add and subtract = 14 s, multiply = 7 s, divide = 12 s, expf = 188 s, logf = 226 s), this table yields the following floating arithmetic time estimate per time step.

TABLE OF FLOATING OPERATIONS
FOR ONE TIME STEP

	Add	Subtract	Multiply	Divide	Expf	Logf
Miscellaneous Nodal Computations, per Node	32	36	64	25	0	0
General Decomposition, per Decomposing Node	22	15	13	3	0	0
Component Decomposition, per Component for each Decomposing Nodelet	1	3	4	3	3	2
Surface Calculations, per Iteration	25	39	50	10	1	0

$$T = [(1136 \cdot I + 645)J \cdot F + 1700]N + K(1534) \ \mu sec/step$$

where

T = execution time for a single time step (μsec)

I = number of decomposing components in the material

J = number of nodelets per node

F = fraction of nodes decomposing

N = total number of nodes

K = number of iterations in surface energy balance

In this equation, F should be an average value for the fraction of nodes actively decomposing during the problem (usually between 1/3 and 1/2). A study of numerous problems reveals that K averages very close to 3.

The resulting total time must be multiplied by a factor to account for "administrative" arithmetic such as DO loop indexing. Experience with this program on the 7094 suggests a factor between 1.4 and 1.5

B.3 DETERMINATION OF NUMBER OF TIME STEPS REQUIRED

To estimate total execution time, the time per time step T may be multiplied by the total number of time steps, a number approximately determined by the user in the choice of the maximum time step allowed (see Section 3.1.3

above). For some problems, however, a built-in limit based on the recession rate turns out to be smaller. This limit prevents the time step $\Delta\theta$ from allowing more than the thickness of one nodelet to ablate during a time step; thus

$$\Delta\theta \leq \min(2\delta_1, \delta_2, \delta_3, \delta_4, \ldots \delta_{NL_{min}})/\dot{S}J$$

where the δ's are the nodal thickness in the main charring material and $\delta_{NL_{min}}$ is the minimum allowed thickness for the last ablating node (Section 3.1.3, p. 3-3 above).

B.4 OTHER CONSIDERATIONS

Additional machine time will be consumed by input and loading operations, overlay or special tape handling (if necessary), and output operations, the details of which are peculiar to individual computing facilities.

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13. ABSTRACT

This two-volume report describes a Fortran-IV computer code which computes the transient thermal and ablation response of a charring insulation material structure. The program is for one-dimensional bodies, but can treat a variety of shapes, including planes, cylinders, spheres, and more general thermal "stream tube" bodies. The program can treat complex systems including a main ablating material, several charring back-up materials, and a multiple non-charring material back-up structure.

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Resin degradation						
Rocket nozzle analysis						
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