AFRPL-TR-72-24

Aerotherm Report No. UM-72-26

AD 744853

USER'S MANUAL

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION COMPUTER PROGRAM (ASTHMA3)

Volume I - Program Description and Sample Problems

January 1972

Air Force Rocket Propulsion Laboratory
Director of Laboratories
Edwards, California 93523
Air Force Systems Command
United States Air Force

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Acurex Corporation/Aerotherm Division 485 Clyde Avenue Mountain View, California 94040	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

User's Manual - Aerotherm Axi-Symmetric Transient Heating and Material Ablation Computer Program (ASTHMA3) - Volume I - Program Description and Sample Problems

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

User's Manual

5. AUTHOR(S) *(First name, middle initial, last name)*

6. REPORT DATE January 1972	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. F04611-69-C-0[illegible] b. PROJECT NO. c d.	9a. ORIGINATOR'S REPORT NUMBER(S) UM-72-26 (Vol. I) 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFRPL-TR-72-24	

10. DISTRIBUTION STATEMENT

Approved for Public Release - Distribution Unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Rocket Propulsion Laboratory Edwards, California

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DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Computer code						
Ablation and thermal response						
Pyrolytic graphite						
Rocket nozzles						
Bulk graphite						

Unclassified

Security Classification

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VOLUME I

PROGRAM DESCRIPTION AND SAMPLE PROBLEMS

Prepared Under the Sponsorship of

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FOREWORD

This report is one of two computer program user's manuals prepared by Aerotherm Division of Acurex Corporation under USAF Contract F04611-69-C-0081. Included herein is Volume I of the manual for Version 3 of the Aerotherm Axi-Symmetric Transient Heating and Material Ablation (ASTHMA3) computer code. This volume describes the problems solved by the code and presents an input (card format) user's guide and sample problems. The code was originally developed under USAF Contract F04611-67-C-0047, and upgraded under the subject contract. The work was administered under the direction of the Air Force Rocket Propulsion Laboratory with Mr. Robert J. Schoner as Project Officer.

Mr. John W. Schaefer was Program Manager and Mr. Mitchell R. Wool was Program Engineer. The ASTHMA code upgrading was performed by Dr. Carl B. Moyer and Mr. Kurt E. Suchsland.

This technical report has been reviewed and is approved.

A. D. Brown, Jr., Lt. Col., USAF
Chief, Technology Division

ABSTRACT

This document presents a user's manual for the Aerotherm Axi-Symmetric Transient Heating and Material Ablation Program, Version 3 (ASTHMA3), including a general description of program capabilities and solution procedures as well as a detailed set of input instructions.

ASTHMA3 is a transient heat conduction program for two-dimensional, axi-symmetric bodies. Multiple non-charring, anisotropic materials may be studied. The surface boundary condition has three options, including an unusually general thermochemical erosion or ablation condition as well as simplified radiation and specified temperature options.

GLOSSARY

Some of the terms used in the text have very particular meanings. These are collected here for ready reference.

back wall	one of the four sides of the nodal mesh layout, located by convention at the bottoms of the columns; may be convectively and radiatively cooled but does not ablate
box	see "nodal box"
column	refers to one direction of the nodal mesh, heated surface is at the top of the columns
heated surface	the one surface of the four sides of the nodal mesh layout which is exposed to the hyperthermal, chemically reactive environment, located by convention at the top of the columns in the mesh; opposite side of mesh network is the back wall
mesh	assemblage of quadrilateral nodal boxes arranged in rows and columns, each row and each column having the same number of nodal boxes; encompasses all the material of interest and divides it into nodes for finite difference heat conduction analysis
nodal box	one quadrilateral zone in the mesh
nodal center, nodal point	a point within the nodal box at which all the material in the box is presumed to be lumped for the finite difference calculation, not necessarily in the center of the node
node	used for nodal box, nodal center, nodal point
null node	a nodal box in the mesh which contains no material, used for bookkeeping operations only, not involved in finite difference solution
row	refers to one direction in nodal mesh, "parallel" to heated surface
side wall	any side of nodal box other than heated surface; has same boundary conditions as "back wall"

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GLOSSARY (Concluded)

surface node	the top node in each column (excepting null nodes), that node next to (adjacent to, at) the heated surface; note that the surface nodal box is next to the heated surface and one of its four sides is exposed to the hyperthermal environment, the nodal point or nodal center however is somewhere within the nodal box; there is a special point on the surface called the surface point which must not be confused with the surface nodal "center"
surface point	the center of the heated surface side of the top nodal box in each column (not counting null nodes); this point is distinct from the nodal point for that nodal box; the temperature of this point is determined by the surface energy balance in Options 1 and 3 or by assignment in Option 2

LIST OF SYMBOLS

A	area of side of nodal box	ft^2
a,b,c	nodal box side and center line lengths, Figure 8, Equation (14)	in
B'	defined as $(B'_c - \sum \dot{m}_{r_\ell}/\rho_e u_e C_M)$ thermochemical ablation parameter	---
B'_c	defined as $\dot{m}_c/\rho_e u_e C_M$, total ablation parameter	---
B'_f	defined as $\sum \dot{m}_{r_\ell}/\rho_e u_e C_M$	---
B'_g	defined as $\dot{m}_g/\rho_e u_e C_M$	---
B'_{tc}	same as B'	---
b	see a,b,c	
c	nodal capacity, Equation (16)	Btu/°F
C_H	Stanton number for heat transfer (corrected for "blowing", if necessary)	---
C_{H_0}	Stanton number for heat transfer not corrected for blowing	---
C_{k_i}	number of k atoms in molecule i	---
C_M	Stanton number for mass transfer	---
c	specific heat	Btu/lb°F
c	see a,b,c	in
$\bar{D}$	constant defined by Equation (39)	ft^2/sec
$\mathcal{D}_{ij}$	binary diffusion coefficient	ft^2/sec

LIST OF SYMBOLS (continued)

F	radiation view factor	---
F_i, F_j	empirical factors appearing in Equation (39)	---
f	denotes general functional relationship	---
H_r	recovery enthalpy	Btu/lb
h	enthalpy	Btu/lb
h	back wall convective coefficient	Btu/ft^{2}sec °R
h_c	enthalpy of ablating material at wall temperature	Btu/lb
h_w	enthalpy of gases adjacent to the wall	Btu/lb
I	total number of identifiable species	---
I	number of iteration cycles in problem	---
i, j	chemical species indices	---
K	total number of elements in system	---
K_i	mass fraction of species i	---
$\tilde{K}_k$	mass fraction of element k (regardless of molecular configuration)	---
k	thermal conductivity	Btu/ft-sec°R
k_f	forward rate constant for kinetically controlled reaction	various
L	path lengths in a nodal box, Figure 6	ft

LIST OF SYMBOLS (continued)

ℓ	total path length, Figure 13	ft
$\mathcal{M}$	system molecular weight $\sum x_i \mathcal{M}_i$	lb/lb mole
$\mathcal{M}_i$	molecular weight of species i	lb/lb mole
m	node corner and center row number	---
$\dot{m}$	mass flow rate per unit area from the surface, thermochemical effects only	lb/ft^2sec
$\dot{m}_c$	total mass flow rate of "char" or main ablating material per unit surface area, all effects (thermochemical plus condensed phase mechanical removal)	lb/ft^2sec
$\dot{m}_g$	mass flow rate of pyrolysis gas out a unit area of surface	lb/ft^2sec
$\dot{m}_{r_\ell}$	flow rate of condensed phase ℓ mechanically removed from surface	lb/ft^2sec
N	total number of nodes	---
n	node corner and center column number	---
P	total pressure	lb/ft^2
P_i	partial pressure of species i	lb/ft^2
q_{chem}	chemical energy flux term defined by Equation (42)	Btu/ft^2sec
q_{cond}	rate of energy conduction into solid material at surface	Btu/ft^2sec
q_{diff}	rate of energy input to solid surface by diffusional processes in the boundary layer	Btu/ft^2sec
$q_{rad\ in}$	rate of energy input to the surface by radiation from the boundary layer or from outside the boundary layer, same as q_{rad}	Btu/ft^2sec

LIST OF SYMBOLS (continued)

$q_{rad\ out}$	rate of energy radiated away from surface	Btu/ft^2sec
q_{sen}	$\triangleq \rho_e u_e C_H (H_r - h_{e_w})$	Btu/ft^2sec
R	thermal resistance, see Equations (17),(18)	sec°F/Btu
R*	contact thermal resistance	$ft^2sec°F/Btu$
r	radius	in
S	see ΔS	°R
T	computing time	hrs
T	temperature	°R
T_w	wall (surface) temperature, general term for $T_{s,n}$	°R
U	thermal conductance, Equation (20)	Btu/sec°R
U'	modified U, Equation (21)	Btu/sec°R
u_e	velocity of gases at edge of boundary layer	ft/sec
V	nodal volume	ft^3
v	gas velocity (see ρv)	ft/sec
x_i	mole fraction of species i	---
Z	axial coordinate	ft
Z_i^*	diffusion driving force, see Equations (36) and (37)	---

LIST OF SYMBOLS (continued)

GREEK

α	heated surface absorbtivity (taken equal to ε_w), thermal diffusivity	---
γ	constant, empirically chosen = 2/3	---
Δ	denotes change	---
ΔS	change in surface point location during $\Delta\theta$	ft
$\Delta\theta$	time step in finite difference solution	sec
ε	emissivity or emittance	---
η	input multiplicative safety factor in time step calculation, Equation (23)	---
θ	time	sec
λ	constant in Equation (41)	---
μ_2	dimensionless factor defined by Equation (38)	---
ρ	density	lb/ft^3
$(\rho v)_w$	$\dot{m}_c - \sum \dot{m}_{r_\ell}$	lb/ft^2sec
$\rho_e u_e$	mass flow at boundary layer edge	lb/ft^2sec
$\rho_e u_e C_H$	heat transfer convective film coefficient	lb/ft^2sec
$\rho_e u_e C_M$	mass transfer convective film coefficient	lb/ft^2sec
σ	Stefan-Boltzmann constant	$Btu/ft^2sec°R^4$
φ	parameter defined by Equation (41)	---

LIST OF SYMBOLS (continued)

SUBSCRIPTS

A,B,C,D	indices for path lengths L (Fig. 6), nodal side areas A (Fig. 7) and thermal resistances R (Fig. 12)
abs	denotes absorbed energy rate not proportional to surface area; Figure 15
B	see A,B,C,D
bw	denotes back wall side
C	see A,B,C,D
CL	denotes nodal column center line
c	denotes "char" or ablating material; see $\dot{m}_c$; denotes nodal mesh corner coordinate
cond	denotes heat conduction; Figure 15
D	see A,B,C,D
diff	denotes diffusive energy fluxes, Figure 15
e	denotes boundary layer outer edge, or boundary layer edge gas (environment)
g	denotes pyrolysis gas
H	see C_H
i,j	denotes any identifiable species: atom, ion, molecule
k	denotes element
ℓ	index of condensed phase species mechanically removed from surface
M	see C_M

LIST OF SYMBOLS (concluded)

SUBSCRIPTS (concluded)

m	node corner and center row number index
N	denotes node center
n	node corner and center column number index
p	denotes virgin plastic
r	see $\dot{m}_{r_\ell}$
rad in	denotes radiation flux to surface; Figure 15
rad out	denotes flux radiated from surface; Figure 15
res	denotes "reservoir" communicating with back wall and side walls
s	denotes heated surface
w	denotes wall, i.e., heated surface
∞	see C_{H_O}
1,2	denote "earlier" and "later"; also see Figure 13
θ,θ'	at times θ and θ', respectively

SUPERSCRIPTS

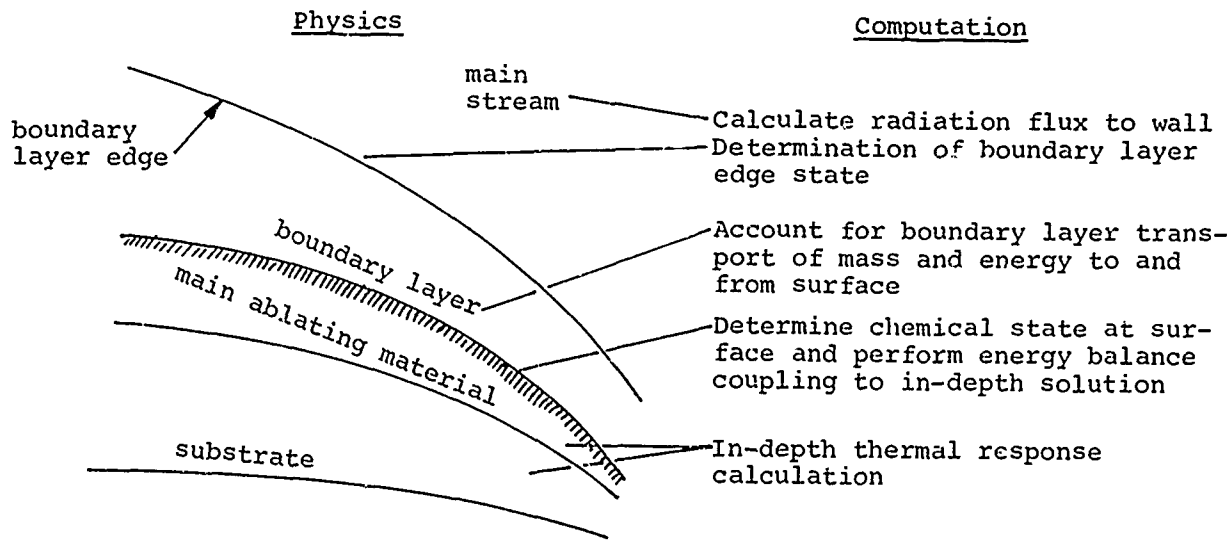
'(prime)	see B', B'_c, B'_f, B'_g, B'_{tc}, U'
'(prime)	denotes at new time $\theta' = \theta + \Delta\theta$
T_w	enthalpy evaluation temperature

SPECIAL SYMBOLS

*	see Z_i^*, R^*

SECTION 1

This report is Volume I of a two volume user's description of the Axi-Symmetric Transient Heating and Material Ablation Program (generally denoted ASTHMA), Version 3 (ASTHMA3). This volume presents an analysis technique and describes the associated computer program (ASTHMA3) for the prediction of the thermal response and ablation of two-dimensional axi-symmetric non-charring materials. Section 2 of this volume (Volume I) presents some of the underlying analysis foundation upon which the computer program is built. Since much of the pertinent analysis work has previously been published elsewhere, these particular parts of the analysis are treated only briefly here and the reader is referenced to the previous reports for more information. Section 3 of Volume I is a complete, but condensed and succinct, user's manual giving explicit instructions for the preparation of input to the program and the interpretation of program output. The in-depth temperature prediction is of the familiar explicit finite-difference type. It allows a completely general finite difference mesh layout relative to the physical r-z axes, and accounts for anisotropic heat conduction effects. The heated surface boundary condition is an unusally general thermo-chemical type. It accounts for two specific kinetically controlled carbon oxidation reactions, one specific kinetically controlled carbon reduction reaction, one kinetically controlled water gas shift reaction, and any number of gas-phase equilibrium reactions for any combination of ablating materials and environments. Chief applications for the computer program are rocket nozzles and entry vehicles. The following sketch serves to clarify various physical aspects of the ablation problem treated. The table below cites the



aspects and indicates which descriptions of the analysis are to be found in the present report and which are to be found elsewhere. Note that the ASTHMA3 Program described in this report is usually used in conjunction with

SUMMARY OF COMPUTATIONAL TASKS

Task	Program	Where Described
1. Determine radiation flux from free stream to wall	Not computed, but accounted for by ASTHMA3. User must provide as input.	--
2. Determine boundary layer edge state (chemical)	GASKET, etc.	Refs. 1-5
3. Account for boundary layer transport of		
a. mass	GASKET, etc.	Refs. 1-5
b. energy	ASTHMA, but user must provide convective transfer coefficients as input	
4. Surface thermochemical state	GASKET, etc.	Refs. 1-5
5. In-depth temperature	ASTHMA3	Below

another program which handles the chemical state computations required in the heated surface boundary condition definition. Any one of several thermochemistry computer programs is suitable for this purpose, including EST (Ref. 1), EST2 (Ref. 2), EST3 (Ref. 3), ACE (Ref. 4), and GASKET (Ref. 5). These codes all differ to various degrees in details of the thermochemical solution. The GASKET version is the newest and contains a simplified chemical kinetics treatment of carbon oxidation particularly pertinent to rocket nozzles. Consequently, this manual, when dealing with communication between ASTHMA3 and the surface state solution, will refer only to GASKET as the partner program. Neither GASKET nor the other chemistry codes is described in this manual. References 1-5 provide appropriate descriptions and user's manuals.

A complete ablation problem may be solved with the GASKET and ASTHMA programs in conjunction in the following steps:

(1) Lay out nodal geometry, provide this and material properties data to ASTHMA3

(2) Determine radiation flux history and convective heat transfer coefficient ($\rho_e u_e C_H$) history; provide to ASTHMA3

(3) Determine chemical nature of environment and generate surface thermochemical ablation tables with GASKET for input to ASTHMA3

(4) Run ASTHMA3, obtain temperature and surface recession histories.

The second volume of this user's description presents listings, flow charts, and lists of FORTRAN variable names for the program.

SECTION 2

DESCRIPTION OF ANALYSIS FOUNDATIONS FOR THE AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM, VERSION 3 (ASTHMA3)

This section describes much of the analysis work upon which the ASTHMA3 program is built. Section 2.1 below defines the problem treated, and Section 2.2 gives some description of the in-depth solution procedure. Section 2.3 briefly describes the heated surface boundary condition treatment.

2.1 PROBLEM TREATED AND GENERAL METHOD OF SOLUTION

2.1.1 Problem Description

The basic problem is to predict the surface and in-depth temperature history and surface location history of a two-dimensional, non-charring, anisotropic (but orthotropic) insulating material exposed to a chemically reactive hyperthermal environment. The chief practical examples are rocket nozzles and nose tips; the general problem is depicted schematically in Figure 1. Below the heated surface, the material response is characterized by anisotropic heat

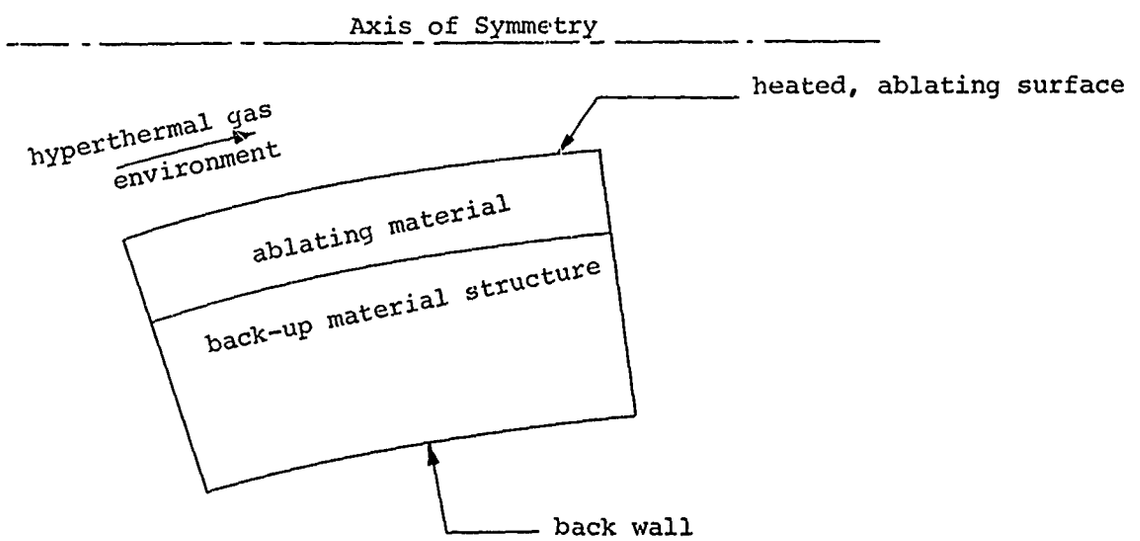


Figure 1. Sketch of Ablating System Considered

conduction with temperature dependent thermal conductivity and specific heat. At the heated surface there is a complex boundary condition involving thermal convection from the hot gases adjacent to the surface, diffusive mass transport, and chemical corrosion. The surface chemical reactions may be in equilibrium or may be kinetically controlled in certain respects (e.g., the oxidation of carbon surfaces).

2.1.2 Summary of Solution Procedure

The solution procedure chosen for this problem is complex and is described in more detail in Sections 2.2 and 2.3 below. As a quick summary, the in-depth procedure is an explicit two-dimensional finite-difference technique. The surface response procedure solves a general energy balance and mass balance based on a film coefficient model. The ablation events are computed through consideration of the complete thermochemical response including up to four specific kinetically controlled reactions with a carbonaceous surface (all other possible chemical reactions are considered to occur in equilibrium). This approach is in contrast to more usual correlation schemes or "heat of ablation" approaches. There is no direct feedback coupling, however, between body shape change and boundary condition history; that is, the program does not include routines to compute pressure distributions and convective transfer coefficient distributions as functions of body shape (these are input a priori as functions of body location and time).

The basic computer program is called ASTHMA, for Axi-Symmetric Transient Heating and Material Ablation." The specific version described here is denoted as Version 3 of ASTHMA, or ASTHMA3.

2.1.3 Coupling to Stress Calculations

The program does not include thermal stress calculations but does provide for punched card output which may be used directly as input to a separate stress program (not described here).

2.1.4 Historical Development

The ASTHMA3 computer code described here constitutes a combination of parts of other programs. Consequently there exists a large amount of background literature on certain parts of the computer code. This literature will be cited below, and the present report will abbreviate descriptions of aspects already presented elsewhere. Consequently the reader may want to consult other publications for more detailed expositions of those aspects, particularly the surface energy balance equations (Refs. 6-10) and the surface thermochemical state solution procedure (Refs. 1-5).

2.2.1 Background Remarks

The ASTHMA3 program uses a fixed finite difference heat conduction grid. Nodes exposed to the heated surface boundary condition may erode or ablate. Nodal boxes at this surface shrink and, as they approach a small size, are dropped (amalgamated into the next node down).

Schemes of this type must be formulated with some care to avoid oscillations in predicted surface temperature. Reference 11 describes some of the background of the development of the node-dropping scheme used in ASTHMA, which has been successful in avoiding undesirable oscillations.

2.2.2 Nodal Layout and Geometry

2.2.2.1 General Pattern

The geometric shape considered, illustrated in Figure 2, is imagined to be divided up into a grid pattern in the customary manner for finite difference computation schemes. The area within each grid "box" will be termed a "node"; this is in contrast to terminology which calls each corner of the grid network a node. The thermal capacity of each node is imagined to be lumped at a single point within the box; this point will be termed the nodal center. It will be convenient to assume for the moment that the nodal center may be located anywhere within the nodal box. Actual locations of the nodal centers will be discussed later.

For convenience, the nodes are imagined to be quadrilaterals, so that the entire nodal network is an assemblage of quadrilaterals. For bookkeeping

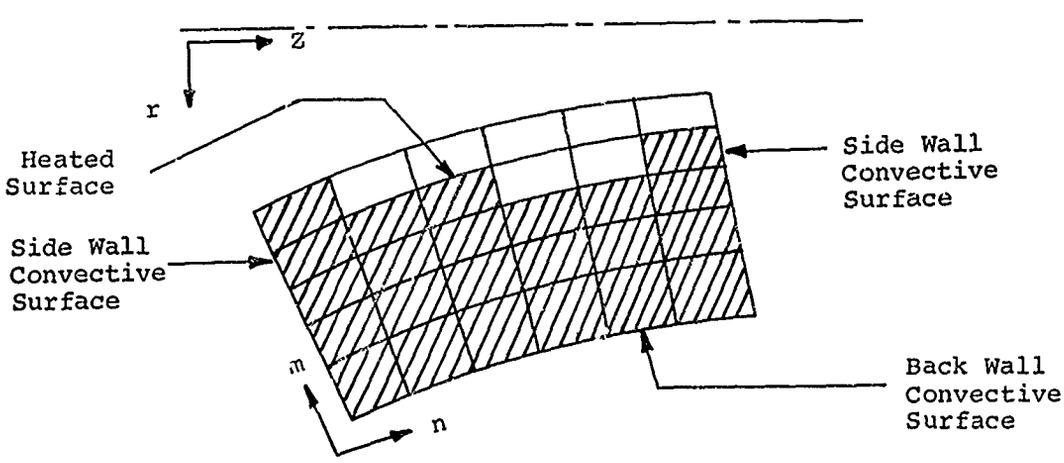


Figure 2. Sketch of Typical Nodal Layout

convenience, the network is imagined to be "complete", even though the shape of the material may dictate that some of the mesh boxes are empty. Both nodes (boxes or centers) and mesh corners are numbered in a row and column system which will be labeled as an m-n system, where m denotes a row and n denotes a column. The m-n mesh scheme may be oriented arbitrarily with respect to the physical r-Z coordinate scheme,* so that in general the row-column description might seem to be merely a descriptive artifice; however, in exploiting the simplicities associated with rocket nozzle geometries it has been assumed in constructing the program that the heated surface is at the top of the columns, as indicated in Figure 2. Thus as surface recession occurs, the boxes at the top of each column shrink; the other boxes remain fixed. This limitation that the heated surface be located at the top of each column is merely a convenience procedure exploited for the special case of the low curvature geometry of rocket nozzles. For high curvature bodies this restriction becomes inconvenient and would have to be relaxed.

The sidewalls and the backwall are either insulated or in communication through a simple heat transfer coefficient law (plus radiation) to a "reservoir" at T_{res}. Thus the boundary condition at these faces do not involve thermochemistry.

Two other "convenience limitations" have been applied to the layout of the nodal grid. First, it is assumed for the purposes of computing thermal conductance between nodal centers that the mesh scheme is nearly orthogonal, so that conductance may be taken as conductivity times side-area divided by length. Secondly it is presumed that the principle direction of thermal anisotropy are aligned with the nodal mesh. This simplifies computations and reduces input requirements. For those applications in which the heated surface intersects the principal directions of anisotropy at "difficult" angles this restriction could become a major inconvenience and more general schemes would have to be divised for those problems.

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* That is, the nodal mesh scheme may be above or below the Z-axis line, may be oriented in any general direction, and may be "bent" or shaped in any manner convenient to the user (subject to the limitations described in the paragraphs following below).

2.2.2.2 Geometry

2.2.2.2.1 Location of Nodal Centers

The present version of ASTHMA has two possible nodal location schemes at the user's option. The study summarized in Reference 11 showed that to minimize surface temperature oscillations during node dropping operations required that no thermal capacity be associated with the surface temperature. Consequently, in both schemes the surface temperature has no thermal capacity and appears as an extra temperature in terms of the number of nodes.

In the back-shifted nodal location scheme, the nodal center is located at the center of the "back wall" of the nodal box, that is, in the center of that side parallel to the heated surface and farthest from it. In terms of the conventional thermal RC network, a one-dimensional (or single nodal column) representation of this scheme is shown in Figure 3. All the capacity of each node

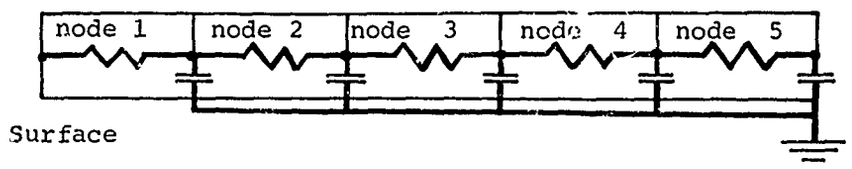

Figure 3. Sketch of One-Dimensional Thermal RC Network

is located at the back of the nodal zone, and all of the thermal resistance of this zone is interposed between it and the temperature of the next "higher" (i.e., m+1) node. Note that for m nodes or boxes the system has m+1 temperature points, in contract to most schemes, for the single column illustrated in Figure 3.

In two dimensions, the nodal center is therefore located at the center of the "back wall" of the nodal box, that is, in the center of that side parallel to the heated surface and farthest from it. Thus for an m x n nodal network scheme, there will be m x n nodal temperatures (associated with thermal capacity) plus n surface temperatures (not associated with thermal capacity).

Denoting the nodal center coordinates as r_N and Z_N, the coordinates for a back-shifted node m, with corner coordinates m,n as shown in Figure 4 may be represented in terms of the corner coordinates by the following:

$$r_{N,m,n} = \frac{r_{c,m,n} + r_{c,m,n+1}}{2} \quad (1)$$

$$z_{N,m,n} = \frac{z_{c,m,n} + z_{c,m,n+1}}{2} \quad (2)$$

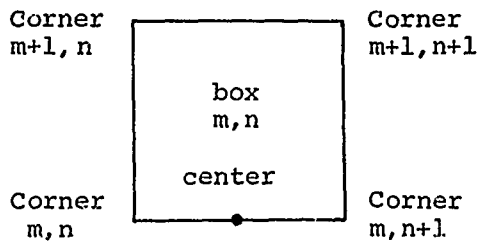

Figure 4. Sketch of Nodal Center Location for Back-Shifted Scheme

The second scheme employed by ASTHMA3 is the "centered" scheme, in which nodes are located in the arithmetic center of the nodal box. Figure 4 illustrates the thermal RC network for a one-dimensional (or single nodal column) version of this scheme

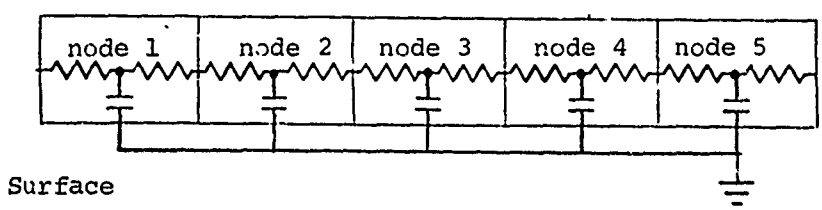

Figure 5. Sketch of One-Dimensional Thermal RC Network; Centered Scheme

In this scheme, the nodal point of the surface nodal box is squeezed toward the back wall as surface recession proceeds so as always to remain in the center of whatever nodal volume remains.

In terms of the nodal box corner coordinates, centered nodes are given by:

$$r_{N,m,n} = \frac{r_{c,m,n} + r_{c,m+1,n} + r_{c,m+1,n+1} + r_{c,m,n+1}}{4} \tag{3}$$

$$Z_{N,m,n} = \frac{Z_{c,m,n} + Z_{c,m+1,n} + Z_{c,m+1,n+1} + Z_{c,m,n+1}}{4} \tag{4}$$

In general, the centered scheme is noticeably more accurate than the back-shifted scheme (for identical node sizes) and is the preferred option. The back-shifted scheme is occasionally useful for matching nodal point to thermocouple locations or to interfaces between different materials.

2.2.2.2.2 Path Lengths for Conductions

In this and the following section, the nodal center will have a general location $r_{N,m,n}Z_{N,m,n}$ for illustrative purposes. For computing thermal conductances, it will be necessary to have thermal path lengths between nodes. Since material properties are associated with each nodal box, it will be convenient first to consider path segments inside each box. In general there are four path segments of interest, as shown in Figure 6. The program computes the lengths $L_{m,n,B}$ and $L_{m,n,D}$ in the m direction as the distances between the nodal

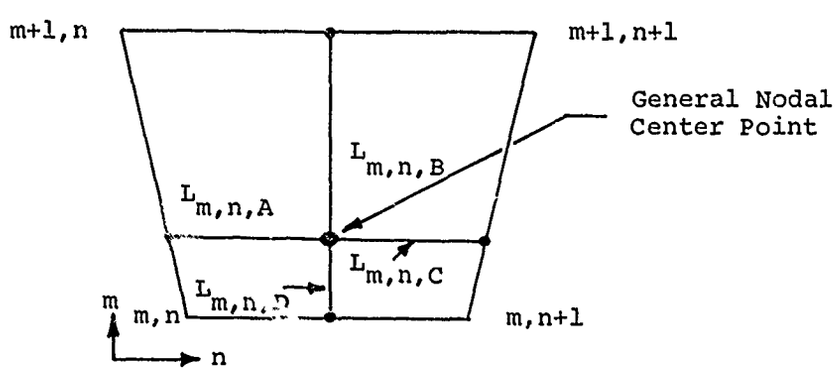

Figure 6. Illustration of Path Lengths

center and the centers of the m+1 and m faces of the box. (This is because the nodal center is always on the line joining the centers of these two faces.) Thus the paths B and D have the lengths

$$L_{m,n,B} = \left[\left(\frac{r_{c,m+1,n} + r_{c,m+1,n+1}}{2} - r_{N,m,n}\right)^2 + \left(\frac{Z_{c,m+1,m} + Z_{c,m+1,n+1}}{2} - Z_{N,m,n}\right)^2\right]^{1/2} \tag{5}$$

$$L_{m,n,D} = \left[\left(\frac{r_{c,m,n+1} + r_{c,m,n}}{2} - r_{N,m,n}\right)^2 + \left[\left(\frac{Z_{c,m,n+1} + Z_{c,m,n}}{2} - Z_{N,m,n}\right)^2\right]^{1/2} \tag{6}$$

The paths between the nodal center and the n and n+1 faces (paths A and C in the sketch) are assumed to end at points on those faces located as far down the face, proportionally, as the nodal center is located in the box. In the back-shifted scheme, the node center is on the face m, for which the paths A and C end at the corners m,n and m,n+1, respectively. For this case, we have

$$L_{m,n,A} = \left[(r_{c,m,n} - r_{N,m,n})^2 + (Z_{c,m,n} - Z_{N,m,n})^2\right]^{1/2} \tag{7}$$

$$L_{m,n,C} = \left[(r_{c,m,n+1} - r_{N,m,n})^2 + (Z_{c,m,n+1} - Z_{N,m,n})^2\right]^{1/2} \tag{8}$$

In the arithmetically centered scheme, the paths A and C end at the centers of faces m and m+1 respectively, for which case we have

$$L_{m,n,A} = \left[\left(\frac{r_{c,m,n} + r_{c,m+1,n}}{2} - r_{N,m,n}\right)^2 + \left(\frac{Z_{c,m,n} + Z_{c,m+1,n}}{2} - Z_{N,m,n}\right)^2\right]^{1/2} \tag{9}$$

$$L_{m,n,C} = \left[\left(\frac{r_{c,m+1,n+1} + r_{c,m,n+1}}{2} - r_{N,m,n}\right)^2 + \frac{Z_{c,m+1,n+1} + Z_{c,m,n+1}}{2} - Z_{N,m,n}\right]^{1/2} \tag{10}$$

2.2.2.2.3 Side Areas

Areas of the sides of each box are also required for thermal conductance calculations. For the sides lettered as shown in Figure 7, the areas are

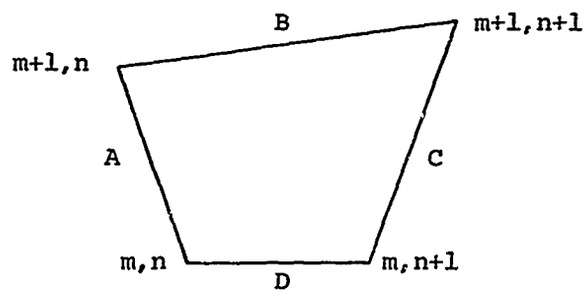

Figure 7. Nomenclature of Nodal Sides

given by elementary geometry (First Theorem of Pappus)

$$A_{m,n,A} = \pi(r_{c,m,n} + r_{c,m+1,n})\left[(r_{c,m+1,n} - r_{c,m,n})^2 + (Z_{c,m+1,n} - Z_{c,m,n})^2\right]^{\frac{1}{2}} \tag{11}$$

$$A_{m,n,B} = \pi(r_{c,m,n} + r_{c,m,n+1})\left[(r_{c,m,n+1} - r_{c,m,n})^2 + (Z_{c,m,n+1} - Z_{c,m,n})^2\right]^{\frac{1}{2}} \tag{12}$$

Only these two areas need to be computed for each box, since the areas on the other sides of the nodal box are identical with the areas A and B of adjacent nodes.

2.2.2.2.4 Volume

The volume of the elemental box is by the Second Theorem of Pappus,

$$V_{m,n} = \Big[\pi/3 \Big\{ Z_{c,m,n} \Big[r_{c,m,n}(r_{c,m,n+1} - r_{c,m+1,n}) + r^2_{c,m,n+1} - r^2_{c,m+1,n} \Big] + Z_{c,m+1,n} \Big[r_{c,m+1,n} \cdot (r_{c,m,n} - r_{c,m+1,n+1}) + r^2_{c,m,n} - r^2_{c,m+1,n+1} \Big] + Z_{c,m+1,n+1} \Big[r_{c,m+1,n+1}(r_{c,m+1,n} - r_{c,m,n+1}) + r^2_{c,m+1,n} - r^2_{c,m,n+1} \Big] + Z_{c,m,n+1} \Big[r_{c,m,n+1} \cdot (r_{c,m+1,n+1} - r_{c,m,n}) + r^2_{c,m+1,n+1} - r^2_{c,m,n} \Big] \Big\} \Big] \tag{13}$$

2.2.2.2.5 Geometric Effects of Surface Recession

For nodes adjacent to the heated surface, side B may move due to surface recession (ablation). This recession reduces the thermal resistance between the surface point and the adjacent nodal point, increases transverse thermal resistances (as discussed below), and reduces the thermal capacity associated with the nodal center of the nodal box adjacent to the surface. The program assumes that the surface recession occurs so as to maintain the ratios

$$\frac{a_2}{a_1} = \frac{b_2}{b_1} = \frac{c_2}{c_1} \tag{14}$$

as shown in Figure 8. The b line joins the centers of the m+1 and m planes and serves to define the location of the surface point S. The moving corners m+1,n and m+1, n+1 are located accordingly, and path lengths, areas and volumes computed as before, except that for these nodes $A_{m,n,A} \neq A_{m,n-1,c}$.

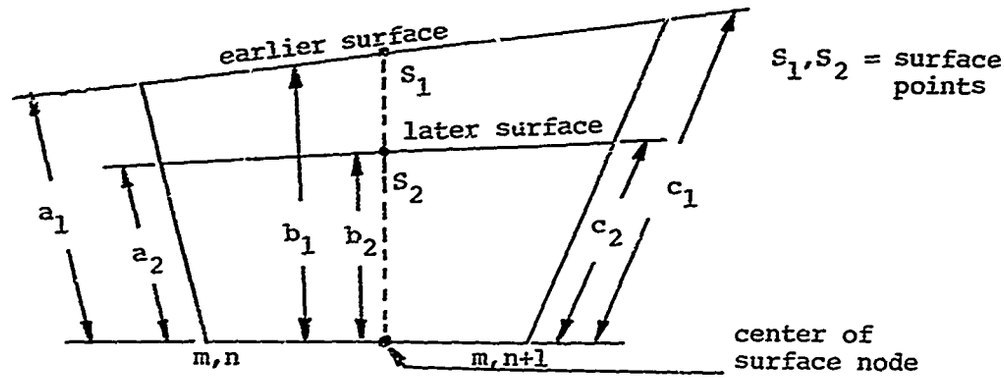

Figure 8. Sketch of Surface Nodal Box Undergoing Recession

2.2.2.2.6 Surface Shape

As noted above and illustrated in Figure 8, it is most convenient to consider the surface points on the heated surface as being always located on the nodal column center line, that is, on the line joining the center points of the m+1 and m planes ("parallel" to the heated surface), where m is the row index of a nodal box at the surface and m+1 is the local corner index of the heated surface (see Fig. 8). The location of the surface points is all the information needed about the surface for those ablation problems with a specified, input surface recession rate as a boundary condition (the various ablation problem boundary condition options are described in Section 2.3 below), since for those problems, it is most convenient to specify, as input, recession history along the nodal center line. The nodal grid as input thus serves to define the various nodal column center lines, and the recession history for each column then defines the history of the surface points in a perfectly straightforward manner. However, another important heated surface boundary condition option involves not input recessions but various energy and chemistry information sufficient to calculate surface mass loss from energy balance considerations (Option 1, discussed in Section 2.3 below). This ablation calculation does not produce recession rates directly, of course; instead it produces rates of mass loss from the surface. It will prove convenient, nevertheless, to adhere to the concept of the surface point which moves along the column center line as recession progresses. To define the surface point motion with computed mass loss rates determined from this general energy-balance-determined option requires knowledge of the angle between the local normal to the surface and the column center line, since computed mass loss may be translated directly into recession along a normal to the surface. Recession along the normal may be projected into the nodal column center line

once the angle between these two lines is known. The direction of the surface normal may conveniently be determined from the slope of the surface, that is the surface shape, and of course the direction of the column centerline is known.

It is obviously not safe to use the slope of the heated (top) surface of the surface nodal box to obtain the surface slope, since in general it is neither possible nor always desirable to lay out a nodal grid which will "conform" to the "real" surface for the entire problem history. Therefore the ASTHMA3 program includes both linear averaging and quadratic curve-fit subprograms which compute a surface shape at each time step during one solution after examining the layout of the surface points.

With surface slope determined, the surface movement ΔS computed during the time step may be projected onto the nodal box centerline, and then the

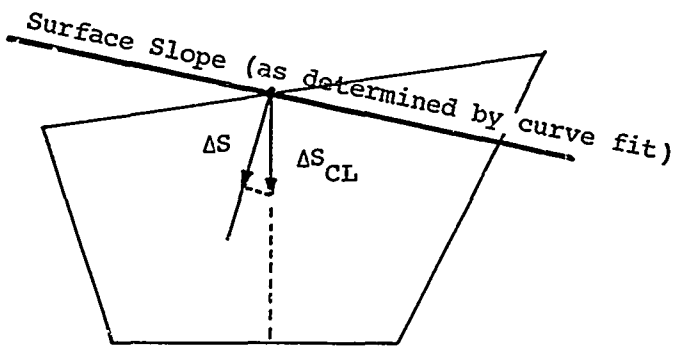

Figure 9. Sketch of Surface Geometrical Relationships (exaggerated)

new nodal volume computed, as indicated in the exaggerated sketch of Figure 9. Actual surface movement during a time step is limited to a small fraction of the nodal thickness to ensure a good approximation to the conservation of mass.

2.2.2.2.6.1 Surface Shape Curve Using Linear Averaging Technique

If the linear averaging option is used, referring to Figure 10, the

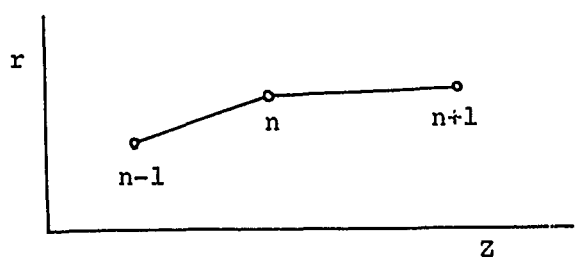

Figure 10. Sketch of Surface Points

slope of the surface, dr/dZ, at surface point n as the average of the slopes between surface points n-1 and n, and n and n+1. Thus

$$\left.\frac{dr}{dZ}\right)_n = \frac{1}{2}\left(\frac{r_n - r_{n-1}}{Z_n - Z_{n-1}} + \frac{r_{n+1} - r_n}{Z_{n+1} - Z_n}\right) \tag{15}$$

Note that n-1, n, and n+1 are surface points, not nodal corner points. (Problems with only one nodal column have only one surface point. This requires the program to abandon the average slope scheme and to use the nodal box heated surface slope as the surface slope.)

2.2.2.2.6.2 Surface Shape Curve Using Quadratic Technique

The quadratic curve fit slope averaging routine known as SLØPQ is described in Reference 13. This routine gives better results for relatively smooth and flat (small dr/dZ) shapes common to rocket nozzles; it usually performs poorly if surface points are closely spaced in the Z direction (large dr/dZ) and gives meaningless answers for double valued r(Z) shapes. For these latter shapes, the linear fit routine should be used.

2.2.3 Internal Conduction Parameters

The thermal resistances between nodes and the thermal capacity of the nodes are calculated each time interval from the material properties of the node corresponding to its temperature at that time. The material properties density (ρ), specific heat (c), conductivity (k), and emissivity (ε) are input as table look up functions of temperature. Linear interpolation is employed for material property determination at temperatures intermediate to those tabulated. Constant thermal contact resistances may be specified between any or all nodes. The nodal capacities and resistances are calculated as follows:

$$C_{m,n,\theta} = \rho_{m,n,\theta} c_{m,n,\theta} V_{m,n} \tag{16}$$

$$R_{m,n,A,\theta} = \frac{1}{A_{m,n+1,A}}\left(\frac{L_{m,n,C}}{k_{m,n,\theta}} + \frac{L_{m,n+1,A}}{k_{m,n+1,\theta}} + R^*_{m,n,B}\right) \tag{17}$$

$$R_{m,n,B,\theta} = \frac{1}{A_{m+1,n,B}}\left(\frac{L_{m,n,B}}{k'_{m,n,\theta}} + \frac{L_{m+1,n,D}}{k'_{m+1,n,\theta}} + R^*_{m,n,A}\right) \tag{18}$$

Figure 12 shows the locations of resistances $R_{m,n,A,\theta}$ and $R_{m,n,B,\theta}$. The

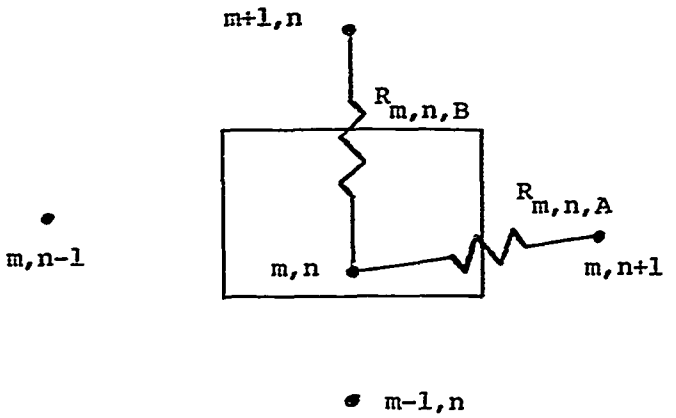

Figure 12. Sketch of Thermal Resistance Nomenclature

resistance on the other two sides of the nodal box are calculated when the quantities for the adjacent nodes are calculated. For nodes adjacent to the surface, however, $A_{m,n,C} \neq A_{m,n+1,A}$ generally (refer to Fig. 7 for area nomenclature); for these nodes

$$R_{m,n,A} = \frac{L_{m,n,C}}{A_{m,n,C}k_{m,n,\theta}} + \frac{L_{m,n+1,C}}{A_{m,n+1,A}k_{m,n+1,\theta}} + \frac{R^*_{m,n,B}}{A_{m,n,C}} \tag{19}$$

It should be noted that anisotropic thermal conductivity values k and k' are used in Equations (17) and (18), respectively.

A subroutine has been added to ASTHMA3 which decreases inaccuracies in the calculated conductances due to non-orthogonality problems. Figure 13 shows the general situation in a conductance calculation (selecting the "along rows" direction as an example).

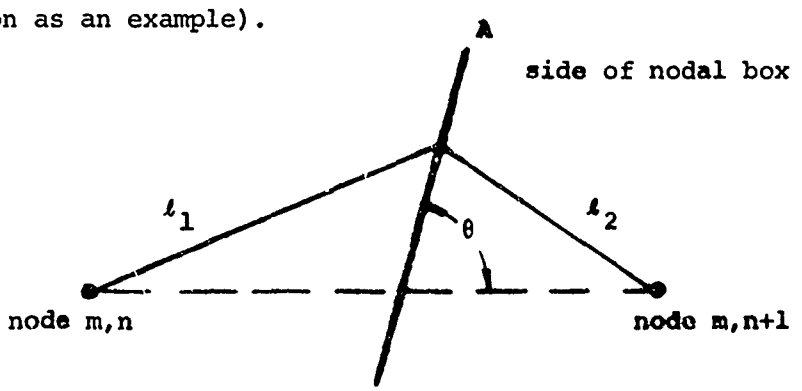

Figure 13. Sketch of Conduction Quantities

The conductance used by the program is

$$U = \frac{A}{\frac{\ell_1}{k_{m,n}} + \frac{\ell_2}{k_{m,n+1}}} \tag{20}$$

An obvious improvement in the number is a modified conductance

$$U' = U \sin \theta \tag{21}$$

This modified conductance accounts exactly for some limited non-orthogonality problems: those in which the basic nodal point array is orthogonal but, for one reason or another, the nodal box sides are not orthogonal to the point array. For funadmental non-orthogonalities of the nodal point array, the conductance improvement does increase the accuracy of computed heat fluxes by a factor of roughly $1/\sin\theta$. Fundamentally, however, this situation requires a nine point difference scheme not treated by ASTHMA.

2.2.4 In-Depth Conduction Solution

The in-depth conduction solution is the explicit finite difference type often employed for transient heat conduction analysis. The temperature of node m,n at time θ' ($T_{m,n,\theta'}$) is obtained by application of the finite difference energy balance and rate equations to the nodal volume.

Solving for $T_{m,n,\theta'}$, one obtains:

$$T_{m,n,\theta'} = \left[\frac{T_{m+1,n,\theta}}{R_{m,n,B,\theta}} + \frac{T_{m,n+1,\theta}}{R_{m,n,A,\theta}} + \frac{T_{m-1,n,\theta}}{R_{m-1,n,B,\theta}} + \frac{T_{m,n-1,\theta}}{R_{m,n-1,A,\theta}} - T_{m,n,\theta} \cdot \left(\frac{1}{R_{m,n-1,A,\theta}} + \frac{1}{R_{m,n,B,\theta}} + \frac{1}{R_{m,n,A,\theta}} + \frac{1}{R_{m-1,n,B,\theta}}\right)\right] \frac{\Delta\theta}{C_{m,n,\theta}} + T_{m,n,\theta} \tag{22}$$

In the program this equation is used to obtain "new" temperatures for all nodes except those adjacent to the heated surface and for back wall nodes. Nodes adjacent to the heated surface are linked to the surface temperature implicitly and hence a special procedure is used for the temperature of these nodes, as described in the next section.

Back wall nodes include a quantity

$$hA_{bw}(T_{res} - T_{m,n,\theta}) + \sigma\varepsilon_{bw}A_{bw}(T^4_{m,n,\theta} - T^4_{res})$$

inside the brackets of Equation (22). Any node other than a heated surface node may be called out as a back wall node, and A_{bw} may, with appropriate input choices, be assigned as one of the two side areas $A_{m,n,A}$ and $A_{m,n,C}$, or as the back area $A_{m,n,D}$. Physically, such assignments only make sense if the back wall node thus specified is located at the sides or back wall of the total material considered, or adjacent to a void space within the material.

The explicit relation (22) imposes the familiar stability restriction on the time step size $\Delta\theta = \theta' - \theta$. The ASTHMA3 program automatically employs a conservative stability equation for interior nodes:

$$\Delta\theta = \eta \left[\frac{C_{m,n}}{\frac{1}{R_{m,n,A}} + \frac{1}{R_{m,n,B}} + \frac{1}{R_{m,n-1,A}} + \frac{1}{R_{m-1,n,B}}} \right] \tag{23}$$

Normally for stability, the input parameter η is less than unity. Surface nodes are not considered for time interval calculation, as will be explained below; back wall nodes include the terms $A_{bw}(h/2 + 4\sigma\varepsilon_{bw}T^3_{m,n,\theta})$ in the denominator.

The automatic stability criterion calculation may be suppressed for any node if the user is sure that the allowed time step for that node will never be the minimum one for the system. This saves some computer time.

Alternatively, the stability criterion calculation can be suppressed entirely. If it is not used, then $\Delta\theta$ must be specified. It is used, then any or all nodes in the conduction network may be specified for time interval determination.

2.2.5 Temperatures of Surface Nodes and Surface Points

Temperatures of surface points are determined either by assignment (Option 2) or by the surface energy balance described in Section 2.3 (Options 1 and 3). The surface energy balance determines the new surface temperature of the nth column T'_{s_n} with an implicit iteration technique. Stability considerations dictate that the first node temperature also be treated implicitly, and that any transverse heat conduction link (across columns) for surface temperatures must be implicit. This latter requirement is a complex one to meet as columns recede; hence the surface temperature points are not linked transversely. Figure 14 shows the implicit and explicit heat conduction paths for two typical columns.

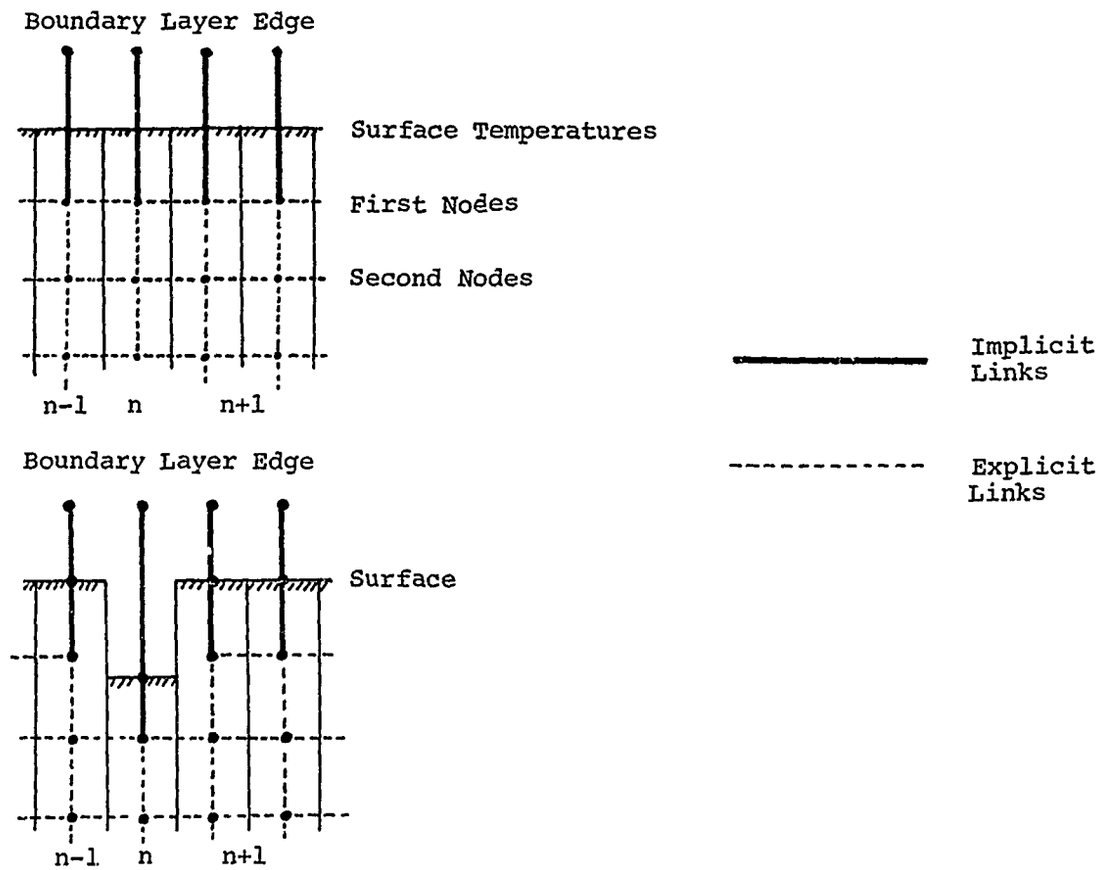

Figure 14. Sketch of Implicit and Explicit Temperature Links in Finite Difference Solution, for Two Typical Situations

For this scheme, the equation for the new temperature of a surface node (not a surface point) is

$$T_{m,n,\theta'} = \left[\frac{T_{m,n+1,\theta} - T_{m,n,\theta}}{R_{m,n,A,\theta}} + \frac{T_{m,n-1,\theta} - T_{m,n,\theta}}{R_{m,n-1,A,\theta}} + \frac{T_{m-1,n,\theta} - T_{m,n,\theta}}{R_{m-1,n,B,\theta}} + \frac{T_{s,n,\theta'} - T_{m,n,\theta'}}{R_{m,n,B,\theta}} \right] \frac{\Delta\theta}{C_{m,n,\theta}} + T_{m,n,\theta} \tag{24}$$

This is linked to the surface energy balance through the surface point temperature $T_{S,n,\theta'}$. Formally we have a relation between the two unknowns as

$$T_{m,n,\theta}' = f(T_{S,n,\theta'}) \tag{25}$$

The surface energy balance has the general form (as described in the next section)

convection and chemical energy terms $(T_{S,n,\theta'})$

+ radiation to wall - radiation out $(T_{S,n,\theta'})$

$$= \frac{T_{S,n,\theta'} - T_{m,n,\theta'}}{R_{m,n,B,\theta}} = f_2(T_{m,n,\theta'}, T_{S,n,\theta'}) \tag{26}$$

where the parentheses denote functional relationship. Relation (25) may be substituted into Equation (26) to give the non-linear surface energy balance Equation for $T_{S,n,\theta'}$. When $T_{S,n,\theta'}$ has been found from this equation, the new surface node temperature $T_{m\ n,\theta'}$ may be found from Equation (25). For surface energy balance options, the method for finding $T_{S,n,\theta'}$ is described in Section 2.3 below. In Option 2, $T_{S,n,\theta'}$ is known immediately and Equation (24) then determines $T_{m,n,\theta'}$ at once.

In some rare cases with very high recession rates, the implicit linkage described above is not sufficiently tight to prevent destructive oscillations. Therefore this linkage was supplemented with a second linkage which implicitizes the first node temperature in the conduction path from the first node to the next deeper node.

In Equation (24), this second option has θ' in place of θ on $T_{m,n,\theta}$ in the $R_{m-1,n,B,\theta}$ term. Similarly, the nodal equation for node $m-1,n,\theta$ has θ' in place of θ on $T_{m,n,\theta}$ (i.e., this heat conduction rate must be identical in the two nodal energy balances). In this scheme, the determination of $T_{m-1,n,\theta'}$ is delayed until $T_{S,n,\theta}'$ and $T_{m,n,\theta'}$ are determined as described above.

This linkage option has always performed stably. It is slightly slower than the first option.

2.3 SURFACE BOUNDARY CONDITION ASPECTS

The ASTHMA program can account for three different types of heated surface boundary conditions:

1. Surface energy balance determined recession rate, employing general film coefficient model for boundary layer transport of energy and mass, and very general thermochemical relations at the surface (Option 1).

2. Specifiied surface temperature and recession rate histories (with a different history at each surface point of interest) (Option 2).

3. Simplified energy balance to determine surface temperature including only radiation terms, no recession allowed (Option 3 - "cooldown option").

Option 2 is so simple that it requires no discussion other than that given in the user's manual below. Option 1 is complex and has many interesting aspects, some of which are discussed below. A brief discussion of Option 3 follows.

2.3.1 General Aspects

The convective surface energy balance option (Option 1) of the program performs the energy balance illustrated in the sketch of Figure 15. The energy balance is performed for the indicated control volume fixed to the receding

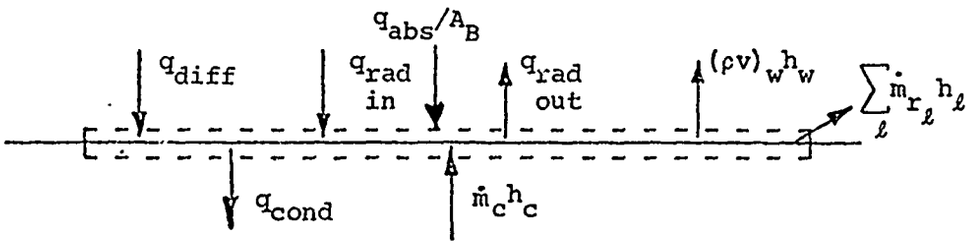

Figure 15. Representation of Surface Energy Terms During Ablation

surface. Energy fluxes leaving the control volume include conduction into the material, radiation away from the surface, energy in any flow of condensed phase material such as mechanical removal,* and gross blowing at the surface. Energy inputs to the control volume include radiation in from the boundary layer and enthalpy flux due to the convection of material to the surface associated with surface recession. The special flux q_{abs} represents an energy addition not proportional to surface area, such as a narrow particle or radiation beam or induction heating. The final input in the sketch is denoted q_{diff}. It includes all diffusive energy fluxes from the gas phase boundary layer and the form of a correlation equation associated with the convective film coefficient model.

*The energy balance procedure has indeed been constructed to include mechanical terms but in this version of ASTHMA failing is not allowed (in order to exploit input conveniences) since it is not provided for in the surface thermochemistry code GASKET associated with this version of ASTHMA.

The computation of the surface energy balance requires from the in-depth solution a relation between the surface temperature and the rate of energy conduction into the material, q_{cond}. This relation derives naturally from the finite difference energy balance for the node just under the surface. With this information the surface energy balance considerations allow determination of the thermochemical erosion rate $\dot{m}$ and surface temperature T_w. It will be useful to keep in mind that, from this point of view, the purpose of the in-depth solution at any instant is to provide information about $q_{cond}(T_w)$. The surface energy balance equation may be written as (ignoring the term q_{abs}, which is only rarely of interest)

$$q_{diff} + q_{\substack{rad \\ in}} + \dot{m}_c h_c - q_{\substack{rad \\ out}} - (\rho v)_w h_w - \sum_{\ell} \dot{m}_{r_\ell} h_\ell - q_{cond} = 0 \tag{27}$$

where

$$(\rho v)_w = \dot{m}_c - \sum_{\ell} \dot{m}_{r_\ell} \tag{28}$$

The relation $q_{cond} = f(T_w)$ is delivered by the in-depth solution. Other dependencies of interest are

$$h_c = h_c(T_w) \tag{29}$$

$$q_{\substack{rad \\ out}} = q_{\substack{rad \\ out}}(T_w) \tag{30}$$

For the other terms, we may write in general

$$T_w,\ q_{diff},\ q_{\substack{rad \\ in}},\ h_w,\ \sum_{\ell} \dot{m}_{r_\ell} h_\ell = \text{functions of boundary-layer-edge enthalpy, pressure, upstream events, laws for conservation of chemical elements, chemical equilibria and/or kinetic relations, } \dot{m}_c\text{, local boundary layer aerodynamics} \tag{31}$$

Relations of the type of Equation (31) come in many forms, and may even take the form of exact solutions to boundary layer and surface chemical state routines. In the present program, the relations (31) are computed by the separate chemistry program (ACE or GASKET), for use by Equation (27) in ASTHMA3 based on a film coefficient model of the boundary layer transport events. The ACE program is fully described in Reference 4, and GASKET is described in

Reference 5. Since relations (31) are obtained by film coefficient based programs (ACE and GASKET), the main energy balance (27) used by the ASTHMA program is also of a film coefficient type.

When the boundary layer transport aspects of the problem are modeled by a film coefficient scheme, then both Equations (27) and (31) can be normalized on the mass transfer coefficient in the customary manner. Equation (27) becomes

$$\frac{q_{diff}}{\rho_e u_e C_M} + \frac{q_{rad_{in}} - q_{rad_{out}}}{\rho_e u_e C_M} + B_c' h_c - B' h_w - \sum_{\ell} \frac{\dot{m}_{r_\ell}}{\rho_e u_e C_M} h_\ell - \frac{q_{cond}}{\rho_e u_e C_M} = 0 \qquad (32)$$

And Equation (31) takes the general form

$$T_w, \frac{q_{diff}}{\rho_e u_e C_M}, \frac{q_{rad_{in}}}{\rho_e u_e C_M}, h_w, \sum_{\ell} \frac{\dot{m}_{r_\ell}}{\rho_e u_e C_M} h_\ell = \text{functions of boundary layer edge enthalpy, pressure, laws for conservation of chemical elements, chemical equilibrium and/or kinetic relations, } B_c' \qquad (33)$$

The generation of the Equation (33) relationships is the goal of the surface thermochemistry code (ACE or GASKET) as noted above. For the present it may be observed that the energy balance coupling to the in-depth solution (ASTHMA3) for each time step proceeds as follows: an initial guess of the dimensionless mass removal rate B_c' is obtained in some manner. With this B_c', the quantities $q_{diff}/\rho_e u_e C_M$, h_w, $\sum \dot{m}_{r_\ell} h_\ell / \rho_e u_e C_M$, and T_w are obtained from the surface thermochemistry solution. The quantities h_c and $q_{rad\ out}$ are then formulated using the T_w so obtained. The surface energy balance is then computed, the q_{cond} as a function of T_w having been provided by the in-depth solution. In general, however, the sum of the terms will not equal zero but some error. An iteration procedure is then used to select successively better estimates of B_c' which drive the error to zero. Experience shows that Newton's procedure, in which the derivative of the error with respect to B_c' is used to compute the next guess for B_c', gives good results.

2.3.2 Computational Approach to Convective Energy Balance

2.3.2.1 General Description of Approach

It is evident that each iteration in the search for a surface energy balance, if performed as described above, would require a new surface chemistry solution, generally in the near neighborhood of many such previous solutions. This suggests that a tabular approach in which the surface state solutions are done only for preassigned B_c' values would offer significant computational economies, since values of dependent quantities at B_c' values between table points would be obtained by interpolation rather than by additional thermochemistry solutions. Referring to Equation (33), we see that such a table would have three independent variables. Two obvious ones are pressure and the ablation rate B_c'. The non-obvious third independent variable involves chemical kinetic control. If surface reactions are kinetically controlled, then the discussions of the ACE and GASKET user's manuals (References 4 and 5 respectively) demonstrate that the kinetically controlled relations show up in the array of chemistry relations to be solved in a very particular form: the pre-exponential factors on forward rate coefficients appear divided by the transfer coefficient $\rho_e u_e C_M$. Therefore the thermochemistry solution routine must be provided either with both numbers (pre-exponential factors and transfer coefficient) or alternatively with their ratio.

The various Aerotherm thermochemistry codes differ at this point, and succeeding discussions will be specialized to the GASKET code, which has rate coefficients built into the data of the code and requires the transfer coefficient $\rho_e u_e C_M$ to be input. Thus the only kinetics parameter evident to the user is the transfer coefficient $\rho_e u_e C_M$, and this will be the third parameter in the table.

The course of a typical ASTHMA solution history at one axial station might be represented as shown in Figure 16. As time proceeds, solutions progress through the space of the table independent variables B_c', $\rho_e u_e C_M$, and P. The dots in the picture represent solutions satisfying the surface energy balance as time progresses. Surrounding these points are a number of other points examined during the iterations to satisfy the surface energy balance. For any iteration, the solution procedure finds itself, so to speak, within a cube formed by the bracketing tabular values of B_c', $\rho_e u_e C_M$, and P. The dependent quantities T_w, $q_{diff}/\rho_e u_e C_M$, h_w and $\sum \dot{m}_{r\ell} h_\ell / \rho_e u_e C_M$ have been precalculated for these tabular points; relevant values of these quantities for the current iteration values of B_c', $\rho_e u_e C_M$, and P can then be formed by interpolation inside the cube and the surface energy balance equation calculated. If the energy balance is not satisfied to some preselected degree of accuracy, a new value of B_c' can be selected and the process repeated.

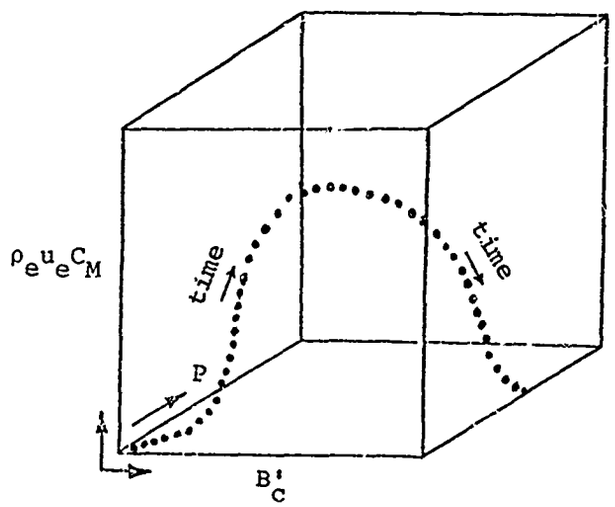

Figure 16. Representation of Course of Independent Variables in Surface History at One Axial Station.

The tabular approach was selected in general because the interpolation feature drastically reduces the number of surface state calculations while at the same time allowing sufficient accuracy.* The precalculated table approach** was chosen for the following reasons:

1. In parametric studies, tables once generated are usable for many different problems, yielding even greater economy.

2. For many problems, it is difficult to specify a priori an "adequate" array of independent tabular values B_c', $\rho_e u_e C_M$, and P. An examination of the precalculated surface tables before execution of the actual ablation-problem-plus-in-depth-solution can reveal if there are any "holes" in the tables in areas where energy terms are varying rapidly. Desirable table points can be added before the in-depth response run.

3. The surface tables are frequently of independent interest in themselves for judging the ablation effects under various conditions.

4. Finally, without the precalculated tabular approach, the occasional nonconvergent surface chemistry solution would stop the entire in-depth solution process. With the precalculated table approach, such solutions are automatically weeded out of the tables without damage to the subsequent in-depth solution.

On the other side of the ledger, some disadvantages in the precalculated table approach are evident however:

1. Figure 16, which is a realistic schematic view of a typical calculation history, indicates that many of the laboriously calculated and assembled surface state points in the table are never used in the course of a given solution.

2. The "mechanical" linkage between the surface state solution and the in-depth solution, i.e., the transfer of punched card surface state output to input of the in-depth program, leads to computing delays

---

*For example, a typical 2000 time step problem with the usual 5 iterations per time step would require 10,000 surface state calculations, which require about 1 second each for machines in the 1108 speed class. A single pressure table, on the other hand, involves only about 200 state solutions (20 char rates times 10 transfer coefficient values), a factor of 50 improvement. Multiple pressure tables reduce this advantage, but usually only a few pressures are required.

**As opposed to a direct coupling scheme in which tabular dependent entries were only calculated as needed.

and occasionally to gross input blunders (wrong decks, missing parts of decks, etc.).

3. Significant storage is required by the large precalculated table.

These disadvantages are usually outweighed by the advantages of the precalculated table approach, however. Hence this same well tested approach has been adopted for the ASTHMA3 program.

2.3.2.2 Pressure Interpolation Not Needed

The preceding general discussion has described how interpolation in a precalculated table with three independent variables can be carried out. Since the ASTHMA3 code described here was designed primarily for rocket nozzle application, a useful simplification is possible. In rocket nozzles, pressure rarely varies by an appreciable amount with time at a given axial station. Therefore surface energy balance solutions need not interpolate on pressure, even though it is necessary to have on hand several thermochemistry solutions at different pressures. It will be sufficient for each axial station to refer to the appropriate pressure.

This simplification allows more economical interpolations (two-dimensional instead of three-dimensional). It is exploited in ASTHMA by the assignment of each surface node to a given pressure table by a simple numerical flag which refers to the number of pressure tables counted in the order in which they are read in (see Section 3.1.6 below).

2.3.3 Forms of the Film Coefficient Model Surface Energy Balance Equation Used in Option 1

In making the surface energy balance calculation described in Section 2.3.2 above, the ASTHMA3 program uses a variety of surface energy balance equations of the general form of Equation (32). The basic equation, derived in Reference (6) with analogy arguments, is*

$$\rho_e u_e C_H (H_r - h_w)_{\substack{edge\\gas}} + \rho_e u_e C_M \left[\sum_i (K_{i_e} - K_{i_w}) h_i^{T_w} + B_c' h_c - B_c' h_w \right]$$

$$+ q_{abs}/\Lambda_B + \alpha_w q_{rad} - F\sigma\varepsilon T_w^4 - q_{cond} = 0 \qquad (34)$$

It should be noted that, like all film coefficient expressions, this equation is not a universally valid one. It is well established for frozen boundary

*ASTHMA3 assumes $\dot{m}_r = 0$. This excludes use of the "fail temperature" option in ACE and GASKET when preparing ASTHMA3 input.

layer, catalytic wall problems with no net mass transfer (Refs. 13, 14). It is presumed accurate for reactive boundary layers as well (see a discussion of similar considerations in Ref. 15). For problems with net mass transfer (ablation), which are of interest here, the equation is less well established, but

1. Has been derived with "respectable" analogy arguments (Ref. 6)
2. Compares well with similar results derived by Lees (Ref. 14)
3. Has given good predictions when compared to some experimental data and to results of "exact" boundary layer solutions.
4. Gives results independent of the choice of enthalpy datum state (an important criterion)
5. Reduces, for $C_M = C_H$, to a widely accepted energy balance law (Refs. 16, 17) for simultaneous heat and mass transfer

Equation (34) has been generalized in Reference 7 to the case of <u>unequal</u> mass diffusion coefficients, again by analogy arguments. The result is

$$\rho_e u_e C_H (H_r - h_w)_{\substack{edge\\gas}} + \rho_e u_e C_M \left[\sum_i (Z^*_{i_e} - Z^*_{i_w}) h_i^{T_w} + B'_c h_c - B'_c h_w \right]$$

$$+ q_{abs}/A_B + \alpha_w q_{\substack{rad\\in}} - F\sigma\epsilon T_w^4 \, q_{cond} = 0 \qquad (35)$$

where

$$Z^*_i \triangleq \frac{Z_i^\gamma K_i^{1-\gamma}}{\sum_j^I Z_j^\gamma K_j^{1-\gamma}} \qquad (36)$$

$$Z_i \triangleq \frac{\mathcal{M}_i x_i}{F_i \mu_a} = \frac{\mathcal{M} K_i}{F_i \mu_a} \quad \text{since} \quad \mathcal{M}_i x_i = \mathcal{M} K_i \qquad (37)$$

and

$$\mu_a \triangleq \sum_i \frac{\mathcal{M}_i x_i}{F_i} = \mathcal{M} \sum \frac{K_i}{F_i} \qquad (38)$$

The factors F_i in these equations derive from the particular relation between the binary diffusion coefficients which must hold if the governing differential equations are to reduce to the forms from which Relation (32) can be inferred. This relation is

$$\mathcal{D}_{ij} = \frac{\bar{D}}{F_i F_j} \tag{39}$$

and can be regarded as an accurate correlation of experimental data for the binary diffusion coefficient $\mathcal{D}_{ij}$. The quantity $\bar{D}$ is a constant for a given pressure. The constants F_i depend weakly on temperature.

Equation (35) is somewhat less well founded than the corresponding Equation (34) but does have plausibility. Furthermore, the equation reduces to Equation (34) for equal diffusion coefficients, as it should, and Equation (35) can be shown to be independent of the enthalpy datum state and thus fulfills a basic physical requirement.

The GASKET program provides to the ASTHMA3 program the four dependent quantities $h_{w_{edge\ gas}}(T_w,P)$, $T_w(B_c',P)$, $\sum_i z_{i_e}^{\pm} h_i^{T_w}(B_c',P)$ and $\sum_i z_{i_w}^{\pm} h_i^{T_w}(B_c',P)$ for a given value of k_f'. With the quantity $h_{w_{edge\ gas}}(T_w,T)$ stored in one table with independent variables T_w and p, and the other three dependent quantities stored in a table with independent variables B_c', $\rho_e u_e C_M$ and P, the ASTHMA3 program may find surface energy balances at any surface point and time (i.e., given pressure and $\rho_e u_e C_M$) by (1) selecting the correct P table, (2) noting $\rho_e u_e C_M$, (3) finding the dependent quantities in the two tables at $\rho_e u_e C_M$ values bracketing the actual $\rho_e u_e C_M$ and for some B_c', (4) interpolating on $\rho_e u_e C_M$, (5) forming the energy balance equation (35) and noting the error or departure from zero, (6) selecting a new B_c' for another try. The Newton-Raphson method is used for selecting the next guess of B_c' in step (6). When that B_c' yielding an energy balance is determined, the new T_w is known as a dependent quantity; thus the new surface temperature is determined.

2.3.4 Input and Correction of Heat Transfer Coefficient

To employ the film coefficient formulation just described, the program user must provide the program with values of the heat transfer coefficient $\rho_e u_e C_H$ as functions of time. Two practical problems must be settled in this respect:

1. How is C_M related to C_H?
2. Can both C_M and C_H be specified as functions of edge conditions (i.e., of time) independent of the subsequent problem solution (i.e., mass transfer rates and body shape)?

In answer to the first question it may be stated that within the present formulation it is adequate to take the ratio C_M/C_H as a constant. The value of this constant is a measure of the ratio of the mean mass transfer aspects of the boundary layer to the mean heat transfer aspects. For equal mass diffusion coefficients, a vast amount of experimental data (as summarized, for example, in Ref. 17 suggest the correlation $C_M/C_H = Le^{\gamma}$. It may be hypothesized that for unequal mass diffusion coefficients the same procedure may be employed with the Lewis Number, Le, defined by the procedure set forth in Reference 7 involving $\bar{D}$. Thus, the input to the program consists of a time table of values for $\rho_e u_e C_H$ and the constant factor C_M/C_H.

In answer to question 2., changes of C_H with body shape are not usually of interest for rocket nozzle problems and hence are not accounted for in the ASTRMA program. A more important problem concerns the dependence of C_H on the actual rate of mass transfer. This problem has been ignored up to now, the implication being that C_H is determined by the boundary layer edge aerodynamics alone. This is known to be incorrect. The value of C_H depends fairly strongly on $\dot{m}$. If we denote the C_H with $\dot{m} = 0$ as C_{H_O}, this dependence is shown by both data and analysis to be accurately represented by

$$\frac{C_H}{C_{H_O}} = \frac{\varphi}{e^{\varphi}-1} \tag{40}$$

where

$$\varphi \triangleq \frac{2\lambda\dot{m}}{\rho_e u_e C_{H_O}} \tag{41}$$

This correction is built into the program.

Most user's prefer a value of 0.4 for λ in turbulent flow, and a value of 0.5 for λ in laminar flow. These values appear to be acceptably accurate for B' values below about 2 provided the molecular weight of the gas at the wall is at least roughly equal to the molecular weight of the environment gas. Very high B' values or large molecular weight discrepancies require higher values of λ Accurate determination of λ values usually require a full boundary layer solution study.

2.3.5 Cooldown Energy Balance Option

For representing radiation controlled situations, such as cooldown after exposure to convective heating, it is useful to have a surface energy balance option which has only radiation terms. Such an option is built into the ASTHMA3 program and is termed "Option 3". The energy balance for this case is simply

$$q_{abs}/A_B + \alpha_w q_{rad} - F\sigma\varepsilon T_w^4 - q_{cond} = 0 \qquad (42)$$

SECTION 3

USER'S GUIDE

ASTHMA PROGRAM

This section of the report summarizes the input requirements of the ASTHMA3 program in a form convenient for users of the program and provides specific instructions for program operation.

3.1 DESCRIPTION OF INPUT

The input to the Axi-Symmetric Transient Heating and Material Ablation Program can conveniently be considered as having nine parts, six of which must be present for each run; the remaining three are optional, depending on various input/output choices and on the heating option chosen. The individual nine parts are described in the nine following sub-sections.

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 General Problem Constants

One card provides the program with certain general constants.

Column	Format	Data	Units
1-3	I3	Largest m index in nodal network, number of rows of boxes (not corners)	---
4-6	I3	Largest n index in nodal network, number of columns of boxes (not corners)	---
7-12	E6.4	Initial value of problem time	sec
13-18	E6.4	Final value of problem time	sec
19-24	E6.4	Output time interval if greater than zero. If blank, the variable output interval option is used (see Section 3.1.3).	sec

Column	Format	Data	Units
71	I1	0 - Back shifted nodes	---
		1 - Centered nodes	---
72	I1	Property look-ups and formulation of conductances and capacities,	
		0 - Uses old AATT program procedures	---
		1 - Uses more efficient procedures written specifically for ASTHMA3 (not operational in some editions)	---
73	I1	0 - Thermal conductance calculations based on rectangular nodal boxes	---
		1 - Thermal conductance calculations using sine correction; improves accuracy for nonorthogonal nodal boxes	---

3.1.3 Special Output Interval Specification (Optional)

A card with the following information is required if columns 19-24 of the card described in Section 3.1.2 are blank.

Column	Format	Data	Units
1-10	F10.0	First output time interval, applied at initial time	sec
11-20	F10.0	Transition time between first output time interval and second output time interval	sec
21-30	F10.0	Second output time interval	sec
31-40	F10.0	Transition time between second output time interval and third output time interval	sec
41-50	F10.0	Third output time interval	sec
51-60	F10.0	Transition time between third output time interval and fourth output time interval	sec
61-70	F10.0	Fourth output time interval	sec
71-80	F10.0	Not used	

3.1.4 Special Punched Temperature Output Specification (Optional)

If KSTRP on the card described in Section 3.1.2 (column 68) is 2, up to eight special output times are to be provided for the punched output on a single card. See output description for further information.

Preceding page blank

Column	Format	Data	Units
1-10	8F10.0	Up to eight output times for punched output data	sec
11-20			
21-30...			

3.1.5 Nodal Net Corner Coordinate Cards

This set of cards provides the nodal box corner coordinates and certain nodal center locations to the program. For m rows and n columns, there will be (m+1) (n+1) corner coordinate cards. It is advisable to run the corner coordinate cards through any convenient plot program to check the nodal layout before any heat transfer calculations are made.

Corner cards must be entered in order beginning at m=1, n=1 and continuing up the first column of corners (n=1) for all m's until column is completed. returning to bottom of next column m=1, n=2, and so on, as indicated in Fig. 17.*

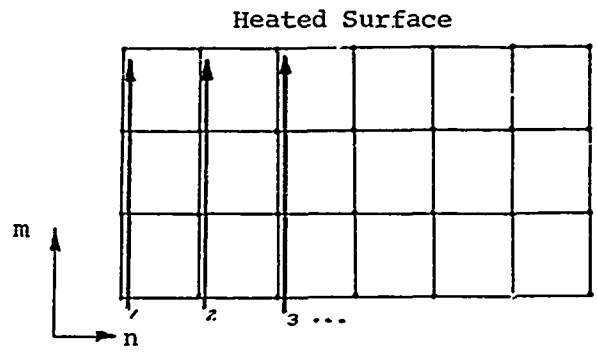

Figure 17. Sketch of Nodal Corner Input Order

Corners m, n representing boxes m, n which have no material (null nodes entered to complete the mesh lattice) may be blank entries, but a card must always be included. There must be (m+1)(n+1) corder cards.

Present dimensions allow 300 nodal boxes, with a maximum of 40 columns.

Column	Format	Data	Units
1-7	E7.5	Corner radius, r_c	inches
8-14	E7.5	Corner axial location, Z_c	inches

*The user should keep in mind the discussion of Section 2.2.2.1. The m,n network may be located completely independently of the physical r-Z coordinate scheme. The heated surface is at the "top" of a column, but "top" merely means the last coordinate card read in a given column.

3.1.6 Nodal Data Cards

This set of cards identifies the materials in the nodal boxes, flags the time tables and surface thermochemistry tables to be associated with the nodes, and specifies radiation view factors. For an m by n mesh network mn cards must appear, blank cards being entered for null (no material) nodes. Cards begin at 1,1 and proceed to m,1, followed by 1,2 to m,2, and so on.

Column	Format	Data	Units
1	I1	Material number of material in this box, refers to numbered material properties tables. Blank for null node	---
2	I1	Enter 1 if used for stability limit calculation of time step. Leave blank if this node can safely be omitted from stability considerations (economy measure)	---
3	I1	Enter 1 if this node is at the heated surface, enter 2, 3, or 4 to that side assigned to backwall boundary conditions (see Figure 18 below), otherwise blank; backwall assignment rules are discussed below	---
4	I1	Enter number of surface thermochemistry table which is to be used for energy balance calculations on this node if it is or becomes a surface node (see the discussion immediately below and Section 3.1.8.3 below)	---
5-6	I2	Enter number of time-function table which is to be used for boundary conditions for this node if it is or becomes a surface node or if it is a backwall (or side) node which has been flagged by 2, 3, or 4 in column 3. If it is a flagged backwall (or side) node, a zero in column 6 dictates that the heat transfer coefficient defined in columns 49-54 of the data card described in Section 3.1.2 will be used. Other rules on backwall assignments are discussed below.	---
7-12	E6.4	Leave blank (reserved for future use)	---
13-18	E6.4	Initial temperature of this node	°R
19-24	E6.4	Interface (contact) resistance at top of node (m+1 plane)	$ft^2 sec °R/Btu$

Column	Format	Data	Units
25-30	E6.4	Interface (contact) resistance at right side of node (n+1 plane)	$ft^2 sec°R/Btu$
31-36	E6.4	Option 1 radiation view factor for this node if it is or becomes a surface node or is a side or back-wall side	---
37-42	E6.4	Option 3 radiation view factor for this node if it is or becomes a surface node	---

Assignments and options for nodes require some amplification over and above the summaries given in the brief column-by-column descriptions given above:

Surface Thermochemistry Table Assignment (Column 4)

Surface thermochemistry tables are described in more detail in Section 3.1.9 below. Each table is made for one pressure and one ablating material. The tables are distinguished during the reading process by the pressures. The pressure is noted for each card. A change in pressure signifies the start of a new table. The pressure sets or tables are numbered as they are read in beginning with number one. It is this number which is referred to in the column 4 punch.

Back Wall Boundary Condition Assignments

The backwall boundary condition may be applied to any of three surfaces of a node (other than the "top of the column" side) and to more than one node in a column (excepting only the node at the heated surface). The backwall boundary condition may vary from node to node and with time and will allow an assigned temperature option. The following notes describe the ground rules for applying backwall boundary condition:

a. A node is exposed to the backwall boundary condition by a 2, 3, or 4 punch in the "side heated" slot of the nodal data card, where the sides are numbered as shown in Figure 18

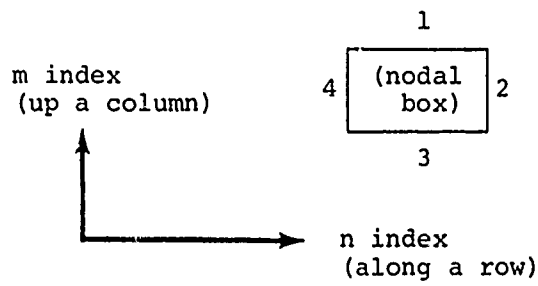

Figure 18. Definition of the Numbering System for the Sides of a Nodal Box

b. Nodes not assigned as "backwall nodes" will be insulated on sides 2, 3, and 4 if these do not communicate with other nodes (i.e., are "exposed")

c. Backwall nodes may be assigned temperature (Option 2) or be convectively and/or radiatively heated or cooled (Option 1). See Section 2.3 for discussion of Options 1 and 2.

d. For Option 1 backwall nodes:

(1) The reservoir temperature with which all such nodes communicate is the constant value given in column 61-66 of the first numerical data card (see Section 3.1.2 above).

(2) The convective transfer coefficient will be obtained from the time table assigned to this node (in which table the coefficient h in Btu/ft^{2}sec°F is entered in columns 31-40 of each card otherwise used for $\rho_e u_e C_H$); however, if no time table is assigned to a backwall node, h will be obtained from the constant value entered in columns 49-54 of the first numerical data card; zero values of h in an Option 1 time table are <u>not</u> allowed; radiation heat flux and recovery enthalpy values in these time tables are ignored.

(3) The radiation view factor will be taken as the Option 1 view factor assigned to the node.

(4) The emissivity or emittances of the exposed backwall surface will be taken from the material properties table values of ε for the material assigned to this node; however, if this ε is zero, ε will be obtained from the constant value entered in columns 55-60 of the first numerical data card (see Section 3.1.2 above).

(5) Backwall convective and radiative transfer reduces the stability time step for a node; high values of h should be avoided; see Section 2.2.4 above.

e. For Option 2 backwall nodes:

(1) The assigned temperature will be obtained from the time table assigned to this node; if no time table is assigned, the node cannot be treated under Option 2.

(2) No recession may be input in time tables for backwall nodes, such nodes never recede.

f. Backwall nodes may never switch heating options.

g. If erosion exposes a back or sidewall node to the heated surface boundary condition, no provision has been made for an automatic smooth reinterpretation. Entries in the time table will be interpreted in the non-backwall sense (see Section 3.1.8 below). In Option 1, this will lead to peculiar results.

3.1.7 Materials Properties Tables

One table of temperature dependent material properties is input for each material appearing in the nodal network. A lead card gives the total number of materials used. The tables are not numbered and are presumed to be encountered in ascending numerical order, beginning at one and including no gaps or omitted table numbers. The main ablating material must have material number and table number one. There must be at least two temperature entries in each table. Present dimensions allow six material property tables, with 15 temperature entires in each table.

First Card

Column	Format	Data	Units
1-2	I2	Total number of materials	---

Tabular Entry Cards

Column	Format	Data	Units
1-2	I2	Flag. Last entry in table has -1; blank for other cards	---
3-8	E6.4	Temperature	°R
9-14	E6.4	Density. Enter in first card only; will not be a function of temperature	lb/ft^3
15-20	E6.4	Specific heat c_p	Btu/lb°R
21-26	E6.4	Thermal conductivity along rows (n-direction, fixed m)	Btu/ft sec°R
27-32	E6.4	Emissivity (emittance)	---
33-38	E6.4	Thermal conductivity along columns (m-direction, fixed n), if blank will be taken as equal to n-direction conductivity	Btu/ft sec°R

3.1.8 Functions-of-Time Tables ("Heating" Tables)

A series of tables provides heated surface boundary condition information as functions of time and in some cases back or sidewall boundary conditions

as well. The input nodes for the two cases are slightly different, but in general the same input format is followed.

The various time tables are independent, and each nodal box in the in-depth layout has been given the number of a time-table for use if and when that node becomes a surface node, or (in some cases)it is a back-wall node.

Three general types of boundary condition sets are available, referred to here as Options 1, 2, and 3. Section 2.3 above provides further description.

The three options are:

Option 1 - General convection-radiation heating with coupled mass transfer, including the effects of unequal heat and mass transfer coefficients (non-unity Lewis number) and unequal mass diffusion coefficients.

Option 2 - Specified surface temperature and surface recession rate (Surface recession rate is not allowed for backwall nodes).

Option 3 - Specified radiation view factor and incident radiation flux, as functions of time, for a stationary surface ("cooldown" option). This specific option is not available for backwall nodes, but the same physics can be modeled with an Option 1 table.

Options 1 and 3 are surface energy balance options; Option 2 does not, of course, use an energy balance.

For heated surface boundary conditions, each time table may have a sequence of heating options; thus it is convenient to think of each time table 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 each time-table is limited to 25. Each sub-table must have at least 2 entries, hence the number of sub-tables in a table cannot exceed 12. (The most common problem has only 2, representing an Option 1 or Option 2 calculation followed by cooldown, Option 3.) Time entries must be in increasing order.

Backwall time tables may not have option switches.

The tables are presumed to be numbered sequentially beginning with table number 1. There may be ten different time tables. The format for the time-tables is as follows:

Column	Format	Data	Units
1-2	I2	Flag, nominally blank, punched to indicate the last card of each time table. Punch +1 for last card of last time table, -1 for last card of any preceding time tables	---
3-10	F8.2	Time (independent variable)	sec
11-20	F10.2	• Surface (or side 1) heating	
		Option 1: Recovery enthalpy, relative to the same chemical-base state as used with the heats of formation	Btu/lb
		Option 2: Surface temperature	°R
		Option 3: Blank	
		• Backwall (or sides 2, 3, or 4) heating	
		Option 1: Blank	---
		Option 2: Backwall node temperature	°R
21-30	F10.5	Option 1: Radiant energy flux to the surface	Btu/ft^2 sec
		Option 2: Surface-recession measured along nodal column centerlines (must be zero for backwall application)	mils
		Option 3: Radiant energy flux to the surface	Btu/ft^{2}sec
31-40	F10.5	• Surface (or side 1) heating	
		Option 1: heat transfer coefficient	lb/ft^{2}sec°F
		Option 2: Blank	
		Option 3: Must be blank	
		• Backwall (or sides 2, 3, or 4) heating	
		Option 1: Heat transfer coefficient	Btu/ft sec°F
		Option 2: Blank	
41-50	F10.5	Option 1: Pressure (not used, information only)	atm
		Option 2: ad lib	
		Option 3: ad lib	
51-60	F10.5	Blowing rate parameter λ (see Section 3.1.2)	---
61-70	F10.5	Heat rate q_{abs} into a surface or backwall node (Options 1 and 3; see Figure 15 and Equations (34), (35), (42))	Btu/sec

3.1.9 Surface Thermochemistry Data (Option 1 Only)

3.1.9.1 Introduction

Problems involving use of the surface thermochemistry option (Option 1) at the heated surface require the input of an array 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 equilibrium data deck. The program can be instructed to use the surface tables from the preceding problem (if any), in which case additional surface tables are not provided. The "surface tables" then consist of only the "lead card" described below. For Option 1 problems involving multiple ablating materials see Appendix A for minor modifications to the surface thermochemistry tables as described here.

3.1.9.2 Ratio of Mass to Heat Transfer Coefficient and Kinetics Parameter

A single card serves to specify the ratio of the convective mass transfer coefficient to the convective heat transfer coefficient (C_M/C_H).

Column	Format	Data	Units
1-10	F10.0	C_M/C_H	---
11-20	F10.0	Not used	---
21-39	19X	Blank	
40	I1	One punch will cause surface tables of preceding job to be used for this job. Read no more input. Otherwise leave blank.	---
41-49	9X	Blank	---
50	I1	Format flag (see Section 3.1.9.3.3).	---
		0 or blank - standard ACE and GASKET format	---
		3 - CMA format	---
51-56	I1	Material number for which $c_p(T)$ will be taken for making surface thermochemistry calculations using first pressure table below (blank implies one); see Appendix A for discussion	---
	F5.0	Heat of formation to be used in performing surface thermochemistry calculations using first pressure table below (blank calls for value entered in columns 37-42 of first data card); see Appendix A for discussion	Btu/lb at 536°R

Column	Format	Data	Units
57-62 63-68 69-74 75-80	I1,F5.0	Same as for 51-56 for second, third, fourth and fifth pressure tables; see Appendix A for discussion; leave blank for simple ablating material problems	

3.1.9.3 Surface Thermochemistry Table

3.1.9.3.1 Introduction

This table supplies the necessary input data for the surface energy balance computations in Option 1. (This energy balance is discussed in Section 2.3.)

Most commonly the deck of cards which make up the surface thermochemistry table is generated by the Aerotherm Chemical Equilibrium Program (ACE or GASKET). The user's manuals for the ACE and GASKET programs describe this table in complete detail (Refs. 4 and 5). 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 the ACE or GASKET programs and the ASTHMA program, since this is of the most general interest.

3.1.9.3.2 Edge Enthalpy Data

Equations (34) and (35) of Section 2.3 indicate that if diffusion coefficients are <u>not</u> equal <u>or</u> if the ratio C_M/C_H is <u>not</u> unity, then the surface energy balance requires data about the edge gases of the boundary layer. These data are provided in special "edge tables" which precede each pressure section of the surface tables (the various sections of the surface tables are described in Section 3.1.9.3.3 below). The independent variables for an edge table are pressure and temperature. Dependent variables are h_{ew} and the sum $\sum Z^*_{ie} h_i^{T_w}$.

If the format flag on the preceding card is 0, 1, or 2, the edge enthalpy data are entered on the cards as follows ("ACE format"):

Column	Format	Data	Units
1-6	E6.4	Pressure	atm
7-26	20X	Blank	---
27-30	F4.2	Unequal diffusion exponent* γ	---

*This quantity is discussed in the user's manual for the ACE program (Ref. 4) and also in References 6-10.

Column	Format	Data	Units
31-37	E7.5	Temperature	°K (°R if negative, in which case enthalpies below are Btu/lb)
38-43	E6.4	Unused	
44-51	E6.5	Summation $\sum Z^{*}_{ie} h_i^{T_w}$	cal/gr (Btu/lb if temperature is entered with minus sign)
52-59	E8.5	h_{ew}	cal/gr (Btu/lb if temperature is entered with minus sign)
60-65	A6	Unused	---
66	I1	0 (flag signifying that this card is part of the edge gas table)	---
67-78	2A6	Problem identification (not read)	---
79-80	I2	Page number of ACE or GASKET output listing containing the data punched on this card (not read)	---

For format flag of 3, the following format applies:

Column	Format	Data	Units
1-8	F8.5	Pressure	atm
9-16	F8.5	Blank	---
17-24	8X	Blank	---
25-33	F9.4	Temperature	(°R if negative in which case enthalpies below are Btu/lb)
34-38	F5.3	Unequal diffusion exponent γ	---
39-47	F9.3	Summation $\sum Z^{*}_{ie} h_i^{T_w}$	cal/gr (Btu/lb if temperature is entered with minus sign)

Column	Format	Data	Units
48-56	F9.3	Enthalpy of edge gases h_{ew}	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)	---
59-60	2X	Blank	---
61-66	A6	Unused	---
67-78	2A6	Problem identification (not read)	---
79-80	I2	Page number on ACE or GASKET output listing containing the data punched on this card (not read)	---

Note that although ACE and GASKET will provide data decks using °K and cal/gr, in those rare cases in which a user wishes to supply his own deck and prefers to work in °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 not more than 25 nor less than 3 temperature entries in each set. The series of temperature values may be different for the edge table at each pressure set. The table is 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. (Decks generated by the ACE and GASKET programs will have been automatically ordered properly.)

3.1.9.3.3 Surface Thermochemistry Tables

3.1.9.3.3.1 Description of Surface Thermochemical Tables

This table comprises a series of sections. Each section represents <u>one</u> pressure* and <u>one</u> transfer coefficient value. Each section consists of two subsections. The second represents surface temperatures too low for ablation;

*The word "pressure" is used as a handy identification parameter. In general, of course, there are two independent edge state variables, which are properly accounted for by the ACE program in its chemistry solution, as well as a specification of the ablating material. The ASTHMA program needs only to be given some "flag" to distinguish the tables. Pressure is chosen for this purpose, and hence the word "pressure" is used here as shorthand.

in this subsection surface temperature is the independent variable. The first subsection contains the ablating cases; here the ablation rate is the third independent variable and the surface temperature is a dependent variable.

Thus one table has three independent variables: pressure, transfer coefficient, 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 $\sum Z_{iw}^{\pm} h_i^{T_w}$ 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.)

The ACE and GASKET programs generate separate groups for each pressure, one at a time. All these groups together make up the surface thermochemistry deck. Within each pressure group the transfer coefficient values will be ordered. Within each transfer coefficient section, non-zero ablation rate entries will be grouped ahead of the zero ablation rate entries. The non-zero ablation rate entries will not be ordered in any particular way on the ablation rates; any necessary ordering is made automatically by the ASTHMA program as it reads in the data. The zero ablation rate entries are ordered with descending temperatures.

(Users providing their own thermochemistry decks must ensure that the transfer coefficients are ordered, but the ordering may be either ascending or descending in each case. Within each transfer coefficient section, the non-zero ablation rate entries and the zero ablation rate entries may be shuffled together but the zero ablation rate entries must be encountered in order of descending temperature during the reading process. Non-zero (ablating) ablation entries need not be ordered. The ablation rate for non-ablating (zero ablation rate) entries need not actually be zero, but may not exceed an ablation rate in the ablation section. These cards are identified as zero ablation rate cards by a unity flag in column 66, as described in the format specification below. (The flag is a zero in columns 57-58 for the CMA format.)

The number of pressure groups may not exceed 5 (and may be only 1); the number of transfer coefficient values in each pressure group may not exceed 8 but may be only one. The sequence of transfer coefficient values need not be the same in the different pressure sections. Within each transfer coefficient section the number of ablation rate entries, including the zero

ablation rate (independent surface temperature) cards, may not exceed 24 and may not be less than 2. The series of ablation values B'_c may be unique for each section.

The °R-Btu/lb option described for the edge tables in Section 3.9.3.2 may be used for these tables also.

3.1.9.3.3.2 Standard ACE Format (0 Punch)

If the format flag given in column 50 of the card described in Section 3.1.9.2 is 0, the card format for the surface equilibrium data as produced by GASKET is as follows:

Column	Format	Data	Units
1-6	E6.4	Pressure	atm
7-12	E6.4	Gas rate $\dot{m}_g/\rho_e u_e C_M = B'_g$ (not used by ASTHMA3)	---
13-20	E8.5	Ablation rate $\dot{m}_c/\rho_e u_e C_M = B'_c$	---
21-26	E6.4	Transfer coefficient $\rho_e u_e C_M$*	$lb/ft^2 sec$
27-30	F4.2	Unequal diffusion exponent γ	---
31-37	E7.5	Surface temperature	°K (°R if negative in which case enthalpies below are Btu/lb)
38-43	E6.4	$B'_f = \dot{m}_{r_\ell}/\rho_e u_e C_M$ (not used in ASTHMA3)	---
44-51	E8.5	Summation $\sum Z^*_{iw} h_i^{T_w}$	cal/gr (Btu/lb if temperature is entered with minus sign)
52-59	E8.5	Enthalpy of wall gases h_w	cal/gr (Btu/lb if temperature is entered with minus sign)
60-65	A6	Chemical symbol of surface species. (ACE and GASKET print such symbols arranged alphabetically and truncated from right end if necessary)	---
66	I1	1 for assigned-temperature entries in the equilibrium program (no ablation); > 1 for surface thermochemistry with ablation (temperature is dependent)	---

*Provided only by GASKET, not by ACE.

Column	Format	Data	Units
67-78	2A6	Problem identification (not read)	---
79-86	I2	Page number on ACE output listing containing the data punched on this card (not read)	---

3.1.9.3.3.3 CMA Format (3 Punch)

A format flag of 3 calls the CMA format. This is an optional ACE and GASKET output format intended for use with the CMA program (Ref. 10). Since so many graphite-in-air surface tables already exist with this format it is useful to have it as an ASTHMA3 input format also. In this format the transfer coefficient is assumed by ASTHMA3 to be in what is the B_g' slot of the CMA input. An ACE problem with kinetics output in the CMA card format will lose the kinetics information, however, since there is no provision for it in the ACE output statement. Hence, for ACE output this format will probably not be used for problems with kinetic control, and the transfer coefficient values entered in the B_g' slot will be fake numbers. Output from GASKET will have the transfer coefficient punched properly.

Column	Format	Data	Units
1-8	F8.5	Pressure	atm
9-16	F8.5	Transfer coefficient*	lb/ft^2sec
17-24	F8.5	Char rate $\dot{m}_c/\rho_e u_e C_M$	---
25-33	F9.4	Surface temperature	°K (°R if negative in which case enthalpies below are Btu/lb)
34-38	F5.3	Unequal diffusion exponent γ	---
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)

*Not provided by ACE; provided properly by GASKET.

Column	Format	Data	Units
57-58	I2	0 for assigned-temperature entries in the thermochemistry table (no ablation); > 0 for surface thermochemistry with ablation (temperature is dependent)	---
59-60	2X	Blank	---
61-66	A6	Chemical symbol of surface species. (ACE and GASKET programs print such symbols arranged alphabetically and truncated from right end if necessary.)	---
67-78	2A6	Problem identification (not read)	---
79-80	I2	Page number on ACE or GASKET output listing containing the data punched on this card (not read)	---

3.1.9.3.4 Termination Card

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

3.1.9.3.5 Assembled Thermochemical Deck

Figure 19 shows a picture of an assembled thermochemical data deck for several pressures.

3.2 PROGRAM OUTPUT

3.2.1 Input Data (Except Surface Thermochemical Tables)

Program output begins with an output of the input title and heading information, output interval specifications and general program constants, nodal data (including any computed nodal center locations), material property tables, and time dependent boundary conditions table.

All this output is fully labeled and is printed exactly as input by the user.

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.

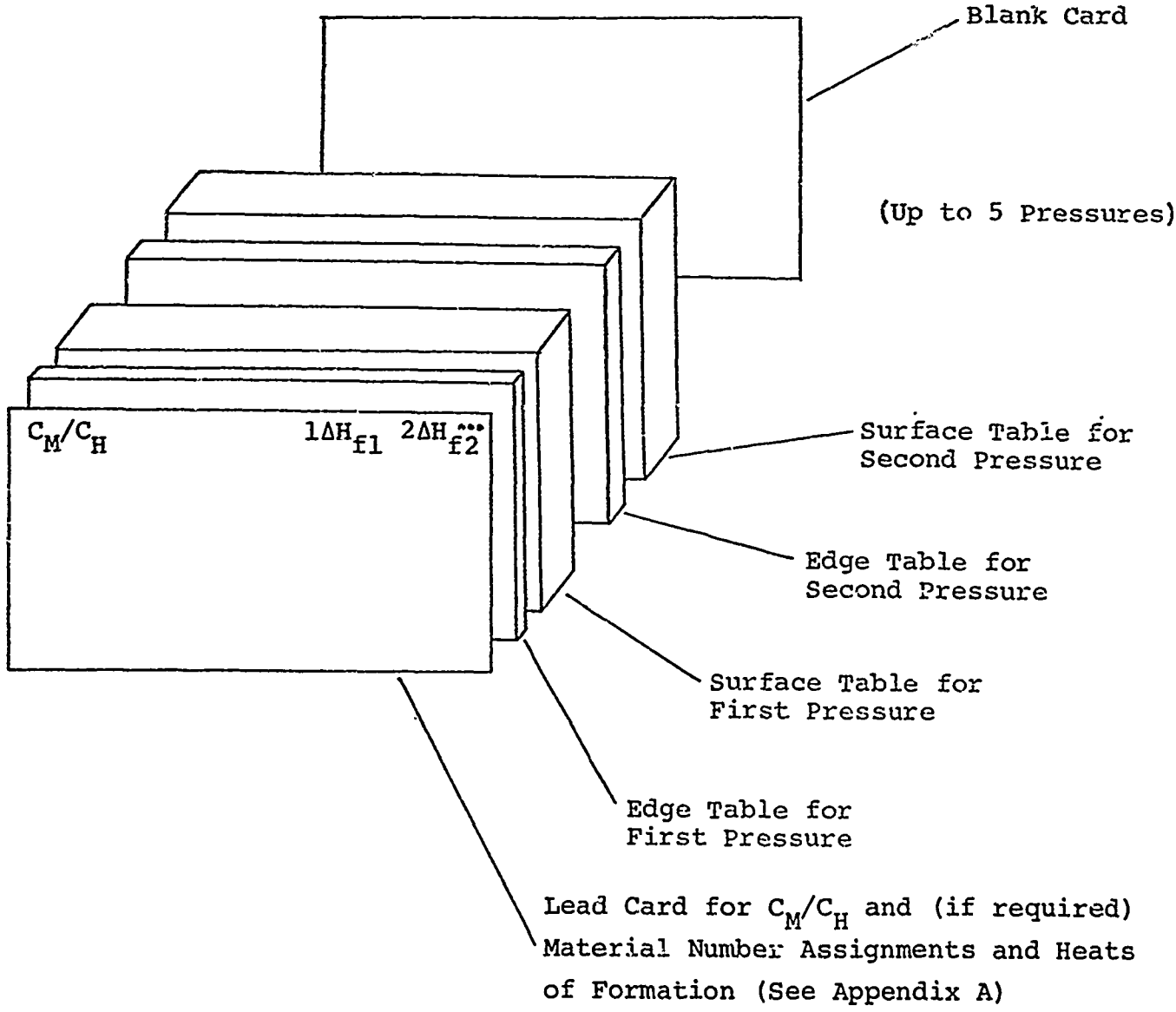

Figure 19. Sketch of Surface Thermochemistry Table Make-Up

3.2.2.2 Surface Thermochemistry Table

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

$$\left[\sum_i (Z^*_{ie} - Z^*_{iw})h_i^{T_w} - B'_c h_w + \frac{\dot{m}_c h_c}{\rho_e u_e C_M}\right] = \frac{q_{chem}}{\rho_e u_e C_M} = \frac{\text{Chem}}{\text{prod}} \tag{42}$$

and then output it as the dependent variable of interest in the output surface equilibrium table.* This term occurs directly in the surface energy balance (Equations (34) and (35) of Section 2.3.3 above) and is a useful diagnostic quantity. In the output, this quantity is labeled CHEM PROD. It has the units $(\text{Btu/ft}^2\text{sec})/(\text{lb/ft}^2\text{sec}) = \text{Btu/lb}$ and can be loosely 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."

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 other supplementary information, as described below.

3.2.3.2 General Information

The first line of output gives the current problem time. The second line shows the current values of a number of miscellaneous quantities:

Heading	
QTOT, SUR	Total energy input to the surface $\iint q_{cond} dA d\theta$, Btu
QTOT, INT	Total energy rise of subsurface materials, Btu
CNSV ENER	Conservation of energy check, ratio QTOT,SUR/QTOT,INT

*If edge tables are omitted, only the last three terms on the left are included. The mechanical removal energy term has been omitted from this equation since it is not presently considered by ASTHMA3.

Heading	
CRNODE	m, n indices of node yielding smallest stability limited time step
ITER	Total number of computational cycles (steps) required to reach the indicated value of output time. Note that the initial time is numbered as 1.
NODE D-TIME	Stability limited time step for critical node, sec
ACT D-TIME	Actual current time step; may be smaller than stability time step due to high surface recession or output matching

3.2.3.3 Miscellaneous Surface Data

A single line gives a set of data for each point on the heated surface. Each line presents the following data:

Heading	
ROW	Row number of node below this surface point (remember that surface points are distinct from nodal points)
COL	Column number of this surface point
OPTN	Current problem (heating) option at this surface point (1, 2, or 3)
SURF ITER	Number of iterations required for the surface energy balance during the previous cycle
SURF TEMP(R)	Surface point temperature in degrees Rankine
H EDGE	The input local recovery enthalpy as determined by linear interpolation in the functions-of-time table
H WALL	Option 1: Enthalpy of edge gases at the wall temperature, h_{ew} Option 2: Blank Option 3: Blank
B PRIME TOT	Parameter $B'/\rho_e u_e C_M = (B'_f + B'_{tc})/\rho_e u_e C_M$ (ASTHMA3 requires $B'_f = 0$)

Heading	
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 $C_H/C_{H_O} = \zeta/(e^{\zeta}-1)$ where $\zeta = 2\lambda\dot{m}/C_{H_O}$ and C_{H_O} is the heat transfer coefficient before being corrected for blowing
CH/CHO	The ratio C_H/C_{H_O}, indicating the amount of blowing correction
PRESSURE	Current value of pressure for this column is interpolated in functions-of-time tables
RADIUS	Current radial coordinate of this surface point (inches)
Z	Current axial location of this surface point (inches)

3.2.3.4 Surface Rate Quantities

A series of lines, one for each surface point, gives the current recession rates, mass loss (ablation rates, and surface energy flux rates.

Heading	
ROW	Row number of node below this surface point
COL	Column number of this surface point
RECESSION RATES - CENTER LINE	Rate of movement of surface point down column center line of surface nodal box (mils/sec)
NORMAL	Rate of movement of surface in direction normal to tangent to surface at this surface point (mils/sec)
MASS RATES MDOT TOTAL	$\dot{m}_{tc} + \sum \dot{m}_{r_\ell}$, total local mass loss rate (ablation), lb/ft^2 sec*
MDOT TCHEM	$\dot{m}_{tc}$

*In ASTHMA3, $\dot{m}_{r_\ell}$ must be zero

Heading

SURFACE ENERGY FLUX RATES

This group of terms all appear in the surface energy balance, Equation (35), and have the units Btu/ft^{2}sec.

CONVECTED IN	$q_{sen} = \rho_e u_e C_H (H_r - h_{e_w})$
RADIATED IN	$q_{rad} = \alpha_w q_{rad}$
RADIATED OUT	$q_{\substack{rad \\ out}} = F\epsilon_w \sigma T_w^4$
CHENICAL GENERATION	$q_{chem} = \rho_e u_e C_M$(chem prod)
CONDUCTION AWAY	q_{cond}

3.2.3.5 Surface Time Integrated Quantities

These lines correspond exactly to the line of surface rate quantities described above. Here the quantities are integrated over time and the column surface area, so that the units of these quantities are "Btu for this column n' or Btu/col, so to speak. The area integration is done since the surface area of a column varies with time and there is no generally preferred area upon which to base the time integrated flux terms.

3.2.3.6 In-Depth Data

This block of data gives the current temperatures (degrees Rankine) of the subsurface nodal points. The m,n index coordinates of the points are included for convenience.

3.2.3.7 Optional Punched Card Format

Optional output called for by the KSTRP flag of Section 3.1.2 above provides punched card temperature input for various thermal stress codes. These cards are punched for all nodal and surface point temperatures for either special punch times or for all regular output times. The card format is:

---

*If frozen edge tables (see Section 3.1.9.3.2 above) have been omitted, then h_{ew} and $\sum z_{ie}^{*} h_i^{T_w}$ are not available for the output of q_{sen} and q_{chem}. Therefore CONVECTED IN is output as $\rho_e u_e C_H H_r$ (the cold wall heat flux, blowing reduction effect included) and CHEMICAL GENERATION is the sum of all other terms in the surface energy balance, Equation (34), except conduction and radiation quantities. Since this division of terms offers little physical insight, many users prefer to use frozen edge tables even when they are not formally required.

Column	Format	Data	Units
1-10	F10.3	Point radius r	in
11-20	F10.3	Point axial coordinate Z	in
21-30	F10.3	Point temperature	^{o}R
31-38	8H	Units ININDEGR	---
39-41	I3	Point row index m (blank if a surface point)	---
42-45	IH/,I3	Point column index	---
46-48	3H	Title MAT (material)	---
49-50	I2	Material number at this point	---
51-57	F7.2	Time	sec
58-59	2H	Sb, units of time	---
60-71	2A6	Problem identification of columns 61-72 of third title card (Section 3.1.1)	---
72	1X		---
73-75	I3	Card number	---
76-77	2H	OF	---
78-80	I3	Total number of cards punched for this time	---

3.3 DUMPS

3.3.1 Introduction

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

3.3.2 Too-Small-Time-Step Dump

A dump occurs if the program selects a time step as small as 10^{-6} seconds. Computation ceases and the program prints out the current surface column number. Then the program sets the final problem time equal to the current time, and thus forces 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 at any column point. 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 data deck, the dump data must often be communicated to the program authors for analysis.

Iteration stops are almost always due to "unfortunate" variations in the tabular energy quantities making up the surface energy balance. Hence the iteration stop dump contains the 51 sets of paired values of the independent variable (either temperature or $\ln B_c'$) and the surface energy balance error generated during the search for a surface energy balance. The program then dumps the surface energy balance equation error (departure from zero) at each tabular B_c' (or temperature if failure occurred in nonablating section) in the two tables bracketing the current value of transfer coefficient, properly interpolated at the current value of transfer coefficient, for current values of CH, $q_{rad\ in}$, and in-depth conduction data. This information, plus the iteration history, permits a rather complete picture of the surface energy balance error function shape, and this in turn should usually allow an accurate assessment of the particular feature of the function currently hindering convergence.

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 single line:

Bad Surface Equilibrium Table of Type ---

Five error types are detected as follows:

Type	
0	C[illegible] section of independent temperature entries (no ablation) is not in descending order in temperature
1	Mass rate in no-ablation subsection has been set greater than a mass rate in the ablation subsection. Although the "zero-mass-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 $\neq 0$).

Type	
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	Only one or no B's in a table

3.3.5 Sense Switch Dumps

Sense Switch 1 calls for output every time step, Sense Switch 2 generates extra diagnostic dumps at every output, and Sense Switch 3 dumps some additional surface table information just prior to execution of the main program iteration loop.

3.4 MISCELLANEOUS

3.4.1 Running Time

On the CDC 6600 the execution time for ASTHMA is well approximated by

$$T(\text{hrs}) = 3 \times 10^{-7}\ NI \qquad \pm 25\% \tag{41}$$

where N = number of nodes and I = number of iterations, provided that the number of iterations per output page exceeds about 3 (otherwise output time begins to be appreciable). Iterations I may be estimated from

$$I = \frac{\text{problem time}}{\text{time step limit}} \tag{42}$$

and the time step limit may usually be estimated fairly closely from a small number of obvious candidate nodes:

$$\text{time step limit} \approx \frac{\ell^2}{4\alpha}$$

for square nodes of side ℓ, and

$$\text{time step limit} \approx \frac{\ell^2}{2\alpha}$$

for "thin" nodes of minimum side ℓ.

Estimates for other machines were made using empirical speed ratios based upon similar Fortran programs for jobs of roughly 10 minutes duration. If we write T = ANI, then we have

Machine	A (hrs)	Estimated Error
Philco 2000-212	5×10^{-7}	±25%
CDC 3800	5×10^{-7}	±50%
CDC 6600	3×10^{-7}	±25%
Univac 1108	3×10^{-7}	±50%
IBM 7094	12×10^{-7}	±50%
360/40	50×10^{-7}	±50%
360/44	25×10^{-7}	±50%
360/50	25×10^{-7}	±50%
360/65	5×10^{-7}	±50%

3.4.2 Storage Requirements

The ASTHMA program itself requires only about 5200_{10} words of storage. Associated subroutines require about 1000_{10} words. Most storage requirement is for dimensioned variables in various commons. With present dimensions, these require about $15,600_{10}$ words. Thus the program is a tight fit in a 32,000 word machine, with present dimension values.

3.4.3 Tape Requirements

The program uses nc scratch tapes. It uses logical unit number 5 for input and 6 for printed output, and uses a punch tape through a PUNCH statement.

3.4.4 Fortran Deck Make-Up

The ASTHMA program is in Fortran IV and consists of the following units:

(1) ARCAST
Main program

(2) Subroutine SURFB
Surface energy balance procedures

(3) Subroutine LCOUNT
Counts lines, turns and numbers pages

(4) Subroutine LOOK
Table look-up with linear interpolation

(5) Subroutine SLOPQ
Quadratic curve fit and slope finder

(6) Subroutine OGLE

Table look-up with cubic curve fit

(7) Subroutine ORDERD

Ordering routine

(8) Subroutine SEQUA

Orders according to results of ORDERD

(9) Subroutine SLOPL

Linear curve fit and slope finder

(10) Subroutine VCOS

Evaluates cosine of angle between surface normal and nodal center line

(11) Subroutine GAP

Dummy version of routine which was used to account for effect of radiation transfer across gaps (no longer used)

SECTION 4

SAMPLE PROBLEM

This section presents an input listing and selected output page listings for a sample problem using the ASTHMA3 code.

The problem selected is one of determining the transient thermal response of a pyrolytic graphite coated substrate located at the throat of a rocket nozzle. Figure 20 shows the nodal gridwork used to model the actual configuration.

An insulated boundary condition is imposed on the substrate backwall. The total problem time is 35.0 seconds consisting of a 29.3 second firing and a 5.7 second cooldown. Output was desired at every 1 second interval. The surface view factor and the incident radiant energy flux for each column during the firing (Option 1) are equated to zero since the propellant is transparent and the nozzle surface essentially sees only itself. By a similar argument for cooldown the Option 3 radiant energy flux and the Option 3 view factors are set equal to zero. Figure 20 also shows the locations and corresponding numbers of the surface thermochemistry/edge enthalpy tables and the functions-of-time tables. The edge static pressure at the upstream thermochemistry/edge enthalpy table (Table 1) is 56.0 atm and 37.2 atm at the throat (Table 2).

The following tables present a listing of the problem input and selected output pages.

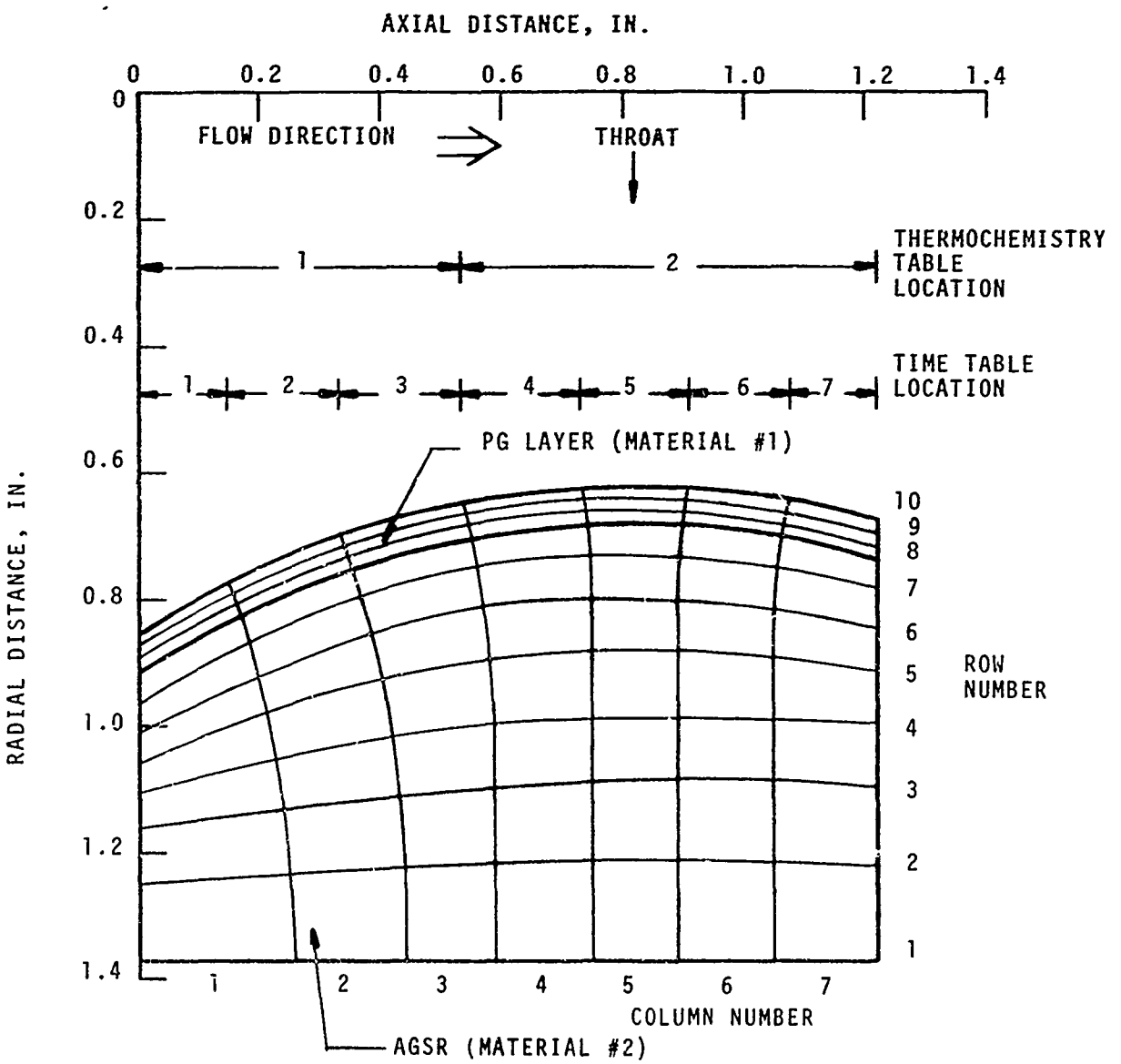

Figure 20. Sample Problem Nodal Layout

```
TRANSIENT HEAT CONDUCTION ANALYSIS OF FO COATED NOZZLE INSERT
MATERIALS ARE (1) MS LATEX AND (2) ASSR
NONMETALIZED PROPELLANT .... CHAMBER PRESSURE = 55.0 ATM.    SAMPLE
10  7  0.0  35.0   1.7          0.75   0.0   0.4   0.0   0.0  530.000211
1.370  0.000
1.250  0.000
1.140  0.000
1.110  0.000
1.060  0.000
1.010  0.000
0.963  0.000
0.910  0.000
0.890  0.000
0.870  0.000
0.850  0.000
1.370  0.258
1.230  0.251
1.130  0.249
1.053  0.226
0.977  0.214
0.913  0.200
0.868  0.185
0.821  0.171
0.807  0.166
0.746  0.158
0.771  0.140
1.179  0.440
1.227  0.440
1.115  0.424
1.015  0.420
0.923  0.423
0.852  0.397
0.795  0.367
0.751  0.352
0.731  0.340
0.717  0.341
0.735  0.334
1.176  0.330
1.115  0.330
1.094  0.340
0.995  0.340
0.992  0.345
0.958  0.374
0.747  0.387
.702  0.731
.665  .767
.756  .7
.947  .7
1.171  0.7
1.215  0.7
1.[illegible]  0.750
.985  .7
.874  .756
.866  .747
.731  .7
.883  .7
.844  .7
.54  .7
.92  .731
1.370  .890
1.215  0.848
1.085  0.890
.985  0.890
.879  0.890
.800  .891
.731  .874
.[illegible]  .7
.866  .7
.941  .7
.920  .7
1.370  1.[illegible]
1.215  1.[illegible]
1.047  1.[illegible]
.988  1.[illegible]
.867  1.[illegible]
.815  1.052
.7[illegible]  1.[illegible]
.9[illegible]  1.[illegible]
.[illegible]  1.[illegible]
.[illegible]  1.[illegible]
.[illegible]  1.[illegible]
1.37  1.[illegible]
1.[illegible]  1.[illegible]
1.09[illegible]  1.[illegible]
.9[illegible]  1.[illegible]
```

INPUT, SAMPLE PROBLEM 1

Reproduced from best available copy.

```
   .412  1.220
   .643  1.224
   .760  1.224
   .732  1.224
   .717  1.225
   .694  1.225
   .574  1.225
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2101 1        530.0
1101 1        530.0
1101 1        530.0
1111 1        530.0
2100          530.0
2000          530.0
2000          530.0
2100          530.0
2000          530.0
2100          530.0
2101 2        530.0
1101 2        530.0
1101 2        530.0
1111 2        530.0
2100          530.0
2000          530.0
2000          530.0
2100          530.0
2000          530.0
2100          530.0
2101 3        530.0
1101 3        530.0
1101 3        530.0
1111 3        530.0
2100          530.0
2000          530.0
2000          530.0
2100          530.0
2000          530.0
2100          530.0
2102 4        530.0
1102 4        530.0
1102 4        530.0
1112 4        530.0
2100          530.0
2000          530.0
2000          530.0
2100          530.0
2000          530.0
2100          530.0
2102 5        530.0
1102 5        530.0
1102 5        530.0
1112 5        530.0
2100          530.0
2000          530.0
2000          530.0
2100          530.0
2000          530.0
2100          530.0
2102 6        530.0
1102 6        530.0
1102 6        530.0
1112 6        530.0
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2100          530.0
2102 7        530.0
1102 7        530.0
1102 7        530.0
1112 7        530.0
2
   525.0 137.3 .244 5.0E-2   0.9 3.61-4
   780.0 137.3 .276 3.03-2   0.9 2.82-4
  1060.0 137.3 .313 4.47-2   0.9 2.64-4
  1390.0 137.3 .357 3.33-2   0.9 2.31-4
  1850.0 137.3 .409 2.31-2   0.9 2.00-4
  2190.0 137.3 .445 2.62-2   0.9 1.84-4
  2850.0 137.3 .480 1.74-2   0.9 1.78-4
  3360.0 137.3 .498 1.01-2   0.9 1.84-4
```

INPUT, SAMPLE PROBLEM 1 (CONTINUED)

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```
 4450.0 137.3 .526 1.42-2  0.0 2.22-2
 7450.0 137.3 .526 1.37-2  0.0 2.07-2
-19996.0 137.3 .526 1.37-2  0.0 2.07-2
  500.0 896.1 .220 1.42-2  0.0 1.00-2
 1000.0 896.1 .363 1.27-2  0.0 1.27-2
 1500.0 896.1 .396 1.00-2  0.0 1.00-2
 2000.0 896.1 .438 7.75-3  0.0 7.75-3
 3000.0 896.1 .461 4.95-3  0.0 4.95-3
 4000.0 896.1 .394 3.93-3  0.0 3.93-3
 5000.0 896.1 .522 3.35-3  0.0 3.35-3
 6000.0 896.1 .530 3.10-3  0.0 3.10-3
-19999.0 896.1 .530 3.10-3  0.0 3.10-3
     00.0   -1097.0        0.0      0.031
     01.0   -1097.0        0.0      0.351
     22.7   -1097.0        0.0      0.065
     24.3   -1097.0        0.0      0.031
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1100.0        0.0      0.035
     01.0   -1100.0        0.0      1.010
     22.7   -1100.0        0.0      1.015
     24.3   -1100.0        0.0      0.035
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1100.0        0.0      0.037
     01.0   -1100.0        0.0      1.130
     22.7   -1100.0        0.0      1.137
     24.3   -1100.0        0.0      0.037
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1115.0        0.0      0.042
     01.0   -1115.0        0.0      1.223
     22.7   -1115.0        0.0      1.225
     24.3   -1115.0        0.0      1.042
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1120.0        0.0      0.041
     01.0   -1120.0        0.0      1.105
     22.7   -1120.0        0.0      1.190
     24.3   -1120.0        0.0      0.041
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1140.0        0.0      0.037
     01.0   -1140.0        0.0      1.071
     22.7   -1140.0        0.0      1.076
     24.3   -1140.0        0.0      0.037
     24.3                  0.0
-1   35.0                  0.0
     00.0   -1170.0        0.0      0.031
     01.0   -1170.0        0.0      0.301
     22.7   -1170.0        0.0      1.105
     24.3   -1170.0        0.0      0.031
     24.3                  0.0
-1   35.0                  0.0
.003                                          31 0.00 1 0.0
56.0 0   .0 0   .  3 30.0000  .0 7-1307.20-1326.210-1  CMAN     .00
56.0 0   .0 0   .  1300.0000  .0 7-1225.077-1176.014-1  CMAN     .00
56.0000  .0 0   .  1300.0000  .067-1226.077-1176.014-1  CMAN     .00
56.0000  .0 0   .  1300.0000  .067-1006.747 -980.033-1  CMAN     .00
56.0000  .0 0   .0 0 0300.0000 .067 -770.011 -773.391-1  CMAN     .00
56.0000  .0 0   .0 0 0300.0000 .067 -537.749 -556.336-1  CMAN     .00
56.0000  .0 0   .0 0 0300.0000 .067 -294.533 -339.901-1  CMAN     .00
56.0000  .0 0   .0 0 0300.0000 .067  -47.979 -115.752-1  CMAN     .00
56.0000  .0 0   .0 0 0300.0000 .067 1351.354  684.142 1  C* F     .00
56.0000  .0 0   .0 1413300.0000 .067  810.067  457.849 1  C* F     .00
56.0000  .0 0   .0 1300.0000 .067  304.703  137.133 1  C* F     .00
56.0000  .00300 .0 0 1300.0000 .067   14.921 -160.334 1  C* F     .00
56.0000  .00000 .0 0 1300.0000 .067 -262.169 -340.283 1  C* F     .00
56.0000  .00000 .0 0 1300.0000 .067 -471.927 -509.661 1  C* F     .00
56.0000  .00000 .0 0 1300.0000 .067 -630.363 -642.351 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067 -757.546 -752.776 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067 -857.054 -851.053 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067 -955.342 -942.073 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1060.449-1029.374 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1151.269-1114.849 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1240.082-1194.300 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1327.544-1284.224 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1414.435-1354.457 1  C* F     .00
56.0000  .0 0   .0 0 1300.0000 .067-1433.054-1401.009 0  CMAN     .00
56.0000  .0 0   .0 0 1300.0000 .067-1736.815-1621.949 0  CMAN     .00
37.2000  .0 0   .0 0 1300.0000 .067-1627.400-1341.064-1  CMAN     .00
37.2000  .0 0   .0 0 1300.0000 .067-1445.300-1375.022-1  CMAN     .00
37.2000  .0 0   .0 0 1300.0000 .067-1242.833-1192.116-1  CMAN     .00
37.2000  .0 0   .0 0 1300.0000 .067-1025.937 -995.079-1  CMAN     .00
37.2000  .0 0   .0 0 1300.0000 .067 -795.833 -780.620-1  CMAN     .00
```

INPUT, SAMPLE PROBLEM 1 (CONTINUED)

37.2000	.00000	.000003000.0000	.667	-356.784	-573.555-1		CHAR	.000
37.2000	.00000	.000003000.0000	.667	-313.600	-355.079-1		CHAR	.000
37.2000	.00000	.000004000.0000	.667	-67.032	-133.811-1		CHAR	.000
37.2000	.00000	.040504000.0000	.667	1679.353	1065.839	1	C* F	.000
37.2000	.00000	.016743000.0000	.667	1020.865	590.340	1	C* F	.000
37.2000	.00000	.009973000.0000	.667	509.378	228.296	1	C* F	.000
37.2000	.00000	.005853000.0000	.667	105.345	-65.056	1	C* F	.000
37.2000	.00000	.003533200.0000	.667	-207.990	-302.564	1	C* F	.000
37.2000	.00000	.002093000.0000	.667	-442.789	-488.726	1	C* F	.000
37.2000	.00000	.001172000.0000	.667	-616.745	-632.632	1	C* F	.000
37.2000	.00000	.000612000.0000	.667	-751.547	-748.616	1	C* F	.000
37.2000	.00000	.000202400.0000	.667	-864.480	-849.088	1	C* F	.000
37.2000	.00000	.000122600.0000	.667	-965.332	-941.052	1	C* F	.000
37.2000	.00000	.000042000.0000	.667	-1059.730	-1028.685	1	C* F	.000
37.2000	.00000	.000011000.0000	.667	-1150.646	-1114.247	1	C* F	.000
37.2000	.00000	.000001000.0000	.667	-1239.515	-1198.963	1	C* F	.000
37.2000	.00000	.000001400.0000	.667	-1327.058	-1283.605	1	C* F	.000
37.2000	.00000	.000001200.0000	.667	-1413.777	-1368.754	1	C* F	.000
37.2000	.00000	.000001000.0000	.667	-1480.179	-1400.435	0	CHAR	.000
37.2000	.00000	.000000 500.0000	.667	-1738.934	-1624.727	0	CHAR	.000

INPUT, SAMPLE PROBLEM 1 (CONCLUDED)

```
AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM
                                                                                                                    PAGE  1

TRANSIENT HEAT CONDUCTION ANALYSIS OF PG COATED NOZZLE INSERT
MATERIALS ARE (1) PG LAYER AND (2) AGSR
NONMETALIZED PROPELLANT .... CHAMBER PRESSURE = 65.6 ATM.     SAMPLE

INPUT DATA

  DIMENSIONS OF INPUT DATA

  TIME                SEC                  TEMPERATURE   DEG R                                DENSITY              LB PER CUBIC FT
  SPECIFIC HEAT       BTU PER LB DEG R     CONDUCTIVITY  BTU PER FT SEC DEG R                 EMISSIVITY           DIMENSIONLESS
  HEAT COEFFICIENT    LB PER SQ FT SEC     ENTHALPY      BTU PER LB                           NODAL COORDINATES    INCHES
  RESISTANCES         SQ FT SEC DEG R PER BTU

  PROBLEM CONSTANTS

  MMAX NMAX      INIT TIME    FINL TIME    PRNT TIME    TIME INCR    TIME CNST

   10    7        .0000        .3500+02     .1000+01    -.0000        .7500-00

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

OUTPUT, SAMPLE PROBLEM 1

NODAL DATA

MATL	THTA	SIDE	ENTR	HTTH	HEAT CONST	EXIT FLOW	CONT RES A	CONT RES B	VF1	VF2
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	1	1	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	1	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	1	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	1	1	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	1	2	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	2	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	2	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	1	2	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	1	3	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	3	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	1	3	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	1	3	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	2	4	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2		-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	4	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	2	4	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	2	5	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	5	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	5	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	2	5	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

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2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	0	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	2	0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	2	0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	0	-0	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
2	1	0	2	7	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	7	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	0	2	7	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000
1	1	1	2	7	-0.000	5.300+02	-0.000	-0.000	-0.000	-0.000

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OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

MATERIAL PROPERTIES TABLE

MATERIAL NO. 1

TEMP	DENSITY	SPEC HEAT	CONDUCT	EMISSIV	CONDUCT2
.5250+03	.1373+03	.2400-00	.5000-01	.9000-00	.3610-03
.7800+03	.1373+03	.2760-00	.5000-01	.9000-00	.2820-03
.1060+04	.1373+03	.3130-00	.4470-01	.9000-00	.2640-03
.1390+04	.1373+03	.3570-00	.3330-01	.9000-00	.2310-03
.1850+04	.1373+03	.4090-00	.2300-01	.9000-00	.2000-03
.2190+04	.1373+03	.4450-00	.2020-01	.9000-00	.1840-03
.2650+04	.1373+03	.4900-00	.1740-01	.9000-00	.1780-03
.3060+04	.1373+03	.4980-00	.1610-01	.9000-00	.1840-03
.4460+04	.1373+03	.5200-00	.1420-01	.9000-00	.2220-03
.7460+04	.1373+03	.5200-00	.1390-01	.9000-00	.2890-03
.9999+04	.1373+03	.5200-00	.1390-01	.9000-00	.2890-03

MATERIAL NO. 2

TEMP	DENSITY	SPEC HEAT	CONDUCT	EMISSIV	CONDUCT2
.5000+03	.9610+02	.2200-00	.1600-01	.9000-00	.1600-01
.1000+04	.9610+02	.3230-00	.1270-01	.9000-00	.1270-01
.1500+04	.9610+02	.3900-00	.1000-01	.9000-00	.1000-01
.2000+04	.9610+02	.4300-00	.7750-02	.9000-00	.7750-02
.3000+04	.9610+02	.4810-00	.4950-02	.9000-00	.4950-02
.4000+04	.9610+02	.5040-00	.3900-02	.9000-00	.3900-02
.5000+04	.9610+02	.5200-00	.3350-02	.9000-00	.3350-02
.6000+04	.9610+02	.5300-00	.3100-02	.9000-00	.3100-02
.9999+04	.9610+02	.5300-00	.3100-02	.9000-00	.3100-02

---TIME DEPENDENT BOUNDARY CONDITIONS---

TIME TABLE NUMBER 1

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	-1097.00	.00	.0310	-.00000	.400
1.00	1	-1097.00	.00	.8810	-.00000	.400
22.70	1	-1097.00	.00	.8850	-.00000	.400
29.30	1	-1097.00	.00	.0310	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

PAGE 5
SAMPLE

TIME TABLE NUMBER [illegible]

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	-110[illegible]	.00	.0390	-.00000	.400
1.00	1	-1105.00	.00	1.0190	-.00000	.400
22.70	1	-110[illegible]	.00	1.0150	-.00000	.400
29.30	1	-110[illegible]	.00	.0390	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

TIME TABLE NUMBER 3

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	-1109.00	.00	.0390	-.00000	.400
1.00	1	-1109.00	.00	1.1320	-.00000	.400
22.70	1	-1109.00	.00	1.1370	-.00000	.400
29.30	1	-1109.00	.00	.0390	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

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AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

TIME TABLE NUMBER [illegible]

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	-1115.00	.00	.0420	-.00000	.400
1.00	1	-1115.00	.00	1.2230	-.00000	.400
22.70	1	-1115.00	.00	1.2280	-.00000	.400
29.30	1	-1115.00	.00	.0420	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

TIME TABLE NUMBER 5

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	-1127.00	.00	.0410	-.00000	.400
1.00	1	-1127.00	.00	1.1850	-.00000	.400
22.70	1	-1127.00	.00	1.1900	-.00000	.400
29.30	1	-1127.00	.00	.0410	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

TIME TABLE NUMBER 6

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	-1140.00	.00	.0370	-.00000	.400
1.00	1	-1140.00	.00	1.0710	-.00000	.400
22.70	1	-1140.00	.00	1.0760	-.00000	.400
29.30	1	-1140.00	.00	.0370	-.00000	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

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OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

TIME TABLE NUMBER 7

TIME (SEC)	PROB OPTN	RECOVERY ENTHALPY (BTU/LB)	RADIATION HEAT RATE (BTU/SQ FT-SECOND)	HEAT COEFF (LB/SQ FT-SECOND)	PRESSURE (ATM)	[illegible]
.00	1	-1157.00	.00	.0310	[illegible]	.400
1.00	1	-1157.00	.00	.0610	[illegible]	.400
22.70	1	-1157.00	.00	.8850	[illegible]	.400
29.30	1	-1157.00	.00	.0310	[illegible]	.400

TIME (SEC)	PROB OPTN	VIEW FACTOR	RADIATION HEAT RATE (BTU/SQ FT-SECOND)
29.30	3	-.00	.00
35.00	3	-.00	.00

CH/CHO = PHI/(EXP(PHI)-1.) WHERE PHI = 2.*BRT*SM DUT/CHO, BRT IN TABLE

---SURFACE EQUILIBRIUM DATA---

RATIO OF MASS TO HEAT TRANSFER COEFFICIENTS = .903
UNEQUAL DIFFUSION EXPONENT = .667
NO RADIUS CORRECTION ON CK

P = 56.0000 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
900.00	-2746.46	3600.00	-1765.45	5300.00	-611.93
1800.00	-2448.57	4500.00	-1392.10	7200.00	-213.75
2700.00	-2119.27	5400.00	-1005.08		

KINETICS PRM = .000 PRESSURE = 56.0000 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	.0000	[illegible]		[illegible]	.0005	51.94	C* F
1800.00	.0000	[illegible]		[illegible]	.0009	-3.94	C* F
2160.00	.0000	[illegible]	C* F	[illegible]	.0015	-114.31	C* F
2520.00	.0000	[illegible]	C* F	[illegible]	.0020	-313.37	C* F
2880.00	.0000	[illegible]	C* F	[illegible]	.0045	-631.45	C* F
3240.00	.0000	[illegible]	C* F	[illegible]	.0077	-1087.99	C* F
3600.00	.0000	[illegible]	C* F	[illegible]	.0141	-1703.48	C* F
3960.00	.0001	96.75	C* F	7200.00	.0292	-2525.03	C* F
4320.00	.0002	78.71	C* F				

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

THIS COMPLETES THE INPUT AND DISPLAY OF SURFACE THERMOCHEMISTRY TABLE NO. 1.
THIS TABLE HAS INCORPORATED BY USER ASSIGNMENT THE SPECIFIC HEAT OF MATERIAL
NO. 1 AND A HEAT OF FORMATION VALUE OF 0. BTU/LB AT 536 DEGREES RANKINE.

P = 37.2000 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
900.00	-2773.92	3600.00	-1792.94	6300.00	-639.14
1800.00	-2476.12	4500.00	-1419.52	7200.00	-240.86
2700.00	-2145.81	5400.00	-1032.40		

KINETICS PRM = .000 PRESSURE = 37.2000 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	.0000	199.72		4680.00	.0006	7.35	C* F
1800.00	.0000	62.62		5040.00	.0012	-61.80	C* F
2160.00	.0000	85.33	C* F	5400.00	.0021	-198.77	C* F
2520.00	.0000	74.34	C* F	5760.00	.0035	-443.10	C* F
2880.00	.0000	70.23	C* F	6120.00	.0058	-826.46	C* F
3240.00	.0000	65.36	C* F	6480.00	.0100	-1369.68	C* F
3600.00	.0000	60.95	C* F	6840.00	.0187	-2101.25	C* F
3960.00	.0001	54.48	C* F	7200.00	.0405	-3094.51	C* F
4320.00	.0003	46.00	C* F				

THIS COMPLETES THE INPUT AND DISPLAY OF SURFACE THERMOCHEMISTRY TABLE NO. 2.
THIS TABLE HAS INCORPORATED BY USER ASSIGNMENT THE SPECIFIC HEAT OF MATERIAL
NO. 1 AND A HEAT OF FORMATION VALUE OF 0. BTU/LB AT 536 DEGREES RANKINE.

NODAL COORDINATES

I	J	RC(IN)	ZC(IN)	RN(IN)	ZN(IN)
1	1	.13700+01	.00000	.13060+01	.12725+00
2	1	.12500+01	.00000	.11945+01	.12275+00
3	1	.11600+01	.00000	.11142+01	.11700+00
4	1	.11100+01	.00000	.10500+01	.11050+00
5	1	.10600+01	.00000	.99125-00	.10350+00
6	1	.10100+01	.00000	.93900-00	.96250-01
7	1	.96000-00	.00000	.88975-00	.89000-01
8	1	.91000-00	.00000	.85700-00	.83750-01
9	1	.89000-00	.00000	.83875-00	.80500-01
10	1	.87000-00	.00000	.81975-00	.77000-01
11	1	.85000-00	.00000		
1	2	.13700+01	.25800-00	.13002+01	.34725-00
2	2	.12340+01	.25100-00	.11775+01	.34125-00
3	2	.11240+01	.24600-00	.10792+01	.33050-00
4	2	.10530+01	.22800-00	.99200-00	.31625-00
5	2	.97700-00	.21450-00	.91750-00	.30100-00
6	2	.91800-00	.20000-00	.85700-00	.28525-00
7	2	.86800-00	.18530-00	.80750-00	.26950-00
8	2	.82100-00	.17100-00	.77800-00	.25900-00
9	2	.80700-00	.16400-00	.76125-00	.25275-00

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

10	2	[illegible]	[illegible]	[illegible]	[illegible]
11	2	[illegible]	[illegible]		
1	3	[illegible]	[illegible]	[illegible]	[illegible]
2	3	[illegible]	[illegible]	[illegible]	[illegible]
3	3	[illegible]	[illegible]	[illegible]	[illegible]
4	3	[illegible]	[illegible]	[illegible]	[illegible]
5	3	[illegible]	[illegible]	[illegible]	[illegible]
6	3	[illegible]	[illegible]	[illegible]	[illegible]
7	3	[illegible]	[illegible]	[illegible]	[illegible]
8	3	[illegible]	[illegible]	[illegible]	[illegible]
9	3	[illegible]	[illegible]	[illegible]	[illegible]
10	3	[illegible]	[illegible]	[illegible]	[illegible]
11	3	[illegible]	[illegible]		
1	4	[illegible]	[illegible]	[illegible]	[illegible]
2	4	[illegible]	[illegible]	[illegible]	[illegible]
3	4	[illegible]	[illegible]	[illegible]	[illegible]
4	4	[illegible]	[illegible]	[illegible]	[illegible]
5	4	[illegible]	[illegible]	[illegible]	[illegible]
6	4	[illegible]	[illegible]	[illegible]	[illegible]
7	4	[illegible]	[illegible]	[illegible]	[illegible]
8	4	[illegible]	[illegible]	[illegible]	[illegible]
9	4	[illegible]	[illegible]	[illegible]	[illegible]
10	4	[illegible]	[illegible]	[illegible]	[illegible]
11	4	[illegible]	[illegible]		
1	5	[illegible]	[illegible]	[illegible]	[illegible]
2	5	[illegible]	[illegible]	[illegible]	[illegible]
3	5	[illegible]	[illegible]	[illegible]	[illegible]
4	5	[illegible]	[illegible]	[illegible]	[illegible]
5	5	[illegible]	[illegible]	[illegible]	[illegible]
6	5	[illegible]	[illegible]	[illegible]	[illegible]
7	5	[illegible]	[illegible]	[illegible]	[illegible]
8	5	[illegible]	[illegible]	[illegible]	[illegible]
9	5	[illegible]	[illegible]	[illegible]	[illegible]
10	5	[illegible]	[illegible]	[illegible]	[illegible]
11	5	[illegible]	[illegible]		
1	6	[illegible]	[illegible]	[illegible]	[illegible]
2	6	[illegible]	[illegible]	[illegible]	[illegible]
3	6	[illegible]	[illegible]	[illegible]	[illegible]
4	6	[illegible]	[illegible]	[illegible]	[illegible]
5	6	[illegible]	[illegible]	[illegible]	[illegible]
6	6	[illegible]	[illegible]	[illegible]	[illegible]
7	6	[illegible]	[illegible]	[illegible]	[illegible]
8	6	[illegible]	[illegible]	[illegible]	[illegible]
9	6	[illegible]	[illegible]	[illegible]	[illegible]
10	6	[illegible]	[illegible]	[illegible]	[illegible]
11	6	[illegible]	[illegible]		
1	7	[illegible]	[illegible]	[illegible]	[illegible]
2	7	[illegible]	[illegible]	[illegible]	[illegible]
3	7	[illegible]	[illegible]	[illegible]	[illegible]
4	7	[illegible]	[illegible]	[illegible]	[illegible]
5	7	[illegible]	[illegible]	[illegible]	[illegible]
6	7	[illegible]	[illegible]	[illegible]	[illegible]
7	7	[illegible]	[illegible]	[illegible]	[illegible]
8	7	[illegible]	[illegible]	[illegible]	[illegible]
9	7	[illegible]	[illegible]	[illegible]	[illegible]
10	7	[illegible]	[illegible]	[illegible]	[illegible]
11	7	[illegible]	[illegible]		

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OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

1	8	.13730+01	.12200+01
2	8	.12200+01	.12200+01
3	8	.10980+01	.12200+01
4	8	.99600-00	.12200+01
5	8	.91200-00	.12200+01
6	8	.84300-00	.12200+01
7	8	.78000-00	.12200+01
8	8	.73200-00	.12200+01
9	8	.71700-00	.12200+01
10	8	.69400-00	.12200+01
11	8	.67400-00	.12200+01

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

OUTPUT DATA

DIMENSIONS OF OUTPUT DATA

TIME	SEC	QTOT.SUM.INT	BTU	CONVECTIVE HEAT COEFF	LB PER SQ FT SEC
TEMPERATURE	DEG R	QNET AND QCONV	BTU PER SQ FT SEC	QTOT	BTU PER SQ FT

********** 1.00 SECONDS **********

GENERAL

TIME	QTOT.SUR	QTOT INT	CNSV ENER	CRNODE	ITER	NODE D-TIME	ACT D-TIME
.1000+01	.1270+02	.1270+02	.1000+01	0 1	113	.93144-02	.86213-02

PRIMARY SURFACE

-------MISCELLANEOUS SURFACE DATA-------

ROW	COL	OPTN	SURF ITER	SURF TEMP(R)	H EDGE (BTU/LB)	H WALL (BTU/LB)	B PRIME TOT	MASS COEFF (LB/FT2-SEC)	CH/CHO	PRESSURE (ATM)	RADIUS (IN)	Z
10	1	1	3	4419.0	-1097.00	-1426.04	.0003	.79547	.99990	.100-05	.810-00	.750-01
10	2	1	3	4591.7	-1105.00	-1391.37	.0003	.91193	.99989	.100-05	.734-00	.242-00
10	3	1	3	4566.7	-1104.00	-1363.74	.0004	1.02206	.99987	.100-05	.672-00	.435-00
10	4	1	3	4582.0	-1115.00	-1384.64	.0005	1.10418	.99983	.100-05	.633-00	.634-00
10	5	1	3	4545.7	-1127.00	-1400.09	.0005	1.06988	.99984	.100-05	.620-00	.820-00
10	6	1	3	4475.7	-1140.00	-1429.34	.0004	.96698	.99986	.100-05	.630-00	.994-00
10	7	1	3	4328.7	-1157.00	-1491.95	.0003	.79546	.99990	.100-05	.657-00	.115+01

--------SURFACE RATE QUANTITIES--------

-LOCATION-		--RECESSION RATES-- (MILS/SEC)		--MASS RATES-- (LB/FT2-SEC)		--SURFACE ENERGY FLUX RATES-- (BTU/FT2-SEC)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	.019562	.018882	.210-03	.210-03	.299+03	.565+02	.000	.000	.346+03
10	2	.025730	.025726	.274-03	.294-03	.289+03	.592+02	.000	.000	.348+03
10	3	.033115	.033065	.370-03	.370-03	.288+03	.614+02	.000	.000	.350+03
10	4	.047954	.047927	.545-03	.545-03	.330+03	.177+02	.000	.000	.347+03
10	5	.042662	.042662	.488-03	.488-03	.324+03	.206+02	.000	.000	.344+03
10	6	.033446	.033137	.379-03	.379-03	.310+03	.247+02	.000	.000	.335+03
10	7	.019891	.019836	.227-03	.227-03	.295+03	.312+02	.000	.000	.326+03

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

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AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

-----SURFACE TIME INTEGRATED QUANTITIES-----

		--RECESSION TOTALS-- (MILS)		--MASS ABLATION TOTALS-- (LB/COL)		--SURFACE ENERGY FLUX TOTALS-- (BTU/COL)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	.0000	.0000	.273-06	.273-06	.171+01	.230-00	.000	.000	.194+01
10	2	.0000	.0000	.425-06	.425-06	.168+01	.266-00	.000	.000	.215+01
10	3	.0000	.0000	.560-06	.560-06	.187+01	.276-00	.000	.000	.215+01
10	4	.0000	.0000	.736-06	.736-06	.179+01	.137-00	.000	.000	.192+01
10	5	.0000	.0000	.580-06	.580-06	.156+01	.125+00	.000	.000	.168+01
10	6	.0000	.0000	.421-06	.421-06	.145+01	.121+00	.000	.000	.157+01
10	7	.0000	.0000	.197-06	.197-06	.118+01	.100+00	.000	.000	.128+01

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

IN-DEPTH DATA

ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE
1	1	540.00	1	2	537.81	1	3	536.16	1	4	534.98	1	5	534.35
2	1	545.34	2	2	542.49	2	3	540.47	2	4	538.83	2	5	537.95
3	1	553.37	3	2	55 .28	3	3	548.16	3	4	545.91	3	5	544.64
4	1	563.03	4	2	561.87	4	3	560.02	4	4	557.12	4	5	555.01
5	1	575.30	5	2	577.35	5	3	576.92	5	4	574.04	5	5	570.63
6	1	589.69	6	2	594.94	6	3	596.70	6	4	593.31	6	5	588.54
7	1	607.29	7	2	614.15	7	3	616.94	7	4	613.26	7	5	607.91
8	1	834.02	8	2	845.33	8	3	845.67	8	4	838.12	8	5	833.57
9	1	1487.34	9	2	1497.34	9	3	1503.30	9	4	1493.93	9	5	1488.49
10	1	2917.16	10	2	2948.52	10	3	2977.24	10	4	2988.85	10	5	2975.84
1	6	534.10	1	7	534.11									
2	6	537.61	2	7	537.69									
3	6	544.18	3	7	544.47									
4	6	554.24	4	7	554.70									
5	6	569.03	5	7	568.75									
6	6	585.84	6	7	585.03									
7	6	604.26	7	7	603.79									
8	6	822.13	8	7	808.67									
9	6	1444.69	9	7	1406.94									
10	6	2877.50	10	7	2802.23									

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

**********[illegible] 20.00 SEC[illegible]**********

GENERAL

TIME	[illegible]	[illegible]	CONV ENER	CHNGES	ITER	NODE D-TIME	ACT D-TIME
.28[illegible]	[illegible]	.1071+03	.1009+01	0	1	1+01	.34513-01	.33978-01

[illegible] SURFACE

-------MISCELLANEOUS SURFACE DATA-------

ROW	COL	OPTN	SURF ITER	SURF TEMP(F)	[illegible] (BTU/LB)	H WALL (BTU/LB)	H PRIME TOT	MASS COEFF (LB/FT2-SEC)	CH/CHO	PRESSURE (ATM)	RADIUS (IN)	Z
10	1	1	2	4384.5	-1137.00	-1440.60	.0003	.17987	.99991	.100-05	.812-00	.752-01
10	2	1	2	4456.4	-1105.00	-1410.61	.0003	.20589	.99989	.100-05	.736-00	.242-00
10	3	1	2	4515.4	-1109.00	-1395.61	.0003	.23048	.99988	.100-05	.674-00	.436-00
10	4	1	2	4531.2	-1115.00	-1405.42	.0004	.24883	.99984	.100-05	.635-00	.635-00
10	5	1	2	4516.7	-1127.00	1412.42	.0004	.24135	.99984	.100-05	.622-00	.820-00
10	6	1	2	4451.1	-1140.00	-1440.23	.0004	.21818	.99987	.100-05	.632-00	.994-00
10	7	1	2	4335.8	-1157.00	-1489.29	.0003	.17987	.99990	.100-05	.659-00	.115+01

AEROTHERM AXI-SYMMETRIC TRANSIENT HEATING AND MATERIAL ABLATION PROGRAM

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SAMPLE

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--------SURFACE RATE QUANTITIES--------

-LOCATION- ROW	COL	--RECESSION RATES-- (MILS/SEC) CENTER LINE	NORMAL	--MASS RATES-- (LB/FT2-SEC) MDOT TOTAL	MDOT TCHEM	--SURFACE ENERGY FLUX RATES-- (BTU/FT2-SEC) CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	.004092	.003951	.452-04	.452-04	.685+02	.133+02	.000	.000	.824+02
10	2	.005261	.005259	.602-04	.602-04	.697+02	.141+02	.000	.000	.844+02
10	3	.006679	.006668	.763-04	.763-04	.706+02	.147+02	.000	.000	.859+02
10	4	.009694	.009625	.110-03	.110-03	.800+02	.507+01	.000	.000	.857+02
10	5	.009011	.009011	.103-03	.103-03	.763+02	.528+01	.000	.000	.822+02
10	6	.007147	[illegible]	.809-04	.809-04	.725+02	.607+01	.000	.000	.792+02
10	7	.004544	[illegible]	.519-04	.519-04	.662+02	.694+01	.000	.000	.737+02

-----SURFACE TIME INTEGRATED QUANTITIES-----

ROW	COL	--RECESSION TOTALS-- (MILS) CENTER LINE	NORMAL	--MASS ABLATION TOTALS-- (LB/CUL) MDOT TOTAL	MDOT TCHEM	--SURFACE ENERGY FLUX TOTALS-- (BTU/CUL) CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	1.0487	1.0437	.736-04	.708-04	.238+02	.411+01	.000	.000	.279+02
10	2	1.2430	1.243	.915-04	.915-04	.249+02	.420+01	.000	.000	.291+02
10	3	1.4624	[illegible]	.103-03	.103-03	.241+02	.389+01	.000	.000	.279+02
10	4	2.0198	[illegible]	.125-03	.125-03	.270+02	-.304+01	.000	.000	.240+02
10	5	1.8756	[illegible]	.106-03	.106-03	.233+02	-.205 01	.000	.000	.206+02
10	6	1.5828	[illegible]	.847-04	.847-04	.215+02	-.139+01	.000	.000	.201+02
10	7	1.0958	[illegible]	.529-04	.529-04	.174+02	.190-00	.000	.000	.176+02

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

IN-DEPTH DATA

ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE
1	1	1898.26	1	2	1882.26	1	3	1866.76	1	4	1853.00	1	5	1842.99
2	1	1923.86	2	2	1905.42	2	3	1890.80	2	4	1876.63	2	5	1866.30
3	1	1951.61	3	2	1939.61	3	3	1928.42	3	4	1913.82	3	5	1902.84
4	1	1985.57	4	2	1984.37	4	3	1978.19	4	4	1964.07	4	5	1951.02
5	1	2024.69	5	2	2036.25	5	3	2038.25	5	4	2027.51	5	5	2011.26
6	1	2066.41	6	2	2088.60	6	3	2099.17	6	4	2089.80	6	5	2071.28
7	1	2112.93	7	2	2139.76	7	3	2154.45	7	4	2146.67	7	5	2128.13
8	1	2529.67	8	2	2565.51	8	3	2587.56	8	4	2588.13	8	5	2583.95
9	1	3359.41	9	2	3394.90	9	3	3436.15	9	4	3457.37	9	5	3459.44
10	1	4095.78	10	2	4156.48	10	3	4208.52	10	4	4233.71	10	5	4229.27

1	6	1836.46	1	7	1833.43
2	6	1859.50	2	7	1856.45
3	6	1895.65	3	7	1892.88
4	6	1942.42	4	7	1938.98
5	6	1999.38	5	7	1991.75
6	6	2055.58	6	7	2044.89
7	6	2109.46	7	7	2098.48
8	6	2549.86	8	7	2503.90
9	6	3397.38	9	7	3329.13
10	6	4155.49	10	7	4057.08

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OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

********** (2.0) SECONDS **********

GENERAL

TIME	QTOT.SUR	QTOT.INT	CNSV ENER	CRNODE	ITER	NODE D-TIME	ACT D-TIME
.3200+02	.1700-03	.1699+03	.1000+01	6 1	1568	.35342-01	.35344-01

HEATED SURFACE

-------MISCELLANEOUS SURFACE DATA-------

ROW	COL	OPTN	SURF ITER	SURF TEMP(R)	H EDGE (BTU/LB)	H WALL (BTU/LB)	B PRIME TOT	MASS COEFF (LB/FT2-SEC)	CM/CHO	PRESSURE (ATM)	RADIUS (IN)	Z'
10	1	3	3	2797.2	.00	.00	.0000	.00000	.00000	.100-05	.812-00	.752-01
10	2	3	3	2835.2	.00	.00	.0000	.00000	.00000	.100-05	.736-00	.242-00
10	3	3	3	2880.7	.00	.00	.0000	.00000	.00000	.100-05	.674-00	.436-00
10	4	3	3	2911.9	.00	.00	.0000	.00000	.00000	.100-05	.635-00	.635-00
10	5	3	3	2924.0	.00	.00	.0000	.00000	.00000	.100-05	.622-00	.820-00
10	6	3	3	2916.1	.00	.00	.0000	.00000	.00000	.100-05	.632-00	.994-00
1	7	3	3	2891.9	.00	.00	.0000	.00000	.00000	.100-05	.659-00	.115+01

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--------SURFACE RATE QUANTITIES--------

-LOCATION-		--RECESSION RATES-- (MILS/SEC)		--MASS RATES-- (LB/FT2-SEC)		--SURFACE ENERGY FLUX RATES-- (BTU/FT2-SEC)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	.000000	.000000	.000	.000	.000	.000	.000	.000	.148-04
10	2	.000000	.000000	.000	.000	.000	.000	.000	.000	.145-04
10	3	.000000	.000000	.000	.000	.000	.000	.000	.000	.288-04
10	4	.000000	.000000	.000	.000	.000	.000	.000	.000	.000
10	5	.000000	.000000	.000	.000	.000	.000	.000	.000	.221-04
10	6	.000000	.000000	.000	.000	.000	.000	.000	.000	.139-04
10	7	.000000	.000000	.000	.000	.000	.000	.000	.000	.139-04

-----SURFACE TIME INTEGRATED QUANTITIES-----

		--RECESSION TOTALS-- (MILS)		--MASS ABLATION TOTALS-- (LB/COL)		--SURFACE ENERGY FLUX TOTALS-- (BTU/COL)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	1.0677	1.0677	.769-04	.704-04	.242+02	.418+01	.000	.000	.284+02
10	2	1.2626	1.2626	.918-04	.918-04	.253+02	.428+01	.000	.000	.296+02
10	3	1.4824	1.4824	.105-03	.105-03	.245+02	.397+01	.000	.000	.284+02
10	4	2.0158	2.0158	.125-03	.125-03	.280+02	-.361+01	.000	.000	.244+02
10	5	1.8756	1.8756	.14[illegible]-03	.14[illegible]-03	.236+02	-.262+01	.000	.000	.210+02
10	6	1.5828	1.5828	.[illegible]	.647-04	.218+02	-.136+01	.000	.000	.204+02
10	7	1.0958	1.0958	.[illegible]	.530-04	.176+02	.215-00	.000	.000	.178+02

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

****-DEPTH DATA****

ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE
1	1	2014.92	1	2	2002.00	1	3	1988.82	1	4	1976.84	1	5	1967.77
2	1	2030.62	2	2	2019.25	2	3	2007.61	2	4	1995.79	2	5	1986.75
3	1	2050.74	3	2	2043.28	3	3	2035.40	3	4	2024.16	3	5	2015.11
4	1	2071.51	4	2	2072.25	4	3	2069.26	4	4	2059.72	4	5	2049.97
5	1	2093.53	5	2	2102.45	5	3	2105.77	5	4	2099.91	5	5	2089.14
6	1	2115.39	6	2	2129.84	6	3	2138.61	6	4	2135.00	6	5	2124.10
7	1	2136.98	7	2	2153.75	7	3	2165.[illegible]7	7	4	2163.49	7	5	2153.56
8	1	2310.05	8	2	2331.65	8	3	2349.29	8	4	2358.72	8	5	2361.18
9	1	2619.72	9	2	2641.61	9	3	2677.38	9	4	2705.41	9	5	2715.70
10	1	2797.19	10	2	2835.18	10	3	2880.65	10	4	2911.89	10	5	2923.96
1	6	1961.64	1	7	1958.65									
2	6	1980.49	2	7	1977.43									
3	6	2008.71	3	7	2005.76									
4	6	2042.83	4	7	2039.20									
5	6	2080.27	5	7	2073.84									
6	6	2113.49	6	7	2105.34									
7	6	2141.97	7	7	2133.89									
8	6	2347.40	8	7	2325.62									
9	6	2702.78	9	7	2683.89									
10	6	2916.09	10	7	2891.68									

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OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

TIME	[illegible]	[illegible]	CNSV CNER	CRNDU ITER	NODE D-TIME	ACT D-TIME
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.35163-01	.35165-01

[illegible]

-------MISCELLANEOUS SURFACE DATA-------

ROW	COL	OPTN	SURF ITER	SURF TEMP (R)	H CLOS (BTU/LB)	H FALL (BTU/LB)	B PRIME TOT	MASS COEFF (LB/FT2-SEC)	CH/CHO	PRESSURE (ATM)	RADIUS (IN)	Z
10	1	3	3	2390.8	.00	.00	.0000	.00000	.00000	.100-05	.812-00	.752-01
10	2	3	3	2398.6	.00	.00	.0000	.00000	.00000	.100-05	.736-00	.242-00
10	3	3	3	2423.2	.00	.00	.0000	.00000	.00000	.100-05	.674-00	.436-00
10	4	3	3	2443.2	.00	.00	.0000	.00000	.00000	.100-05	.635-00	.635-00
10	5	3	3	2455.0	.00	.00	.0000	.00000	.00000	.100-05	.622-00	.820-00
10	6	3	2	2458.4	.00	.00	.0000	.00000	.00000	.100-05	.632-00	.994-00
10	7	3	3	2452.6	.00	.00	.0000	.00000	.00000	.100-05	.659-00	.115+01

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SAMPLE

--------SURFACE RATE QUANTITIES--------

-LOCATION-		--RECESSION RATES-- (MILS/SEC)		--MASS RATES-- (LB/FT2-SEC)		--SURFACE ENERGY FLUX RATES-- (BTU/FT2-SEC)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	.000000	.000000	.000	.000	.000	.000	.000	.000	.149-04
10	2	.000000	.000000	.000	.000	.000	.000	.000	.000	.728-05
10	3	.000000	.000000	.000	.000	.000	.000	.000	.000	.216-04
10	4	.000000	.000000	.000	.000	.000	.000	.000	.000	.292-04
10	5	.000000	.000000	.000	.000	.000	.000	.000	.000	.146-04
10	6	.000000	.000000	.000	.000	.000	.000	.000	.000	.690-05
10	7	.000000	.000000	.000	.000	.000	.000	.000	.000	.138-04

-----SURFACE TIME INTEGRATED QUANTITIES-----

		--RECESSION TOTALS-- (MILS)		--MASS ABLATION TOTALS-- (LB/COL)		--SURFACE ENERGY FLUX TOTALS-- (BTU/COL)				
ROW	COL	CENTER LINE	NORMAL	MDOT TOTAL	MDOT TCHEM	CONVECTED IN	CHEMICAL GENERATION	RADIATION ABSORBED	RADIATION EMITTED	CONDUCTION AWAY
10	1	1.0677	1.0677	.739-04	.739-04	.242+02	.416+01	.000	.000	.284+02
10	2	1.2626	1.2626	.918-04	.918-04	.253+02	.428+01	.000	.000	.296+02
10	3	1.4828	1.4828	[illegible]	.105-03	.245+02	.397+01	.000	.000	.284+02
10	4	2.0158	2.0158	[illegible]	.125-03	.260+02	-.361+01	.000	.000	.244+02
10	5	1.8756	1.8756	[illegible]	[illegible]	.236+02	-.262+01	.000	.000	.210+02
10	6	1.5828	1.5828	[illegible]	.849-04	.215+02	-.136+01	.000	.000	.204+02
10	7	1.0958	[illegible]	[illegible]	[illegible]	.17[illegible]+02	.215-00	.000	.000	.178+02

OUTPUT, SAMPLE PROBLEM 1 (CONTINUED)

[illegible]

ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE	ROW	COL	TEMPERATURE
1	1	2058.64	1	2	2[illegible].70	1	3	2042.15	1	4	2034.05	1	5	2027.59
2	1	2066.25	2	2	2[illegible].52	2	3	2052.18	2	4	2044.51	2	5	2038.34
3	1	2075.77	3	2	2071.44	3	3	2066.50	3	4	2059.59	3	5	2053.74
4	1	2085.36	4	2	2[illegible].30	4	3	2083.23	4	4	2077.65	4	5	2071.85
5	1	2095.26	5	2	2[illegible].15	5	3	2100.37	5	4	2097.03	5	5	2091.14
6	1	2104.68	6	2	2111.23	6	3	2115.09	6	4	2113.13	6	5	2107.58
7	1	2113.98	7	2	2121.39	7	3	2126.47	7	4	2125.67	7	5	2120.85
8	1	2185.52	8	2	2195.22	8	3	2203.76	8	4	2209.23	8	5	2211.38
9	1	2310.53	9	2	2[illegible].82	9	3	2339.22	9	4	2355.19	9	5	2363.81
10	1	2380.80	10	2	2398.57	10	3	2423.15	10	4	2443.19	10	5	2454.99
1	6	2023.00	1	7	2020.58									
2	6	2033.83	2	7	2[illegible].45									
3	6	2049.39	3	7	2047.16									
4	6	2067.38	4	7	2064.89									
5	6	2086.12	5	7	2082.37									
6	6	2102.01	6	7	2097.61									
7	6	2115.08	7	7	211[illegible].89									
8	6	2206.36	8	7	2197.33									
9	6	2362.33	9	7	2356.76									
10	6	2458.39	10	7	2452.56									

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OUTPUT, SAMPLE PROBLEM 1 (CONCLUDED)

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APPENDIX A

MULTIPLE ABLATING MATERIALS CAPABILITY

More than one material may appear on the surface at a given time, and the materials exposed may change with time (e.g., one material is ablated away, exposing a new material). Since the multiple ablating material feature is seldom used, the instructions for it have been collected in this appendix.

Use of the multiple ablating materials capability in Option 1 calculations requires special input information for surface thermochemistry table assignments. Each pressure table must be assigned to a material identification number, so that the specific heat of the proper ablating material can be integrated into the surface thermochemistry. Furthermore, a heat of formation must be input for each ablating material. These assignments have all been relegated to the surface thermochemistry deck lead card (see Section 3.1.9.2). Columns 51-80 of this card are divided into five fields each of I1, F5.0 format which are to contain the following information:

I1 Material number for which $c_p(T)$ will be taken for amalgamation into surface thermochemistry calculatons

F5.0 Heat of formation (Btu/lb at 536°R) to be used in this amalgamation

The five material number and heat of formation assignments will be as assigned by the ASTHMA3 program as needed to the following pressure tables (up to five in number). A blank material number calls for the use of $c_p(T)$ of material number one and of the heat of formation entered in columns 37-42 of the first numerical data card (see Section 3.1.2).

Since many different nodes may be assigned to a given thermochemistry table (pressure), and any material may appear in a given node, then (since a given thermochemistry table is assigned to a given node) it is possible to in effect assign the same thermochemistry table to different materials. The input conventions described above serve to remind the user that he must choose one $c_p(T)$ to assign, and one heat of formation for a given table. Therefore, if more than one material is assigned (through nodal assignments) to a given thermochemistry table, these materials must, for overall problem consistency, be thermodynamically identical (i.e., have the same $c_p(T)$ and heat of formation).

Such materials may, however, have different thermal conductivities or different densities.

Note that for a problem with a single ablating material, it is most convenient to number this material as number one. Columns 51-80 of the lead card are then left blank, and the heat of formation is entered in columns 37-42 of the first numerical data card.