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**A USER'S GUIDE FOR THE CONTINUOUS WAVE
LASER DAMAGE COMPUTER PROGRAM**

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DECEMBER 1974

Technical Memorandum

**A USER'S GUIDE FOR THE
CONTINUOUS WAVE LASER
DAMAGE COMPUTER PROGRAM**

by R. W. NEWMAN

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1. INTRODUCTION AND SUMMARY

Recent progress in the development of high power lasers has evolved lasers capable of causing thermal damage to material surfaces. In order to adequately evaluate the effects of material properties and laser beam characteristics on material damage, a reliable analytical model is needed. After reviewing many of the available analytical models, it was found that most were limited to one-dimensional heat conduction, constant thermal properties, constant irradiation, and no radiation relief or aerodynamic cooling. In many flight applications these effects are significant. Therefore, extensive modifications have been made to the APL finite difference heat transfer program (Ref. 1) to analyze laser heating of flight vehicles. This new program is known as the Continuous Wave Laser Damage Computer Program (CLAD). It computes mass loss and temperature histories of laser heated bodies accounting for three-dimensional conduction, temperature dependent thermal properties, vaporization, melting, chemical reactions, aerodynamic heating, radiation relief, and material removal.

The APL/BBE Continuous Wave Laser Damage Computer Program (CLAD) uses finite difference techniques to predict temperature histories in laser heated materials. The program is written in PL/I computer language, and includes: (a) three-dimensional conduction, (b) thermal properties as functions of temperature (thermal conductivity, thermal capacitance, absorptivity, and emissivity), (c) radiation relief, (d) latent heat of fusion, and (e) laser irradiation of each surface element specified as a function

Ref. 1. D. W. Fox, H. Shaw, and J. Jellinek, "Numerical Approximations in Heat Transfer Problems and Usage of IBM 7090 Computer for Solutions," APL/JHU CF-2954, 17 May 1962.

of time, with an option to specify irradiation by a moving Gaussian beam. CLAD has recently been expanded to include: (a) aerodynamic heating and cooling, (b) material vaporization, (c) chemical reactions at the surface, (d) material removal of vaporized and ablated elements, and (e) cylindrical elements.

This report has been written as a user's manual for the CLAD program and includes an overview of the program, a discussion of assumptions and limitations, a main program description and a sample problem.

2. OVERVIEW OF CLAD CALCULATIONS

The following discussion presents a brief overview of calculations performed in CLAD, and is followed by detailed discussions of: (a) the surface energy balance, (b) time step calculations, (c) corrections for blowing, (d) an option for mechanical erosion, and (e) assumptions and limitations.

The CLAD computer program is a finite difference program written for analysis of laser heated plates and cylinders. The program includes radiative and convective heating with heat relief via radiation and conduction. In addition, the program can account for in-depth melting and material removal at the heated surface. The material removal process can be via vaporization or chemical reactions at the surface. The vaporization process occurs at a specific temperature and heat of vaporization, while the chemical reactions occur over a range of surface temperatures and either absorb or release heat at a rate dependent on the surface temperature and the chemical nature of the ablating material.

A pictorial view of some of the parameters included in CLAD is presented in Fig. 1. The program computes a surface temperature (T_w) of each zero volume surface node, by iteratively solving an energy balance at the surface. For ablating surfaces the surface energy balance includes a chemical heating term which is obtained from the Equilibrium Surface Thermochemistry Program (EST) (Ref. 2), as a function of surface temperature and local pressure. Following computation of the surface temperature, CLAD computes the ablation mass loss rate as a function of the surface temperature and local pressure. Capacitances of all finite volume elements (2 and 3) are then computed as functions of temperature, and conduction heating rates are computed

Ref. 2. "User's Manual, Aerotherm Equilibrium Surface Thermochemistry Program," Version 3, Aerotherm Corporation, Mountain View, California, Report UM-70-13, May 1970.

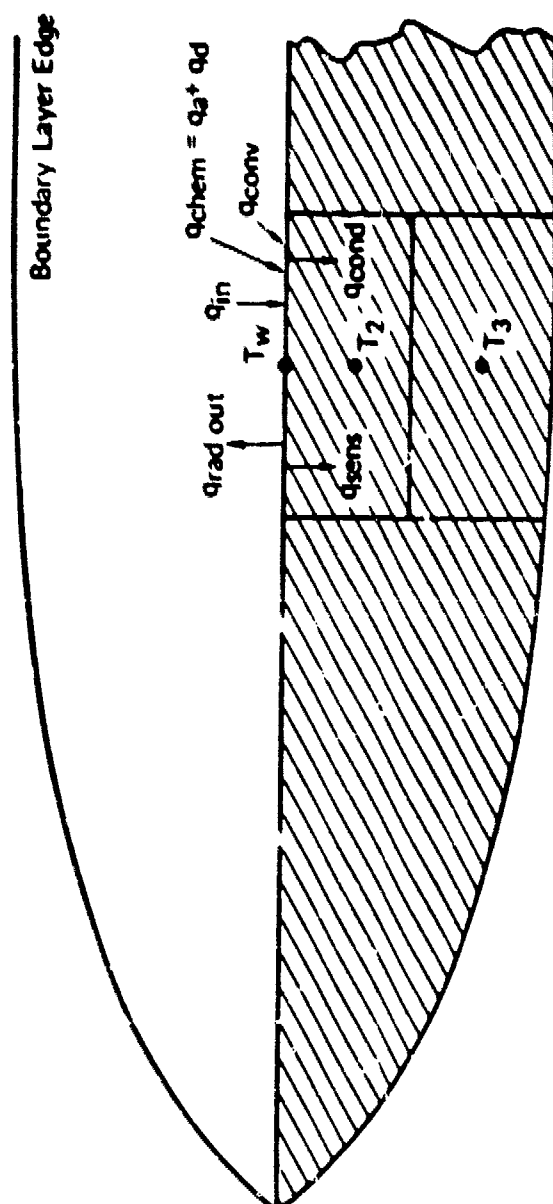


Fig. 1 CLAD Surface Energy Model

between adjacent nodes. A critical stability time step is then used to compute node temperatures at the next time step. Corresponding surface temperatures are then computed for the zero volume surface elements, and the above calculations are repeated for the next time step. This sequence continues until the end time is reached.

SURFACE ENERGY BALANCE

The chemical reaction model used in CLAD is the same as used in Ref. 3. In this model (Fig. 1) the surface energy balance per unit area is:

$$q_{in} + q_{chem} + q_{conv} + q_{cond} - q_{rad\ out} - q_{sens} = 0. \quad (1)$$

Looking at the individual terms, the incoming heat rate (q_{in}) is made up of laser heating and radiative heating as follows:

$$q_{in} = \left[(q_{las}) (VIEW) + q_{rad\ in} \right] ALPHA_w. \quad (2)$$

where:

- q_{las} is the incident laser heat flux per unit area,
- VIEW is a view factor to account for angular beam impingement,
- $q_{rad\ in}$ is an incident radiation heat flux per unit area, and
- $ALPHA_w$ is the surface absorptivity evaluated at T_w .

Ref. 3. "User's Manual Aerotherm Charring Material Thermal Response and Ablation Program," Version 3, Aerotherm Corporation, Mountain View, California, Report RM-70-14, April 1970.

Like all such models, the model used to obtain q_{chem} is an approximation. A discussion of its validity is beyond the scope of this report but has been made in Refs. 4 and 5. In this model (Fig. 1) free stream gases diffuse through the boundary layer to the surface, where they react with the ablating material and either release or absorb heat. The resulting gases are then removed from the surface via diffusion and convective mass transfer into the boundary layer. Appendix A presents a derivation of the chemical heating rate (q_{chem}) in terms of diffusion and mass transfer rates.

However, the chemical reaction model contains several important assumptions, which are:

1. All chemical reactions take place at the wall and no reactions occur in the boundary layer.
2. No solid reactants are produced at the wall and no ablative material leaves the surface due to mechanical erosion. For special cases where ATJ graphite is used, mechanical erosion can be included (see Mechanical Erosion Option later in this Section).
3. There is no pyrolysis within the ablative material; all pyrolysis is confined to the surface.

Ref. 4. C. B. Moyer and R. A. Rindall, "Finite Difference Solution for the In-Depth Response of Charring Materials Considering Surface Chemical and Energy Balances," Aerotherm Corporation Final Report 66-7, Part II, 14 March 1967 (also NASA CR-1061, June 1968).

Ref. 5. E. P. Bartlett and R. D. Grose, "An Evaluation of a Transfer Coefficient Approach for Diffusion Coefficients," Aerotherm Corporation, Mountain View, California, Report 69-50, 30 June 1969.

4. Gases diffuse through the boundary layer according to their mass concentrating gradients and these gradients are assumed linear through the boundary layer.
5. There is no thermal diffusion of gases in the boundary layer.

The chemical heating term (q_{chem}) of Eq. (1) is made up of two parts. The first term (q_d) is the rate of energy release due to diffusing gases reacting at the surface. In this process, each free stream specie i diffuses through the boundary layer to the surface where it reacts with the surface and releases heat. The product specie i then leaves the surface at a total enthalpy ($\Delta H_{i,w}$) different than it had on arrival. This heating rate is expressed as:

$$q_d = \rho_e U_e (C_m)_b \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} \quad (3)$$

where:

$$\rho_e U_e (C_m)_b \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \quad \text{is the diffusion}$$

mass flow rate of specie i arriving at a unit surface area,

$(C_m)_b$ is the mass transfer Stanton number $(m_d/\rho_e U_e \Delta Z)_b$, corrected for blowing as shown later in this Section (Blowing Rate Correction), with ΔZ = the diffusion driving potential which produces the diffusion mass flow rate (m_d) into the surface,

$Z_{i,e}$ and $Z_{i,w}$ are the diffusion driving potentials for the i th specie diffusing through the boundary layer to the

surface ($Z_{i,e}$ is the potential at the boundary layer edge and $Z_{i,w}$ is the potential at the wall), and

$\Delta H_{i,w}$ is the enthalpy change of each diffusing specie due to its reaction with the surface material ($\Delta H_{i,w} = H_{i,w} - \bar{H}_{rg,w}$).

The second part of the q_{chem} term represents the rate of energy released (q_a) by the ablating material as it changes from a solid ablative to reacted gases:

$$q_a = \rho_e U_e (C_m)_b \beta (H_{a,w} - \bar{H}_{rg,w}), \quad (4)$$

where

$\rho_e U_e (C_m)_b \beta$ is the ablation rate (m_a)

β is the ablation to diffusion mass flux ratio defined as $\beta = m_a / \rho_e U_e (C_m)_b$.

$H_{a,w}$ is the total enthalpy (above T_{ref}) of the solid ablative material evaluated at the wall temperature (T_w), and

$\bar{H}_{rg,w}$ is the total enthalpy (above T_{ref}) of the gaseous reactants evaluated at T_w ($\bar{H}_{rg,w}$ is the sum of the chemical and sensible enthalpy of the gases and is averaged according to the mass fraction of each gas present at the surface).

Hence, the total chemical heating term is:

$$q_{chem} = q_a + q_d = \rho_e U_e (C_m)_b \left[\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \bar{H}_{rg,w}) \right]. \quad (5)$$

In Eq. (1) the convective heat transfer term is:

$$q_{\text{conv}} = \rho_e U_e (C_H)_b (H_r - \bar{H}_{e,w}), \quad (6)$$

where:

- $\rho_e U_e (C_H)_b$ is the enthalpy based heat transfer coefficient corrected for blowing as will be discussed later,
- $(C_H)_b$ is the heat transfer Stanton number corrected for blowing,
- H_r is the total recovery enthalpy (above T_{ref}), and
- $\bar{H}_{e,w}$ is the total enthalpy (above T_{ref}) of the gases at the boundary layer edge and evaluated at the wall temperature.

The convective heat flux is more usually written in the form:

$$q_{\text{conv}} = \rho_e U_e (C_H)_b (h_r - h_w), \quad (7)$$

where:

- h_r and h_w are the sensible recovery and wall enthalpies, respectively.

The derivation of Eq. (6) from Eq. (7) is given in Refs. 4 and 6.

Ref. 6. R. M. Kendall, R. A. Rindall, and E. P. Bartlett, "A Multicomponent Boundary Layer Chemically Coupled to an Ablating Surface," AIAA Journal, Vol. 5, No. 6, June 1967, pp. 1063-1071.

For unity Lewis number, q_{chem} and q_{conv} can be combined and simplified. When the Lewis number equals 1, the mass and thermal boundary layers are coincident in space and $Z_{i,e}$ is evaluated at the thermal boundary layer edge. Hence:

$$(C_H)_b = (C_m)_b.$$

and

$$(C_m)_b \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} = (C_H)_b \left[\bar{H}_{e,w} - \bar{H}_{rg,w} \right].$$

For the unity Lewis number:

$$q_{\text{conv}} + q_{\text{chem}} = \rho_e U_e (C_H)_b \left[(H_r - \bar{H}_{rg,w}) + \beta (H_{a,w} - \bar{H}_{rg,w}) \right]. \quad (8)$$

where the heat transfer coefficient $\rho_e U_e (C_H)$ and recovery enthalpy H_r are time dependent variables input by the user. The heat transfer coefficient is automatically adjusted for blowing as is discussed later in this Section. The quantity $H_{a,w}$ is obtained from a utility program which computes $H_{a,w}$ as a function of wall temperature as follows:

$$H_{a,w} = \int_{T_{\text{ref}}}^{T_w} \frac{(\rho c_p)}{\rho} dT. \quad (9)$$

The remaining terms in Eq. (8) are obtained from the Equilibrium Surface Thermochemistry Program (EST) (Ref. 2). For unity Lewis number EST supplies T_w and $\bar{H}_{rg,w}$ as tabular functions of local pressure (P_L) and the ablation to diffusion ratio (β). As part of the CLAD program, a utility subroutine accepts EST output directly and converts it to tables of $\bar{H}_{rg,w}$, $\beta (H_{a,w} - \bar{H}_{rg,w})$, and β as functions of P_L and T .

For Lewis numbers not equal to 1, q_{chem} and q_{conv} are as presented in Eqs. (5) and (6), and the EST program

supplies T_w , $\bar{H}_{rg,w}$, $\bar{H}_{e,w}$, and $\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$

as tabular functions of P_L and β . The utility subroutine accepts this data directly and converts it to tables of

$\bar{H}_{rg,w}$, $\bar{H}_{e,w}$, $\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \bar{H}_{rg,w})$,

and β as functions of P_L and T_w .

The remaining terms in Eq. (1) are:

$$q_{\text{cond}} = \frac{K_{w-2}}{L_{w-2}} (T_2 - T_w),$$

$$q_{\text{rad out}} = F \sigma \epsilon_w (T_w^4 - T_{sp}^4), \text{ and}$$

$$q_{\text{sens}} = m_a (h_{a,w} - h_{a,2}),$$

where:

K_{w-2} is the material thermal conductivity evaluated at $(T_w + T_2)/2$,

L_{w-2} is the conduction path length from the wall to node 2,

F is a view factor,

σ is the Stefan-Boltzman constant,

ϵ_w is the surface emissivity, and

q_{sens} is the sensible energy required to raise the ablating material from temperature T_2 to surface temperature T_w .

In Ref. 3 this is referred to as the "velocity term."

TIME STEP CALCULATIONS

At the beginning of time step a , Eq. (1) is solved iteratively for surface temperatures at time τ_a . For ablating surfaces the ablation to diffusion ratio (β) is found from tables as a function of T_w and P_L . β is then used to find the ablation mass loss rate per unit area from:

$$m_a = \beta \left[(\rho_e U_e (C_m)_b) \right] ,$$

where:

$$\rho_e U_e (C_m)_b = \rho_e U_e (C_H)_b (C_m / C_H) ,$$

and $\rho_e U_e C_H$ is input as a function of time and corrected for blowing as will be shown later. C_m / C_H is also an input value.

For surfaces that are vaporizing instead of chemically ablating, the surface energy balance becomes:

$$q_{in} + q_{conv} + m_a Q_{vap} + q_{cond} - q_{rad\ out} - q_{sens} = 0, \quad (10)$$

where Q_{vap} is the heat of vaporization per pound of material. By setting the surface temperature equal to the vapor temperature, Eq. (10) is used to compute m_a .

Following computation of m_a , the CLAD program computes heat conduction between elements and elemental capacitances. These values are then used in the Dusenberre stability equation (Ref. 7) to find the stability time step which equals 90% of the smallest value of:

$$\frac{(\rho c_p V)_i}{\sum_j \left(\frac{KA}{L} \right)_{ij}} ,$$

Ref. 7. G. M. Dusenberre, Heat Transfer Calculations by Finite Differences, International Textbook Co., Scranton, 1961.

where i is all elements having a capacitance associated with them, and the sum is taken over all elements j connected to i . The temperature of interior elements 2, 3, etc. are then computed at time τ_b . If any element has gone above its melt temperature, then subroutine QFUSON computes the melt depth in each element. If an element has not completely melted, then it is set to the melt temperature. If the element is resolidifying then QFUSON accounts for the heat of fusion and reduces the melt depth accordingly.

The laser surface heating rate (Q_{lag}) is next computed at time τ_b . CLAD then uses the mass loss rate computed at τ_a to determine the volume of element 2 removed during the time interval $\tau_b - \tau_a$. As the volume of element 2 decreases, the stability time step approaches zero. Therefore, after a specified portion of element 2 (usually 50%) has ablated away, the program lumps the remaining portion with element 3. Element 2 then becomes a zero volume surface node and element 1 is removed from the model (as shown at τ_c in Fig. 2). In this manner elements are removed without seriously reducing the stability time step.

As each element shrinks, conduction paths to adjacent elements are also changed. Conduction paths perpendicular to the surface are adjusted according to the distance between elements, assuming the node always remains in the center of each element. It is important to remember, that during mass removal, the location of element 2 is continually moving toward the backface.

Thermal resistance between longitudinally adjacent elements are computed as the sum of the resistances of each element. For example the thermal resistance between elements 2 and 5 in Fig. 2 at τ_b is:

$$\left(\frac{KA}{L}\right)^{-1}_{2-5} = \left(\frac{K_2 A_2}{0.5 L_{2-5}}\right)^{-1} + \left(\frac{K_5 A_5}{0.5 L_{2-5}}\right)^{-1} \quad (11)$$

where the conductivities K_2 and K_3 are evaluated at T_2 and T_5 , respectively. At time τ_c in Fig. 2 the conduction path

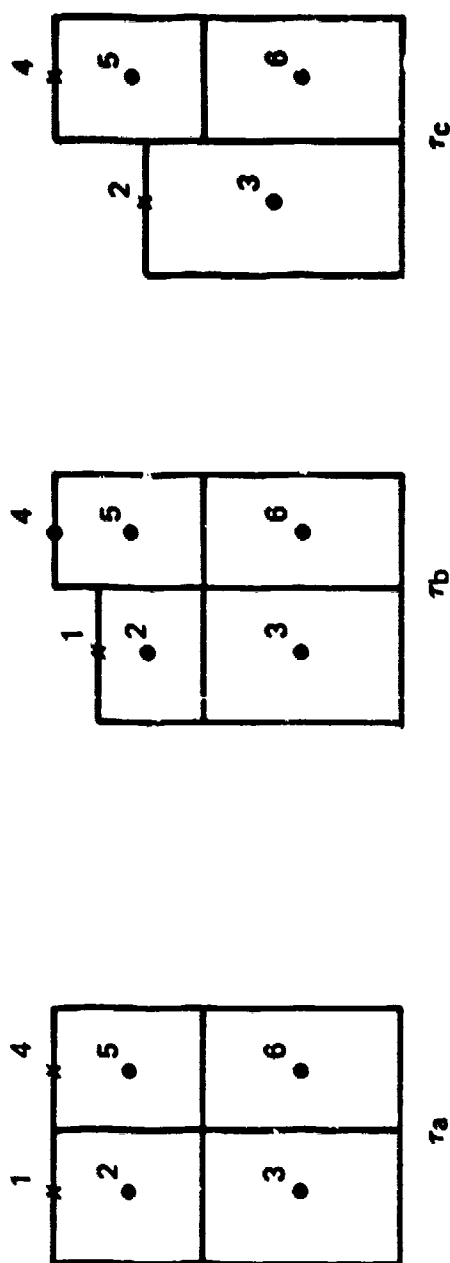


Fig. 2 Schematic of the Node Dropping Process

between elements 3 and 6 is calculated in the same manner as between 2 and 5 in Eq. (11). Notice that even though elements 3 and 5 have a common interface they are not directly connected; however, they are indirectly connected through element 6.

After computing the thermal resistance between ablating elements the program calculates surface temperatures at time τ_b using Eq. (1), as done previously at time τ_a . The procedure is continued computing m_a , T_2 , T_3 , etc. at each time step until the end time is reached.

BLOWING RATE CORRECTION

The CLAD program automatically reduces the heat and mass transfer Stanton numbers (C_H and C_m) to account for the familiar blowing effect according to the equation:

$$(C_H)_b = C_H \frac{\alpha}{e^{\alpha} - 1} \quad (12)$$

where:

$$\alpha = \frac{2\lambda m_a}{\rho_e U_e C_H} \quad (13)$$

and λ is an empirical constant known as the "blowing parameter." Reference 3 recommends that $\lambda = 0.5$ be used for laminar flow and that $\lambda = 0.4$ correlates with turbulent data somewhat better.

The CLAD program computes $(C_m)_b$ from an analogy between heat and mass transfer, where $(C_m)_b = (C_H)_b C_m / C_H$ and the constant ratio C_m / C_H is input to the program.

For graphite, the user has the option of using the Putz and Bartlett correlation (Refs. 8 and 9) instead of Eq. (12). The Putz and Bartlett equations are as follows:

$$(C_H)_b = C_H \left[1.0 - 0.6563 \beta_o + 0.01794 \beta_o^2 + 0.06365 \beta_o^3 - 0.01125 \beta_o^4 \right] \quad (14)$$

and

$$(C_m)_b = C_H \frac{2\lambda\beta}{e^{2\lambda\beta} - 1} \quad (15)$$

where:

$$\beta_o = \beta \frac{(C_m)_b}{C_h} \quad (16)$$

and

$$\lambda = (0.012 + 0.018 \beta_o + 0.0814 \beta_o^2) * (0.762 - 0.038 \beta_o) \quad (17)$$

The user initiates the Putz and Bartlett correlation for graphites by changing CM_CH to a negative value in the CALL ABAROS statement (see Section 3). This also initiates the mechanical erosion option discussed below.

MECHANICAL EROSION OPTION

In the above discussion of CLAD, the ablation mass loss (m_a) is computed assuming no mechanical erosion. At

Ref. 8. K. E. Putz and E. P. Bartlett, "Heat Transfer and Ablation-Rate Correlations for Reentry Heat Shield and Nose Tip Applications," AIAA Preprint Paper No. 72-91, January 1974.

Ref. 9. L. L. Perini, "Heat and Mass Transfer Correlation Equations for Subliming Graphite in High Speed Flow," APL/JHU ANSP-M-11, August 1974.

high temperatures and in a high shear environment, mechanical erosion can become significant. Although CLAD, in general, cannot handle mechanical erosion, it does have a special calculation for ATJ graphite, where the total mass loss rate is the sum of the chemical ablation mass loss rate (m_a) and the mechanical mass loss rate (m_{mech}). In Ref. 10 the m_{mech} is derived from the difference between experimentally measured mass loss data of Lundell and Dickey (Ref. 11) and analytical values computed neglecting mechanical erosion. A curve through the bulk of the points gives:

$$m_{mech} = m_a \left[\frac{314}{4178 - (T_w/1.8)} - 0.155 \right], \quad (18)$$

which is applicable over the temperature range $4500 \leq T \leq 7245^\circ R$ and local stagnation pressure range $0.3 \leq P_L \leq 4.4$ atm. Since no experimental data are available above $7245^\circ F$, m_{mech} is set equal to $1.89 m_a$ at values above $7245^\circ R$. It should be emphasized that the above calculation is only valid for ATJ graphite. The user may initiate the mechanical erosion option by changing CM_CH to a negative number in the CALL ABAR03 statement.

CLAD - ASSUMPTIONS AND LIMITATIONS

There are several assumptions and limitations in CLAD of which the user should be aware. These are discussed in the following paragraphs:

1. The CLAD program is limited to only one ablating material in any given analysis. This restriction can be eliminated in the future if the need arises, but will require some reprogramming.

Ref. 10. L. L. Perini, "Review of Graphite Ablation Theory and Experimental Data," APL/JHU ANSP-M-1, December 1971.

Ref. 11. J. H. Lundell and R. R. Dickey, "Graphite Ablation at High Temperatures," AIAA Preprint Paper No. 71-418, April 1971.

Although CLAD is limited to one ablating material there may be several substrates of different materials as long as these substrates don't ablate. In addition CLAD is restricted to models which either chemically ablate or vaporize but cannot handle models which do both. For one-dimensional models, both these restrictions can be handled by running the program twice. The first run was continuous until the first surface layer is completely ablated, then the second run is made using the second surface material initialized to the temperatures at the end of the first run.

The user should realize that although CLAD is restricted to a single ablative per run, it is not restricted to a single vaporizing material per run. It can have several material layers each vaporizing when it becomes the surface layer.

2. As elements ablate or vaporize the surface temperature fluctuates in a "sawtooth" manner caused by node lumping. This sawtoothing is usually not too severe and may be reduced by using smaller elements (Ref. 12).
3. If during a single time step, a vaporizing surface has not yet melted, then its heat of fusion is ignored for that time step. This is usually not very serious since the heat of vaporization is usually much larger than the heat of fusion.
4. As surface elements ablate the node adjacent to the surface is always located in the center of the element. Hence as the element ablates the node is continually moving towards the backface. This

Ref. 12. J. D. Randall, "A Survey of Possible Node Dropping Methods for Use in the Standard Heat Transfer Program," APL/JHU ANSP-M-10, August 1974.

can sometimes be confusing when plotting a temperature history of this node, since the element location is not constant.

5. No attempt has been made to heat the side of those elements whose neighboring elements have ablated or vaporized.
6. Mass removal, chemical reactions, and vaporization occur only at the surface.
7. The number of different materials is presently limited to nine. If additional materials are required, CLAD could be reprogrammed to handle them.

Although the CLAD analysis contains several assumptions and limitations, it is still quite general and can be utilized for a wide variety of applications. The programming details necessary for implementing CLAD are discussed in the following section.

3. MAIN PROGRAM DESCRIPTION

The CLAD program consists of a series of subroutines called by a main program. A typical main program is as follows:

NAME: PROCEDURE OPTIONS (MAIN)

DECLARE STATEMENTS

CALL STORE

A series of initialization statements
which might include: GET COPY
DATA, GET LIST, CALL READRK,
CALL READTM, CALL READAB,
and CALL RFDCPS

CALL THREEED*

CALL SET

11: IMAX = DECIDE (TIMS, IOX, TIMEI)*

CALL GAUSBM*

CALL QFUSON*

CALL ABAROS

CALL CAPCN3

CALL WRITE

CALL STEP

*These statements are optional.

GO TO 11

END NAME

The order in which the above subroutines are called is very important and should be exactly as shown for the program to function correctly.

A complete description of each section of the main program is presented below. In reading this material, the reader may find it helpful to refer to Appendix B, which presents the main program used to analyze a sample problem discussed later in the text.

1. NAME: PROCEDURE OPTIONS (MAIN) defines procedure NAME as the main program.

2. DECLARE STATEMENTS define all variables and subroutines used in the main program. All subroutines are declared as entry points using DCL ENTRY statements exactly as they appear in the sample problem in Appendix B. In addition all variable names used in the program are declared with the following attributes: FIXED or FLOAT; BINARY or DECIMAL; AUTOMATIC, STATIC, CONTROLLED, or EXTERNAL; and double or single precision. The following variable names must be declared EXTERNAL and must always appear in the declare statements QVAPOR(*), TVAP(*), RO(*), and AIRPRNT. Additional variables declared EXTERNAL for GAUSBM or QFUSON are: IMAX, QMELT(*), TIMS, TMELT(*), and NDX (20,20). In addition variable names QVAPOR, TVAP, QMELT, TMELT, and RO are specified as CONTROLLED and must be assigned array lengths in an ALLOCATE statement. The array length is equal to the number of vaporizing materials. These variable names are defined as follows:

QVAPOR	is an array defining the latent heat of vaporization for each material assigned thermal properties in READRK, where the subscript of QVAPOR is
--------	--

	the index defining the material (FLOAT BINARY) (Btu/lb),
TVAP	is an array of corresponding vapor temperatures (FLOAT BINARY) ($^{\circ}$ R); <u>TVAP(*) is zero if material I ablates with a chemical reaction instead of vaporizing.</u> (In addition, for cases with vaporization, $\bar{H}_{rg}$ is set to air enthalpy values in the input to READAB. Hence CLAD is restricted to models which either vaporize or chemically ablate, and cannot handle models with both),
QMELT	is an array defining the latent heat of fusion for each material assigned thermal properties in READRK, where the subscript of QMELT is the index defining the material (FLOAT BINARY) (Btu/lb),
TMELT	is an array of corresponding melt temperatures (FLOAT BINARY) ($^{\circ}$ R), and
RO	is an array of corresponding densities (FLOAT BINARY) (lb/ft ³).

The attributes assigned to other variables in the declare statements are discussed below as they are encountered in the program.

3. CALL STORE (LASCAP, LASCAP, 3) specifies all allocatable variables as arrays of length LASCAP, and

initializes them to 0.0. LASCAP is a fixed binary number equal to the largest capacitor number used in the program. The "3" informs STORE to allocate variables used in routines THREED, QFUSON, ABAROS, and CAPCN3.

4. If variable names are not assigned initial values in the above DECLARE statements, they are given values in one of several ways. One of these is through an assignment statement such as $X = 10$; Another is through GET statements such as GET LIST (X); or GET COPY DATA. If the variables are a function of temperature then they should be initialized by calling subroutine READRK as follows:

```
CALL READRK (I, IND, D1, D2, D3, D4, NI,  
INFILE);
```

where:

I	is an index (FIXED BINARY),
IND	the name of the table containing values for the independent temperature variable (FLOAT BINARY array of length NI+1) (°R),
D1, D2, D3, D4	are variable names of tables for the first, second, third, and fourth temperature dependent variables (FLOAT BINARY numbers of length NI),
NI	is a number identifying the length of the tables (FIXED BINARY), and
INFILE	is the data file from which the tables are to be read (this variable is declared as a

FILE in the declare statements above. If the input is to be read from data cards then INFILE is SYSIN, (FILE)).

Data cards required for READRK are as follows:

Two comment cards, followed by NI cards, each containing the appropriate values for:

IND in columns 1 to 14	}	All in F-Format
D1 in columns 15 to 29		
D2 in columns 30 to 44		
D3 in columns 45 to 59		
D4 in columns 60 to 75		

Thermal properties of each material must be initialized by a call to READRK, where:

I	is a unique number from 1 to 9 identifying the material,
IND	is temperature ($^{\circ}\text{R}$),
D1	is the product of density and specific heat ($\text{Btu}/\text{ft}^3 \cdot ^{\circ}\text{R}$),
D2	is thermal conductivity ($\text{Btu}/\text{ft} \cdot \text{h} \cdot ^{\circ}\text{R}$),
D3	is surface emissivity, and
D4	is surface absorptivity.

Thermal contact conductances must also be input via READRK, where:

I	is a number from 1 to 9 identifying the conductance table (this number must be different from that used for material property tables and other conductance tables),
IND	is temperature ($^{\circ}\text{R}$),
D1	is a dummy variable or another variable with dependence on temperature,
D2	is contact conductance ($\text{Btu}/\text{ft}^2 \cdot \text{h} \cdot ^{\circ}\text{R}$),
D3 and D4	are dummy or other variables.

Output from READRK includes the two comment cards and numerical values assigned to each argument.

5. CALL READTM (I, IND, D1, D2, D3, D4, D5, NI, INFILE); reads time dependent variables, where:

I	is an index defining the READTM statement (FIXED BINARY),
IND	is an array containing values for the independent time variable (FLOAT BINARY array of length NI+1) (seconds),
D1, D2, D3, D4, D5	are arrays of the first, second, third, fourth, and fifth dependent variables (FLOAT BINARY arrays of length NI),

NI

is the length of the above
arrays (FIXED BINARY),
and

INFILE

is the data file from which
above arrays are to be read
(this variable is declared as
a FILE in the declare state-
ments. If input is read from
data cards then INFILE is
SYSIN (FILE)).

Data cards required for READTM are as follows:

Two comment cards, followed by NI cards, each con-
taining values for:

IND in columns 1 to 9

D1 in columns 10 to 19

D2 in columns 20 to 29

D3 in columns 30 to 39

D4 in columns 40 to 49

D5 in columns 50 to 59

All in F-Format

6. CALL READAB - Subroutine READAB per-
forms two basic functions. First it computes the enthalpy of
the ablative material in its solid state. This is accomplished
by trapezoidal integration of the capacitance/density versus
temperature curve. The second operation of READAB is to
read the thermochemistry data supplied by the EST program
(Ref. 2). The subroutine reads this thermochemistry data,
changes it to the appropriate units, and adapts it to the form
required by subroutine ABAR03. For a Lewis number not
equal to 1 the conversion process is as follows. The EST
program provides values of gas temperature ($T_{rg,w}$), gas

enthalpy at the surface ($\bar{H}_{rg,w}$), the enthalpy of the gas constituents at the boundary layer edge evaluated at the wall temperature ($\bar{H}_{e,w}$), and the chemical activity function

$$\left(\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} \right), \text{ all as tabular functions of gas}$$

pressure (P_L) and the ablation to diffusion mass loss ratio (β). The EST data is expressed in calories, grams, and °K. READAB has as a parameter the conversion factor required to covert these values to Btu, lbm, and °R. Furthermore, the routine computes $\log_{10} \beta$, $\bar{H}_{rg,w}$, $\bar{H}_{e,w}$, and "QCHEM" as functions of P_L and T_w , where:

$$\text{"QCHEM"} = \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \bar{H}_{rg,w}).$$

Notice that $q_{chem} = \rho u (C_m)_b \text{"QCHEM"}$. The values of T_w used in this table are specified in the parameters of READAB.

For a Lewis number equal to 1, READAB converts EST values as follows. The EST program provides values of T_w and $\bar{H}_{rg,w}$ as functions of P_L and β . The data is converted to units of Btu, lbm, and °R. In addition READAB also computes $\log_{10} \beta$, $\bar{H}_{rg,w}$, and "QCHEM" as functions of P_L and T_w , where values of T_w are specified by parameters READAB and "QCHEM" = $\beta (H_{a,w} - \bar{H}_{rg,w})$. Notice that in this case "QCHEM" is a misnomer since it is really a portion of q_{conv} and q_{chem} (Eq. (8)), and cannot be related to q_{chem} alone.

In its output READAB prints the ablative material enthalpy ($H_{a,w}$) Eq. (9), as a function of temperature (T_w). It also prints both the dimensionally converted input data from EST as functions of P_L and β , and the reformat data as functions of P_L and T_w . Occasionally one may not wish to have these tables printed in the output as they can be quite lengthy. If so, the following statement is placed in the main program:

DCL AIRPRNT INIT(0) FIXED BIN EXT;

Subroutine READAB is invoked by the calling sequence:

```
CALL READAB (#PL, #BETA, LEW#,  
RHO, RHOC, TEMP, TWMIN, TWMAX,  
TWINC, CONV, INFILE);
```

where:

#PL	specifies the number of pressure entries being supplied by the EST program (FIXED BIN),
#BETA	specifies the number of ablation to diffusion mass loss ratio (β) values being supplied by the EST program at each value of pressure (FIXED BINARY),
LEW#	is the Lewis number (FLOAT BINARY),
RHO	is the surface material density (FLOAT BINARY) (lbm/ft ³),
RHOC, TEMP	is a list of density times specific heat values for the surface material (from which values of $H_{a,w}$ are calculated) (the values correspond to temperatures in the list TEMP (FLOAT BINARY) (Btu/ft ³ , °R); the length of array TEMP is one greater than array RHOC),
TWMIN, TWMAX, and TWINC	are constants that specify the beginning value of temperature, the ending value of temperature, and the increment of temperature between these limits for the variable

T_w , which is used in converting EST data from function of P_L and β to functions of P_L and T_w .

CONV

is the conversion factor required to convert input data to $^{\circ}\text{R}$. If data is in $^{\circ}\text{K}$ and cal/g, then CONV = 1.8; otherwise CONV = 1.0 and input data have units of $^{\circ}\text{R}$ and Btu/lbm (FLOAT BINARY), and

INFILE

is the data file from which input to READAB is to be read (if input is read from data cards then INFILE is SYSIN (FILE)).

READAB automatically assumes an enthalpy reference temperature (T_{ref}) of 536°R . If a different value is desired the user may declare TREF as FLOAT BIN EXT in the main program and assign it the appropriate value in $^{\circ}\text{R}$.

In addition to the above arguments READAB also receives information from data cards or a data tape. These data consist of: two commentary cards followed by chemical data tables obtained from the EST program. The data are formatted as follows: First there are #BETA cards defining chemical data at a given local pressure (P_L) as a function of β . This set of cards is followed by subsequent sets defining chemical data at other local pressure levels. Hence for each local pressure there are #BETA cards and there are #PL pressures, i.e., #PL*#BETA data cards in the table. #BETA and #PL must be greater than 1.

The data included on each card depend on the Lewis number. If LEW# = 1 then each card contains the following, in F-format:

	<u>Column</u>	<u>Units</u>
P_L	1 to 13	atmospheres
β	14 to 26	none
T_w	27 to 39	$^{\circ}\text{C}$ or $^{\circ}\text{R}$
$\bar{H}_{rg, w}$	40 to 52	cal/gm or Btu/lbm

For nonunity Lewis numbers each card contains the following, in F-format:

	<u>Column</u>	<u>Units</u>
P_L	1 to 13	atmospheres
β	14 to 26	none
T_w	27 to 39	$^{\circ}\text{C}$ or $^{\circ}\text{R}$
$\bar{H}_{rg, w}$	40 to 52	cal/g or Btu/lbm
$\bar{H}_{e, w}$	53 to 65	cal/g or Btu/lbm
N		
$\sum_{i=1} (Z_{i, e} - Z_{i, w}) \Delta H_{i, w}$	66 to 78	cal/g or Btu/lbm

It is noted here that the above described variables should not be of direct concern to the user. They do not enter into the calling sequence of any of the subroutines and their allocation and subsequent use of controlled internally by READAB and ABAR03. Their description is included only for completeness.

Both subroutines (ABAR03 and READAB) make use of a number EXTERNAL variables that have not yet been described. These variables are essentially the storage locations for the thermochemical data (supplied by the EST program) as needed by ABAR03 to perform the ablation analysis. These variables are:

PL is a one-dimensional array (or list) of pressure values (P_L) given by the EST program in atmospheres, and is one of the independent variables for the property data (during actual use, this variable is converted to the base 10 logarithm of the pressure value),

BETA is a list of ablation to diffusion mass loss ratio values (β) supplied by the EST program and is the other independent variable for the given property values (during actual use this variable contains the natural logarithm of β),

TW is a two-dimensional array of values specifying absolute temperature ($^{\circ}\text{R}$) (each row of this dependent variable is a list of values for which the pressure is constant and given by the corresponding value in PL),

TWI is a one-dimensional array of temperatures ($^{\circ}\text{R}$) specified by TWMIN, TWMAX, and TWINC as described above (this list is the independent variable used with PL to describe QCHEM, HW, and HEW,

QCHEM is a two-dimensional array of either

$$\left[\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} \right] + \beta (H_{a,w} - \bar{H}_{rg,w})$$

for a Lewis number not equal to 1, or

$$\beta (H_{a,w} - \bar{H}_{rg,w})$$

for a Lewis number equal to 1, converted by READAB to depend on PL and TWI (Btu/lb),

HW

is a two-dimensional array of wall enthalpy ($\bar{H}_{rg,w}$) converted by READAB to depend on PL and TWI (Btu/lb), and

HEW

is a table of enthalpy of gases at the boundary layer edge ($\bar{H}_{e,w}$) evaluated at T_w , converted to depend on PL and TWI by READAB (Btu/lb).

To summarize the function of READAB with respect to the thermochemical data, the following sequence is listed;

1. The EST program is run to produce output of $\bar{H}_{rg,w}$, T_w , $\bar{H}_{e,w}$ and the chemical activity function:

$$\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$$

as bivariant tables depending on local pressure P_L and ablation to diffusion mass loss ratio β .

2. The above EST output is rearranged so that the pressure and β values are ascending in magnitude and are then reformatted for input to READAB according to the following format:

	<u>Format</u>	<u>Columns</u>
P_L	F-format	1 to 13
β	F-format	14 to 26
T_w	F-format	27 to 39
$\bar{H}_{rg,w}$	F-format	40 to 52

	<u>Format</u>	<u>Columns</u>
$\bar{H}_{e,w}$	F-format	53 to 65
$\sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$	F-format	66 to 78

(There is available a simple reformatting utility program which accepts EST format and produces punched output in the above described APL format. Note that for a Lewis number equal to 1 the last two items may be omitted.)

3. The reformatted EST output is placed in the input stream of the CLAD job and is read by subroutine READAB.

4. READAB applies the conversion factor CONV and prints out the converted input. This printed output will contain, in addition to the data supplied, the calculated values of "QCHEM".

5. The variables $\bar{H}_{rg,w}$ and "QCHEM" are then converted to depend on P_L and T_w . The results of this conversion are then printed out.

6. Subroutine ABARO3 uses the converted data, stored in the appropriate EXTERNAL variables by READAB, to solve the required surface energy balances.

Since the thermochemical data are supplied as tables, extensive use of interpolation is required to obtain the precise values needed in ABARO3. This interpolation, while not of direct concern to the user, is done in a logarithmic sense with regard to pressure (P_L) and (β). When these variables are required for use in interpolation, their logarithms are first taken and then the linear interpolation is performed. The antilog of this interpolated result is then supplied as the required value. This completed the discussion of READAB.

7. CALL THREEED and CALL REDCP3 - Geometric data necessary to describe each capacitor in the thermal network are input to the CLAD program in one of two ways. For evenly spaced, rectangular elements the user can call subroutine THREEED to automatically divide the model into elements and make the appropriate thermal connections. For nonrectangular elements and for unevenly spaced rectangular elements the user can use subroutine REDCP3 to read the geometry data. These two subroutines are used as follows:

a. CALL THREEED - Subroutine THREEED divides the analytical model into rectangular elements similar to Fig. 3a. The body is divided into finite volume sub-surface elements and zero volume elements on the irradiated surface. All nodes are located at the center of each element. The length of the test section is specified for the x, y, and z directions with each length divided into a specified number of elements. In the z direction the model may be made up of several different materials separated by contact conductances. Each material and contact conductance is assigned an identification number corresponding to the number (I) in READRK. The largest permissible identification number is 9. However, each material and contact conductance may be used more than once, which permits an unlimited number of layers in the Z direction.

THREED also contains an option which allows for a slightly different element break-up as shown in Fig. 3b. In this configuration elements adjacent to the xz and yz planes are half as large as the interior elements and have their nodes located on the planes. This configuration may be particularly useful when analyzing stationary laser beams or other arrangements having two planes of symmetry. In both models elements are numbered sequentially starting at $x = 0$, $y = 0$, $z = 0$ and going first in the z direction, then x, then y (as shown in Fig. 3b). In addition to dividing the model into elements, THREEED also computes the volume of each element and the area to length ratio between adjacent elements. These values are stored in the array, XCAP, and passed on to subroutine CAPCN3 (see Number 13 following).

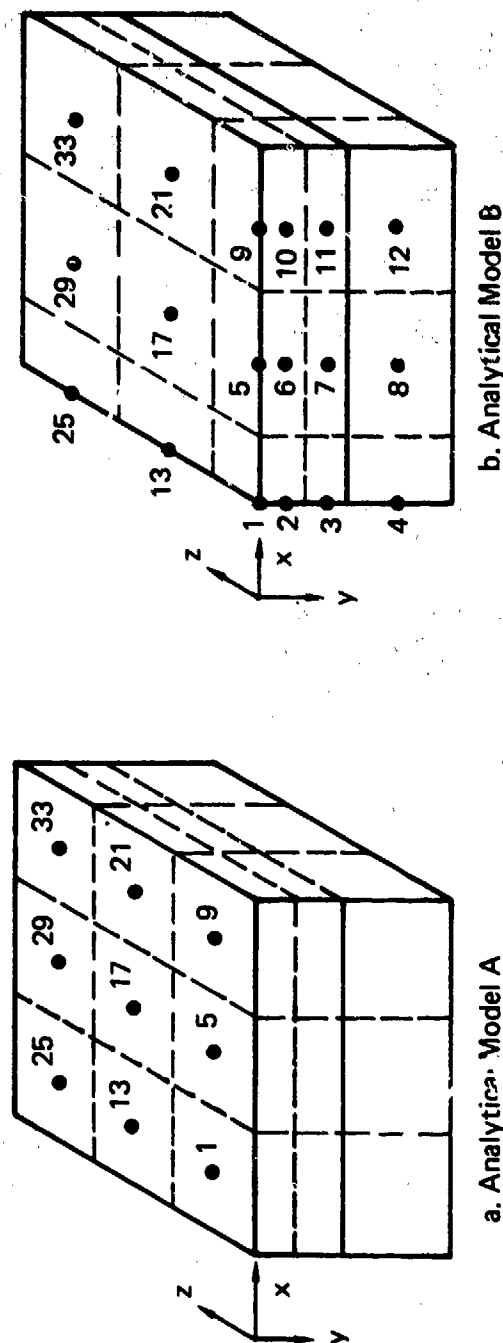


Fig. 3 Two Models Used in Subroutine THREEED to Subdivide Rectangular Bodies into Elements

CALL THREED (J, LX, NX, LY, NY, NMZ,
LZ, NZ, IPROP, ICONT, FEL, SURF);

where:

J	is an index identifying the THREED statement (FIXED BINARY),
LX, NX, LY, NY	is the model length and number of nodes in the x and y directions (lengths LX and LY are float binary numbers in feet, while NX and NY are fixed decimal values not greater than 10),
NMZ	is the number of material layers in the z direction (a fixed decimal number from 1 to ∞),
LZ	is an array defining the length of each material layer in the z direction starting with the irradiated material (LZ is a float binary array of size NMZ with units of feet),
NZ	is an array of length NMZ defining the number of elements in each material layer (FIXED DECIMAL),
IPROP	is an array of length NMZ identifying the material property tables for each layer (FIXED DECIMAL), where IPROP(1) is the property index of the material at the irradiated surface and IPROP(2) is the property index of the adjacent material, and so forth (values assigned

to IPROP must correspond to the appropriate I in READRK),

ICONT is an array of length (NMZ-1) identifying tables defining contact conductivity between material layers, starting with ICONT(1) for the conductance between the irradiated material (IPROP(1)) and the adjacent layer (IPROP(2)) (FIXED DECIMAL),

FEL is the index number of the element located at (0, 0, 0) in Fig. 3 (FIXED DECIMAL), and

SURF is a flag (if SURF = 0.0 the model is as shown in Fig. 3a; however, if SURF = 1.0 then the model is as shown in Fig. 3b (FLOAT BINARY)).

The output from THREEED is in a tabular format with the following headings:

I1 VOLUME MATERIAL #CON I2 A/L I3 or A A/L I4 A/L I5 A/L

These headings are followed by a table of corresponding values. The headings stand for:

I1 is the element in question,

VOLUME is the volume of element I1 (ft³),

MATERIAL is a single digit number identifying the material of element I1 (if I1 has a contact conductance connecting it to I2 then MATERIAL is a three digit number, the first digit

identifying material (I1), the second digit identifying the contact conductivity, and the third digit identifying material (I2)),

#CON

specifies the number of conduction paths from I1 to elements with identifiers greater than I1,

I2

is the element to which I1 conducts,

A/L

is the area to length ratio of element I2 (feet) (if there is a contact resistance between I1 and I2 then A/L is the area to length ratio between I1 and the contact interface (feet),

I3 or A

if I1 and I2 have a contact resistance between them, then I3 is the area of contact interface (ft²), otherwise I3 is the second element to which I1 conducts,

A/L

if I1 and I2 have a contact resistance between them then A/L is the area to length ratio between the interface and I2 (feet), otherwise A/L is the area to length ratio between elements I1 and I3 (feet),

I4

is the element to which I1 conducts,

A/L

is the area to length ratio between I1 and I4 (feet),

I5

is the element to which I1 conducts, and

A/L

is the area to length ratio between I1 and I5 (feet).

The reader should note that, by convention, the element located below I1 must be I2. However if there is no element below I1 then I2 is a side element. Also note that the printout contains only connections to elements located below, to the right, and behind element I1.

b. CALL REDCP3 (INFILE) - Subroutine REDCP3 reads the geometric data necessary to describe each capacitor in the thermal network. The only argument to REDCP3 is INFILE which is the name of the file containing the data. The data list consists of: two comment cards followed by two data cards for each capacitor in the network to be described. The data defining each capacitor is the same as discussed in the printout of subroutine THREED.

The necessary card format and units are listed below:

<u>Data</u>	<u>Column</u>	<u>Format</u>	<u>Units</u>	
Capacitor number (I1)	0 to 4	Fixed		
Volume	5 to 19	E-format	ft ³	} First data card
Material	20 to 29	F-format		
#CON	30 to 39	F-format		
I2	40 to 49	F-format		
A/L	50 to 59	E-format	feet	
I3	60 to 69	F format		} Second data card
A/L	70 to 79	E-format	feet	
I4	0 to 9	F-format		
A/L	10 to 19	E-format	feet	
I5	20 to 29	F-format		
A/L	30 to 39	E-format	feet	

By convention, I2 is always the element adjacent to I1 in the direction of ablation (if there is such an element). In addition, elements in an ablating string must be numbered consecutively starting with the element at the ablating surface.

8. CALL SET (START, STOP, TEMPIN, L, INDEX, TEMP); - Subroutine SET specifies the start and end times of the computer analysis and sets all elements to their initial temperature. The arguments of SET are:

START, STOP	start computation at time START and stop at STOP (FLOAT BINARY) (seconds),
TEMPIN	all elements are initialized to temperature TEMPIN (FLOAT BINARY) ($^{\circ}$ R),
L	the number of elements to be initialized to temperatures other than TEMPIN (FIXED BINARY), and
INDEX, TEMP	arrays of length L defining the index and temperature of elements not initialized to TEMPIN (FIXED BINARY and FLOAT BINARY), where TEMP has units of $^{\circ}$ R.

9. I1: IMAX = DECIDE (TIMS, IOX, TIMEI); - This statement defines the maximum intensity (IMAX) of the Gaussian beam at a specific time, TIMS:

IMAX	is the maximum beam intensity at time, TIMS (FLOAT BINARY EXTERNAL) ($\text{Btu}/\text{ft}^2 \cdot \text{s}$),
TIMS	is the present time (FLOAT BINARY EXTERNAL) (seconds),

IOX is an array of maximum intensity as a function of time (FLOAT BINARY) (Btu/ft² · s), and

TIMEI is the corresponding time where: TIMEI(1) is the number of entries in the table, TIMEI(2) is the time corresponding to IOX(1), etc. (FLOAT BINARY) (seconds).

If the surface is not irradiated by a Gaussian beam then the above statement may be replaced by a series of statements defining the heating rate to each surface node as a function of time. For example:

11: Q(J) = DECIDE (TIMS, QJ, TIMEJ);

where:

Q(J) is the heating rate to element J (FLOAT BINARY EXTERNAL CONTROLLED) (Btu/h),

TIMS is the present time (FLOAT BINARY EXTERNAL) (seconds),

QJ is an array defining heating rate to element J as a function of time (FLOAT BINARY) (Btu/h), and

TIMEJ is the corresponding time (FLOAT BINARY) (seconds) where TIMEJ(1) = length of table and the remaining values define times for values given in QJ.

10. CALL GAUSBM (XO, TIMEG, XINIT, RBEAM, XN, TIMEP); - GAUSBM is called if the surface is being irradiated by a Gaussian beam. The beam may be stationary

or may move along the x axis as a function of time. In either case the beam center is assumed to be on the x axis. Within GAUSBM the heating rate to each surface element is computed from the equation:

$$Q(J) = \text{IMAX} * \text{AREA} * \exp(-\text{XN} * \text{XY}^2 / \text{RBEAM}^2), \quad (19)$$

where JMAX is the maximum beam intensity at time (TIMS), AREA is the surface area of element J, XY is the distance from the beam center to the element J, XN is a constant, and RBEAM is the beam radius.

The arguments to GAUSBM are:

XO	is an array defining the distance from $x = 0$ to the beam center measured along the x axis as a function of time (FLOAT BINARY) (feet),
TIMEG	is the corresponding array of time (FLOAT BINARY) (seconds) TIMEG(1) = length of array XO,
XINIT	is the initial location of the beam center along the x axis measured from $x = 0$ (FLOAT BINARY) (feet),
RBEAM	is the radius at which the intensity is $\exp(-\text{XN} * \text{IMAX})$ (FLOAT BINARY) (feet),
XN	is the constant in Eq. (19) (usually either 1.0 or 2.0) (FLOAT BINARY), and
TIMEP	is an array listing desired printout times of surface intensity, usually the same as specified in WRITE (FLOAT BINARY) (seconds).

At times specified by TIMEP subroutine GAUSBM prints the following:

BEAM DEFINITION

CENTERED AT X = ____ FT IMAX = ____ BTU/S FT ** 2

IRRADIATED ELEMENT AREA = ____ FT ** 2

INTENSITY AT EACH ELEMENT (BTU/S * FT ** 2)

I (____) = ____ I (____) = ____ I (____) = ____ , etc., etc.

If the elements are not divided such that each element has the same surface area, then the IRRADIATED ELEMENT AREA given above is the area of elements not adjacent to either the x or y axes.

11. CALL QFUSON; - QFUSON computes the latent heat of fusion remaining as an element is heated or cooled at its melting point. Values of latent heat of fusion (QMELT), melt temperature (TMELT) and density (RO) for each material are obtained from the main program as EXTERNAL variables.

12. CALL ABAR03 (I, #SURF, CYL, LAMBDA, TSP, CM_CH, LEW#, VIEW, FACTOR, TLIM, QLIM, ITLIM, TIMEP, IPLOT); - ABAR03 computes the temperature of each zero volume surface node using the energy balance given in Eq. (1). The equation is solved iteratively using temperature dependent values of surface absorptivity, material thermal conductivity, emissivity, and chemical energy. ABAR03 also removes material from ablating and vaporizing elements, and adjusts conduction paths to adjacent elements.

Arguments of ABAR03 are:

I is an index identifying the ABAR03 statement (FIXED BINARY),

#SURF is the number of surface elements being aerodynamically heated in the call statement (FIXED BINARY),

CYL is a flag for cylindrical or rectangular geometry (FIXED BINARY),

Input: 0 for rectangular elements
1 for heating on the outer surface of cylindrical elements
-1 for heating on the inner surface of cylindrical elements,

LAMBDA is the "blowing parameter" in Eq. (13) (FLOAT BINARY) (a complete discussion of LAMBDA is presented in Ref. 3 — the "classical" value is LAMBDA = 0.5; however, Ref. 3 recommends that LAMBDA = 0.5 for laminar flow and LAMBDA = 0.4 for turbulent data),

TSP is the radiation space temperature (FLOAT BINARY) (°R),

CM_CH is the ratio of mass transfer Stanton number to heat transfer Stanton number (FLOAT BINARY) (if CM_CH is negative then the mechanical erosion is included as presented in Eq. (18), and the Putts and Bartlett blowing equations are used — Eqs. (14) through (17)),

LEW# is the Lewis number (FLOAT BINARY),

VIEW is the view factor of incoming laser irradiation (FLOAT BINARY) (note this value

applies only to laser irradiation and not to q_{rad} ; see Eq. (1)),

FACTOR is a lumping factor (if the volume of chemically ablating or vaporizing element drops below this fraction of its original volume, then it is lumped with the element below (FLOAT BINARY)),

TLIM is the temperature convergence limit of energy balance Eq. (1) (FLOAT BINARY) ($^{\circ}\text{F}$),

QLIM is the heat convergence limit of energy balance (FLOAT BINARY) ($\text{Btu}/\text{ft}^2 \cdot \text{s}$),

ITLIM is the maximum number of iterations allowed for convergence of energy balance to within the two tolerance values listed above (FIXED BINARY); if this limit is exceeded then the following message is printed and the program continues:

ITERATION ON SURFACE NODE # _____ HAS EXCEEDED _____ TSURF =

_____ AND DELTA TSURF = _____. HEAT IMBALANCE = _____. .

TIMEP is an array of printout data (FIXED BINARY) (seconds),

IPLOT is a flag for plotting data (FIXED BINARY) if 0 then plots are not desired (if nonzero then many of the values computed in ABAROS are stored in the temperature vector and may be plotted by calling subroutine PLOTTER;

for more information on the use of this routine the reader is referred to Ref. 13). The following values are stored in the temperature array T:

- $T(IPLLOT) = \beta \left(\frac{C_m}{C_H} \right)_b$.
- $T(IPLLOT+1) =$ total mass loss (lbm/ft²),
- $T(IPLLOT+2) =$ mass loss rate (lbm/ft² · s),
- $T(IPLLOT 3) =$ accumulated error in the surface energy balance (Btu/ft²),
- $T(IPLLOT+4) =$ current error in the surface energy balance (Btu/ft² · s),
- $T(IPLLOT+5) =$ current recession rate (in/s),
- $T(IPLLOT+6) =$ total recession (inches),
- $T(IPLLOT+7) =$ convective heating rate $(\rho_e U_e (C_H)_b (H_r - \bar{H}_{e,w}))$ when the Lewis number does not equal 1; and when the Lewis number equals 1 then $T(IPLLOT+7)$ is the first term in Eq. (8), i.e. $(\rho_e U_e (C_H)_b (H_r - \bar{H}_{rg,w}))$ (Btu/ft² · s),
- $T(IPLLOT+8) =$ accumulated conduction away from the surface (Btu/ft²),
- $T(IPLLOT+9) =$ current heating rate from the "QCHEM" * m_a term (Btu/ft² · s) where: for a Lewis number not equal to 1,

Ref. 13. R. K. Frazer, "A Subroutine for Obtaining CalComp Plots of SHTP Variables," APL/JHU EM-4496, 13 December 1972.

$${}^{\prime}\text{QCHEM}'' = \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \bar{H}_{rg,w})$$

and for a Lewis number equal to 1,

$${}^{\prime}\text{QCHEM}'' = \beta (H_{a,w} - \bar{H}_{rg,w}).$$

- T(IPLOT+10) = accumulated heating from the ${}^{\prime}\text{QCHEM}''$ * m_a term (Btu/ft²),
- T(IPLOT+11) = current radiative energy flux absorbed at the surface, including laser radiation and radiation from a radiating body (Btu/ft² · s),
- T(IPLOT+12) = current heat radiating from the surface (Btu/ft² · s),
- T(IPLOT+13) = current conduction loss rate from the surface (Btu/ft² · s),
- T(IPLOT+14) = current rate of sensible energy required to heat the ablating material from the node temperature (T_2 in Fig. 1) to the surface temperature (T_w) (Btu/ft² · s),
- T(IPLOT+15) = surface node number,
- T(IPLOT+16) = current value of surface node area (ft²),
- T(IPLOT+17) = current radius of surface node (feet), and
- T(IPLOT+18) = accumulated sensible energy required to heat ablating material from T_2 to T_w (Btu/ft²).

Since the above information is stored in temperature array (T) it is necessary that IPLOT be greater than the largest element number in the analysis. Also, be sure to set LASCAP to a large enough value in statement 3.

In addition to its arguments, ABARO3 also receives information in the form of data cards. Data input in this manner are the surface area and radius of each surface element aerodynamically heated in this call statement. Therefore, there will be #SURF cards, each containing: the surface element number, the surface area (ft^2), and the surface radius (feet). If the elements are not cylindrical a radius of 0.0 may be input. There is no column or format restriction on these input data.

13. CALL CAPCN3; - CAPCN3 computes capacitance of each element and heat conduction between elements using geometry values placed in array XCAP by THREED or REDCP3. No arguments are required for CAPCN3, since all values are obtained from previously computed EXTERNAL variables.

14. CALL WRITE (TIMEP); - Subroutine WRITE prints out element temperatures at times specified in array TIMEP.

TIMEP	is an array of desired printout times (FLOAT BINARY) (seconds) (if TIMEP(1) is a negative, non-zero number, the output will be printed for each time step).
-------	---

15. CALL STEP (MINSTP, MAXSTP); - Subroutine STEP computes the stability time step and the element temperatures at the next step in time.

MINSTP	is the minimum allowable time step (FLOAT BINARY) (seconds), and
--------	--

MAXSTP	is the maximum allowable time step (FLOAT BINARY) (seconds).
--------	--

If the time step is greater than MAXSTP then it will be set to MAXSTP and the program continues. However, if the

time step is less than MINSTP, the following message is printed and the program is terminated.

TIME STEP LESS THAN MINIMUM ALLOWED

CRITICAL INDEX NO. _____ DFLTIM = _____

If subroutine WRITE has printed during the present time step then STEP prints the following:

CRITICAL INDEX NO. = _____ TIME STEP = _____ SEC.

The row of asterisks signifies the end of printout for the present time step. When the end time has been reached (i.e. time STOP as defined in the argument of SET), the following message is printed and the program is terminated:

THE TIME IS _____ SECONDS, AND THE NUMBER OF
STEPS EXECUTED WAS _____.

16. GO TO I1; - Sends control of the program back to I1, which is the first statement in the time loop (see Step 9). Note that the loop is exited via the routine step and is not infinite.

17. END NAME; - This statement signifies the end of MAIN program NAME.

4. SAMPLE PROBLEM

Each phase of the CLAD program has been checked against available analytical and/or experimental data. The main program used to check ablation computations in CLAD is presented here as a sample problem. A schematic of the analytical model is shown in Fig. 4. The model consists of a cylindrical, ATJ-S blast tube, convectively heated on the inner surface. From Ref. 14 the enthalpy based convective heat transfer coefficient is $3.96 \text{ lb/ft}^2 \cdot \text{s}$ and the recovery temperature is 4880°R . The chemical ablation data for ATJ-S graphite was obtained from the EST computer program (Ref. 3) using a reference temperature of 536°R . Hence, the recovery enthalpy above 536°R is the enthalpy of air at 4880°R minus the enthalpy of air at 536°R , which is $1416 - 129$ or 1287 Btu/lb .

The cylinder is 1.4 inches thick and has an inner radius of 0.435 inch. The analysis begins at 0.2 second with the model temperature distribution shown in Fig. 4.

The main program (ABMAIN) used in the analysis is presented in Appendix B. The reader should refer to Appendix B as the statements of ABMAIN are discussed below. ABMAIN is divided into sections headed by comment cards:

/* DECLARE ENTRY STATEMENTS */

Under this heading are entry points for all subroutines called in ABMAIN.

/* DECLARE VARIABLES */

These statements declare variable names used in call statement arguments. These variables are discussed later, as they are encountered in the CALL statements.

Ref. 14. R. K. Frazer, "Preliminary Calculations of Temperature and Ablation Histories for a Proposed Blast Tube at ARC," APL/JHU EM-4547, 7 January 1974.

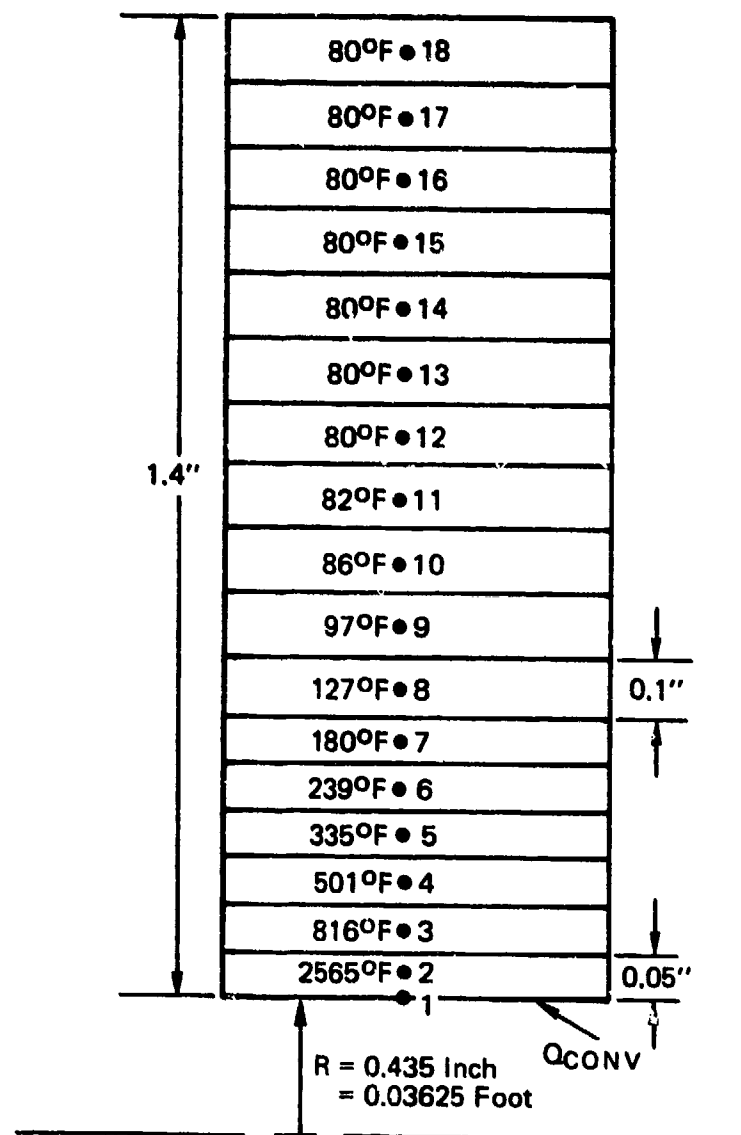


Fig. 4 Sample Problem — Blast Tube Model

/* ALLOCATE AND INITIALIZE VARIABLES */

The allocate statement assigns space to controlled variables RO, QVAPOR, and TVAP, while the GET COPY DATA statement assigns initial temperatures to elements 2 through 11. Subroutine STORE assigns an array size of LASCAP to allocatable variables used in the laser heating subroutines. The remaining statements assign printout times to variable TIMEP.

/* READ INPUT DATA */

In this section values are assigned to variables which have not been previously initialized in the above declare statements. The first few statements read and print values for heat of vaporization (QVAPOR), vapor temperature (TVAP), and material density (RO) of the first material. These statements are followed by call statements which read input values.

READRK assigns thermal properties to material 1 as a function of temperature.

READTM assigns time dependent values to recovery enthalpy (HR1), radiation heating rate (QRAD), cold wall enthalpy based heat transfer coefficient (RHOCH1) and local pressure (PLTM1).

Since the Lewis number equals 1, READAB reads local pressure and β dependent values of wall temperature (T_w) and reacted gas wall enthalpy ($\bar{H}_{rg,w}$). Using these values READAB computes "QCHEM" i.e., $[\beta (H_{a,w} - \bar{H}_{rg,w})]$ and $\bar{H}_{rg,w}$ as functions of $\log_{10}$ (PL) and wall temperature (T_w).

REDCP3 reads the volume of each element and the conduction paths between elements.

/* INITIALIZE MODEL TEMPERATURE */

CALL SET specifies the analysis to run from 0.2 (TZERO) to 0.5 (ENDTIME) second. SET also initializes elements 12 through 18 to 540°R (TINIT) and assigns elements 2 through 11 the initial temperatures read in GET COPY DATA.

/* STATEMENTS IN THE TIME STEP LOOP */

Subroutine ABARO3 computes model surface temperatures, ablation rates, heat of vaporization, and chemical heat of reaction, and adjusts conduction paths to ablating elements. The first argument indicates this is the first call to ABARO3. There is one (#SURF) surface node and it is located on the inside of a cylinder (CYL = -1). The blowing parameter constant is 0.4 (LAMBDA) and the surface radiates to a 0.0°R space temperature (TSP). The ratio of mass transfer to heat transfer is 1, as is the Lewis number. If there were laser irradiation, it would impinge on the surface with a view factor of 1 (VIEW). When half (FACTOR) an element is ablated it is then lumped with the adjacent element. Convergence criteria for the surface temperature iteration are $\pm 0.1^\circ\text{F}$ (TLIM) and $\pm 0.5 \text{ Btu/ft}^2$ (QLIM). The iteration stops after 10 (ITLIM) iterations. Printout times are specified in TIMEP and there are no plots (PLTCODE = 0).

CALL CAPCN3 computes heating rates between elements and has no arguments.

CALL WRITE specifies printout times (TIMEP).

CALL STEP indicates the critical time step is not to be less than 0.005 second (MINSTP) or greater than 0.5 second (MAXSTP).

TO TO IMX: sends control of the program back to the beginning of the time loop.

END ABMAIN: signifies the end of MAIN procedure.

The main program is followed by data cards which are listed in Appendix B in the order they are required in the MAIN procedure. Data cards define the following variables:

1. The number of elements to be assigned initial temperatures and a table of temperatures and corresponding element numbers.
2. Heat of vaporization, vapor temperature, and density of material number 1. Zero vapor temperature indicates the material is ablating and not vaporizing.
3. Temperature dependent values of capacitance, conductivity, emissivity, and absorptivity for material number 1.
4. Time dependent values of recovery enthalpy, input radiation, enthalpy based heat transfer coefficient, and local pressure at the surface.
5. Pressure and β dependent values of wall temperature (T_w) and gas enthalpy at the wall ($\bar{H}_{rg,w}$) for the ablative material in air.
6. Geometry values defining each element, its volume, its material, the number of elements connected to it via conduction, and the adjacent conduction elements and corresponding area to length ratio.
7. The surface area and radius of element 1.

This ends the sample problem computer program. The reader should realize this program has been written in a general form which allows its application to a great many problems simply by changing a few data cards. This makes parametric studies very easy and eliminates recompilation of the MAIN program for each run.

Printout resulting from the above program is shown in Appendix C. The first six and one half pages consist of input data for the GET COPY DATA, GET LIST, READRK, READTM, READAB, REDCP3, and ABARO3 statements of the MAIN program (see above discussion of input data). This is followed by a series of values computed for each time step. At a typical time step (0.2317 second) the first call to ABARO3 prints the following values: recovery enthalpy = 1287 Btu/lb, cold-wall enthalpy based heat transfer coefficient = 3.960 lb/ft² · s, local pressure = 100 atmospheres, ratio of mass transfer to heat transfer = 1, Lewis number = 1, blowing coefficient = 0.4, and radiation space temperature = 0.0001°R. Node number 1 has a "convective heating rate" of 2925.3 Btu/ft² · s and a cumulative "convective heating rate" of 90.2 Btu/ft². When the Lewis number is equal to 1, as in this case, the "convective heating rate" is a misnomer and is really equal to the first term in the right side of Eq. (8), i.e., $\rho_e U_e (C_H)_b (H_r - \bar{H}_{rg,w})$. Continuing with the printout in Appendix C, there is no incoming radiation and the mass loss rate is 0.6484 lb/ft² · s with a total mass loss of 0.0210 lb/ft². The accumulated error in the surface energy balance is -0.00164 Btu/ft². Node number 1 is at 4381.8°F. The heating rate into the surface due to "QCHEM" is 740 Btu/ft² · s and the total heating due to "CHEM" is 24.4 Btu/ft². There is no radiation from the surface. The recession rate is 0.0701 in/s with a total recession of 0.00227 inch. The heat imbalance for the present time step is 0.142 Btu/ft² · s. The mass loss coefficient (BETA) equals 0.175. Heat conduction away from the surface is 3218.7 Btu/ft² · s with an accumulated heat conduction loss of 104.6 Btu/ft². The sensible energy to increase the surface material from T₂ to T₁ is 446.2 Btu/ft² · s with an accumulated value of 4.91 Btu/ft². The ratio of heat transfer coefficient with blowing to no blowing is 0.9359. The wall gases have an enthalpy ($\bar{H}_{rg,w}$) of 497.6 Btu/lb and the mass flow Stanton number is 3.706. The surface energy balance data is followed by temperature data. The temperature of each element is printed in degrees Fahrenheit. The final printout for this time step is the critical index number (6) and the critical time step (0.0112 second).

Surface temperature histories from this analysis are presented in Fig. 5. Notice the sawtooth effect caused by nodal lumping as the surface ablates. This sawtooth effect can be greatly reduced by using more elements near the surface. With smaller elements the true surface temperature will fall between the peaks and valleys of the CLAD curve presented in Fig. 5. Also shown in Fig. 5 are results from the one-dimensional CMA program (Ref. 3). CMA results are slightly lower because it uses a finite volume surface node while CLAD uses a zero volume node. Also note that because CMA drops nodes from the back surface it does not have any sawtooth effect. The apparently better back node dropping technique is very difficult to implement in a three-dimensional node-dropping analysis and consequently was not used in CLAD.

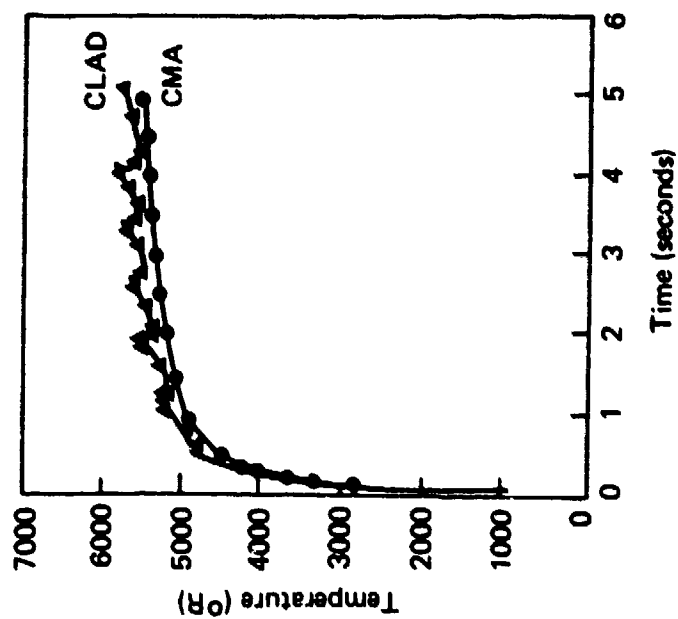


Fig. 5 Sample Problem Surface Temperature Histories Using CLAD and CMA Computer Programs

5. CONCLUSIONS AND RECOMMENDATIONS

A comprehensive computer program has been written to evaluate material damage to laser irradiated flight bodies. The CLAD program includes many features such as aerodynamic heating, radiation relief, and temperature dependent thermal properties that are also contained in similar laser damage computer programs. However, CLAD contains several unique features which are not generally included in the other programs (e. g., three-dimensional material removal, chemical reactions and vaporization at the surface, and in-depth melting). The combination of all these features into a single program provides an analytical tool that should be very useful in analyzing laser heated flight vehicles.

There are also several areas where CLAD can be expanded and improved. For example it could be expanded to include melt removal by aerodynamic shear forces at the surface or to include in-depth chemical reactions which occur in charring ablators.

The reader should also realize that the CLAD program was written for continuous wave laser applications, which have relatively low power densities compared with pulsed lasers. At the high intensities of a pulsed laser, ordinary thermal analysis no longer holds. Consequently the CLAD program will have to be extensively modified for application with pulsed lasers. These modifications are planned for the future.

Even without the above modifications, CLAD is still a powerful analytical tool for a wide range of laser heated material analyses.

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14. R. K. Frazer, "Preliminary Calculations of Temperature and Ablation Histories for a Proposed Blast Tube Test at ARC," APL/JHU EM-4547, 7 January 1974.

Appendix A

DERIVATION OF EQUATION USED TO COMPUTE CHEMICAL HEATING RATE

The components of the chemical heating term in Eq. (1) are shown schematically in Fig. A-1. In Fig. A-1, gases diffuse through the boundary layer at a rate of (m_d) and have an average total enthalpy $\bar{H}_{dg,w}$. At the surface some of the gases react with the ablating material (m_a) and release chemical energy q_{chem} . The resulting gases then mix with the unreacted diffusion gases and form a gaseous mixture whose average total enthalpy is $\bar{H}_{rg,w}$. The resulting mixture leaves the surface via diffusion and convection at a rate of (m_{rg}) . The rate of heat released at the surface is:

$$q_{chem} = m_d \bar{H}_{dg,w} + m_a H_{a,w} - m_{rg} \bar{H}_{rg,w}. \quad (A-1)$$

Notice that all enthalpies in Eq. (A-1) are total enthalpies (i.e., they are the sum of the sensible and chemical enthalpies).

Obtaining Eq. (A-1) in the form shown in Eq. (5) of the text is accomplished as follows. Since there is no mass build-up at the surface and the mass flow out (m_{rg}) equals the mass flow in ($m_a + m_d$). Substituting for m_{rg} in Eq. (A-1) and rearranging q_{chem} results in:

$$q_{chem} = m_d (\bar{H}_{dg,w} - \bar{H}_{rg,w}) + m_a (H_{a,w} - \bar{H}_{rg,w}). \quad (A-2)$$

However, m_a can be defined by a parameter, β , where $m_a = \beta \rho_e U_e (C_m)_b$. For an informative discussion of the physical meaning of β , see Ref. 14.

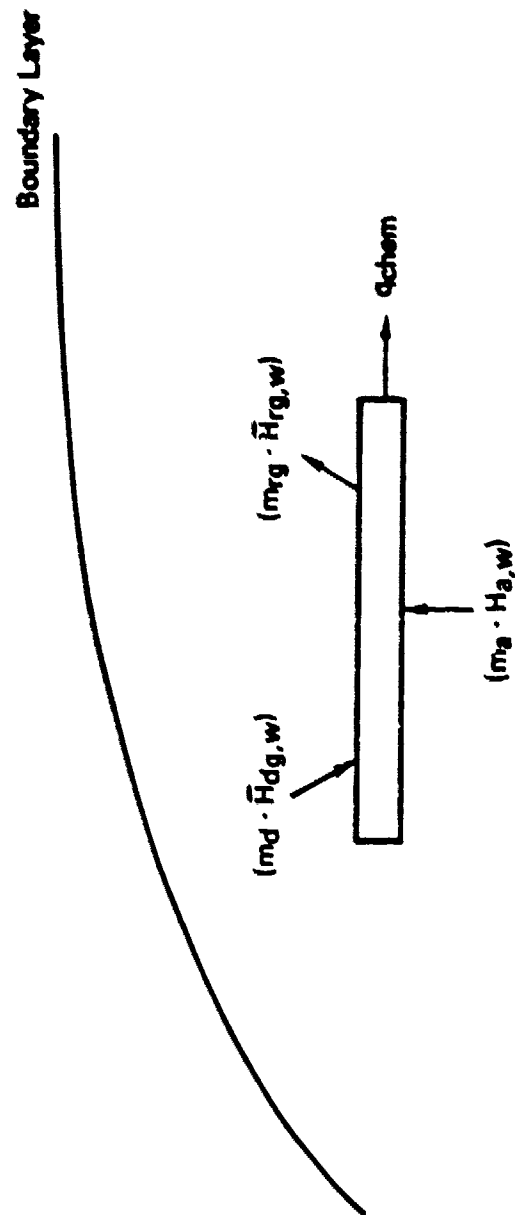


Fig. A-1 Chemical Energy Balance at an Ablating Surface

In Eq. (A-2) the total diffusion mass flow rate ($\dot{m}_d$) arriving at the wall is the sum of the flow rates of individual species, each arriving at enthalpy $H_{i,w}$ and, after chemical reaction, leaving at $\bar{H}_{rg,w}$. Hence, the energy term $\dot{m}_d (\bar{H}_{dg,w} - \bar{H}_{rg,w})$ in Eq. (A-1) becomes $\sum_{i=1}^N \dot{m}_i (H_{i,w} - \bar{H}_{rg,w})$.

Furthermore, according to Ref. 5, diffusion mass transfer can be related to concentration coefficients at the boundary layer edge ($Z_{i,e}$) and at the wall ($Z_{i,w}$) as follows:

$$\sum_{i=1}^N \dot{m}_i = \rho_e U_e (C_{m,b}) \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) . \quad (A-3)$$

In addition, the enthalpy difference ($H_{i,w} - \bar{H}_{rg,w}$) is simply the chemical enthalpy change of each species ($\Delta H_{i,w}$).

Hence, Eq. (A-2) becomes:

$$q_{chem} = \rho_e U_e (C_{m,b}) \sum_{i=1}^N (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \bar{H}_{rg,w}) , \quad (A-4)$$

which is in the form presented in Eq. (5).

Appendix B

MAIN PROGRAM FOR SAMPLE PROBLEM

This appendix presents the complete program used in analyzing the sample problem discussed in Section 4. The program contains the following comment statements which describe its overall organization.

```
/* DECLARE ENTRY STATEMENTS */  
  
/* DECLARE VARIABLES */  
  
/* ALLOCATE AND INITIALIZE VARIABLES */  
  
/* READ INPUT DATA */  
  
/* INITIALIZE MODEL TEMPERATURE */  
  
/* STATEMENTS IN THE TIME STEP LOOP */  
  
ABARO  
  
CAPCN3  
  
WRITE  
  
STEP
```

The program is followed by input data.

```

ADMIN: PROC OPTIONS(MAIN) ;

/* DECLARE ENTRY STATEMENTS */
DCL A9A03 ENTRY ( FIXED BIN, FIXED BIN, FIXED BIN, FIXED BIN,
  FLOAT BIN, FLOAT BIN,
  FLOAT BIN, FLOAT BIN, FLOAT BIN,
  FLOAT BIN,
  FLOAT BIN, FLOAT BIN, FIXED BIN, ( ) FLOAT BIN,
  FIXED BIN );

DCL CAPC3 ENTRY ;
DCL DECIDE ENTRY( FLOAT BIN, ( ) FLOAT BIN, ( ) FLOAT BIN, ( )
  RETURNS ( FLOAT ) ;
DCL READAB ENTRY ( FIXED BIN, FIXED BIN, FLOAT BIN, FLOAT BIN, ( )
  FLOAT BIN, ( ) FLOAT BIN, FLOAT BIN,
  FLOAT BIN, FLOAT BIN, FLOAT BIN,
  FILE );
DCL READFM ENTRY ( FIXED BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  ( ) FLOAT BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  FIXED BIN, FILE );
DCL READOK ENTRY ( FIXED BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  ( ) FLOAT BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  FIXED BIN, FILE );
DCL READTM ENTRY ( FIXED BIN,
  ( ) FLOAT BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  ( ) FLOAT BIN, ( ) FLOAT BIN, ( ) FLOAT BIN,
  FIXED BIN, FILE );
DCL REOC3 ENTRY( FILE );
DCL SET ENTRY( FLOAT BIN, FLOAT BIN, FLOAT BIN, FIXED BIN,
  ( ) FIXED BIN, ( ) FLOAT BIN );
DCL STEP ENTRY ( FLOAT BIN, FLOAT BIN );
DCL STORE ENTRY( FIXED BIN, FIXED BIN, FIXED BIN );
DCL WRITE ENTRY( ( ) FLOAT BIN );

/* DECLARE VARIABLES */
DCL SYSIN FILE;
DCL ( ABS1(20),
  CPl(20),
  DELTIME,
  DUM1(14),
  DUMY(30),
  EMIS1(20),
  ENDTIME INIT(.5),
  FACTOR INIT(.5),
  HRI(30),
  KI(20),
  LAM INIT(.4),
  LEW# INIT(1.0),
  MAXSTP INIT(.5),
  MINSTP INIT(.005),
  PLM1(30),
  QLM INIT(.5),

```

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```

OVAPOR(*) EXT CTL.
TVAP(*) CTL EXT.
ORAD(30).
RHOCH(130).
RHOC(13) INIT(10.09,10.09,33.3,42.05,40.0,
52.4,54.4,55.25,55.0,56.65, 57.55,58.45,563.04).
TEMP(14) INIT(13., .001,500.,900.,1460.,1960.,
2400.,2960.,3400.,3960.,4460.,
4960.,10460.,11000.).
RO(*) EXT CTL.
T1(21), T2(21), T3(21),
TIME1 (31),
TIMEP(30),
TINC INIT(100),
TINIT INIT(540.),
TLIM INIT(.1),
TLIM INIT (.9000),
TMAX INIT(500),
TMIN INIT(500),
TRI(10) INIT((10)0.0),
TREF EXT INIT(536.),
TSP INIT(.0001),
TZERO INIT(.20),
VIEW INIT(1.) FLOAT BIN:

DCL CYL INIT(-1),
I,
ITLIM INIT(10),
INPUT INIT(1),
#SURF INIT(1),
#BETA INIT(39),
#PL INIT(2),
LASCAP INIT( 18),
N1 INIT(13),
N4 INIT(5),
N6 INIT(20),
NDEXR(10) INIT((10)300),
NHAT INIT(1),
PLYCODE INIT(0),
AIRPRINT EXT INIT(1),
NTS INIT(0) FIXED BIN:

/* ALLOCATE AND INITIALIZE VARIABLES */
ALLOCATE RO(9),OVAPOR(9),TVAP(9),
GET COPY DATA
CALL STORE (LASCAP,LASCAP,3)
DELTIME = (ENDTIME-TZERO)/N6
DO I = 1 TO N6+1
TIMEP(I) = TZERO + (I-1)*DELTIME
END

```

```

/* READ INPUT DATA */
PUT LIST (1 MATERIAL HEAT OF VAP(RTU/PT003) MELT TEMP
DENSITY)))
DO I = 1 TO NMAT:
  GET LIST (OVAPOR(I),TVAP(I),RO(I)))
  PUT EDIT(1,OVAPOR(I),TVAP(I),RO(I))
  (SKIP,F(6),E(20,3),F(10,2),E(20,3),F(10,2),E(20,3)))
END:
CALL READRK(1,1,CP1,K1,EMIS1,ARS1,N),SYSIN:
CALL READTM (1,TIME1,MR1,GRAD,PHOC1,M,TM), DMY,M4,SYSIN:
CALL READAB ( @PL, @BETA, LEW,RO(1),RHOCP,TEMPR,
TMIN, TMAX, TINC, 1.0,
SYSIN:
CALL REDCP3(SYSIN)

/* INITIALIZE MODEL TEMPERATURE */
CALL SETTZERO,ENDTIME,TINIT,NTS,NOEHP,TR1)

/* STATEMENTS IN THE TIME STEP LOOP */
INX: CALL ABAR03(1,RSURF,CYL,LAN,TSP,1.1,VIEW,FACTOR,
TLM,OLTM,ITLM, TIME,PLYCODE)
CALL CAPCN3:
CALL WRITE(TIME)
CALL STEP(INXSTP,MAXSTP)
GO TO INX:
END ABMAIN:

```

```

WTS= 10  TR1(1)=3025.  NDEX(1)=2  TR1(2)=1274.  NDEX(2)=3
          TR1(3)=961.   NDEX(3)=4  TR1(4)=795.   NDEX(4)=5
          TR1(5)=699.   NDEX(5)=6  TR1(6)=640.   NDEX(6)=7
          TR1(7)=587.   NDEX(7)=8  TR1(8)=557.   NDEX(8)=9
          TR1(9)=546.   NDEX(9)=10 TR1(10)=542.  NDEX(10)=11
          ;
          4000.  0.0  111.
          THERMAL PROPERTIES OF ATJ - S HMO CP SAME AS POCU
          TEMP DEG K  RHOCIP  K  FMISS  0.0  0.0  0.0
          0.  18.89  58.00
          560. 18.89  72.00
          960. 33.30  53.70
          1460. 42.95  41.20
          1960. 48.80  32.10
          2460. 52.40  25.20
          2960. 56.40  20.00
          3460. 55.25  17.10
          3960. 55.80  15.40
          4460. 56.60  15.40
          4960. 57.50  16.60
          10460. 58.45  18.75
          21000. 58.45  18.75
          HEATING PARA: FTKMS  AKC - ATJ  ST-00Y
          TIME  SEC  ENTH  RADIN  CONV  CW  P LOC  NUMMY
          0.0  1287.  0.0  3.95967  100.001
          0.1  1287.  0.0  3.95967  100.001
          10.  1287.  0.0  3.95967  100.001
          13.  1287.  0.0  3.95967  100.001
          15.  1287.  0.0  3.95967  100.001
          ENTHALPY DATA FOR ATJ-S AND AIR
          LOCAL PHESS  HFTA  TW  HW
          100.00000  0.00001  298.14995  1.00000
          100.00000  0.00002  699.00000  140.50000
          100.00000  0.00270  1000.00000  154.20000
          100.00000  0.01930  1100.00000  60.30000
          100.00000  0.04290  1150.00000  -94.30000
          100.00000  0.08130  1200.00000  -369.00000
          100.00000  0.12520  1250.00000  -238.50000
          100.00000  0.16860  1300.00000  -62.40000
          100.00000  0.17430  1450.00000  -15.30000
          100.00000  0.17480  1666.66667  51.00000
          100.00000  0.17491  2200.07444  204.50000
          100.00000  0.17500  2427.84444  344.02383
          100.00000  0.17600  3100.89258  503.05444
          100.00000  0.17800  3355.70450  594.13590
          100.00000  0.18000  3447.02117  646.13241
          100.00000  0.19000  3745.44477  797.61597
          100.00000  0.20000  3426.44390  499.13644
          100.00000  0.35000  4446.30466  1413.29442
          100.00000  0.50000  4597.35154  2451.33164
          100.00000  1.00000  4740.43359  3419.44141
          100.00000  2.00000  4926.04444  5134.92464
          100.00000  2.50000  4957.05466  5505.51053
          100.00000  3.00000  4979.13672  5779.50741
    
```

Does not
attach

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SILVER SPRING, MARYLAND

100.00000	3.50000	4905.74600	5991.03125
100.00000	4.00000	5008.71094	6159.15625
100.00000	4.50000	5019.14653	6295.91797
100.00000	5.00000	5027.77047	6408.29484
100.00000	5.50000	5034.93359	6504.74953
100.00000	6.00000	5041.05859	6586.23047
100.00000	6.50000	5046.33594	6656.53516
100.00000	7.00000	5050.93750	6717.82422
100.00000	7.50000	5054.99219	6771.70313
100.00000	8.00000	5058.59504	6819.43759
100.00000	8.50000	5061.67574	6865.43594
100.00000	9.00000	5065.27344	6909.13281
100.00000	9.50000	5068.54297	6951.85156
100.00000	10.00000	5071.23478	6994.56441
100.00000	10.50000	5073.74516	7037.26574
100.00000	11.00000	5076.00000	7079.96141
100.00000	11.50000	5078.19995	7121.65125
100.00000	12.00000	5080.34990	7162.33609
100.00000	12.50000	5082.44985	7202.01694
100.00000	13.00000	5084.50980	7240.69379
100.00000	13.50000	5086.52975	7278.36664
100.00000	14.00000	5088.50970	7315.03549
100.00000	14.50000	5090.44965	7350.70034
100.00000	15.00000	5092.34960	7385.36119
100.00000	15.50000	5094.20955	7419.01804
100.00000	16.00000	5096.02950	7451.67089
100.00000	16.50000	5097.80945	7483.31974
100.00000	17.00000	5099.54940	7514.96459
100.00000	17.50000	5101.24935	7545.60544
100.00000	18.00000	5102.90930	7575.24229
100.00000	18.50000	5104.52925	7603.87514
100.00000	19.00000	5106.10920	7631.50399
100.00000	19.50000	5107.64915	7658.12884
100.00000	20.00000	5109.14910	7683.74969
100.00000	20.50000	5110.60905	7708.36654
100.00000	21.00000	5112.02900	7731.97939
100.00000	21.50000	5113.40895	7754.58824
100.00000	22.00000	5114.74890	7776.19309
100.00000	22.50000	5116.04885	7796.79394
100.00000	23.00000	5117.30880	7816.39079
100.00000	23.50000	5118.52875	7834.98364
100.00000	24.00000	5119.70870	7852.57249
100.00000	24.50000	5120.84865	7869.15734
100.00000	25.00000	5121.94860	7884.73819
100.00000	25.50000	5122.99855	7899.31504
100.00000	26.00000	5123.99850	7912.88789
100.00000	26.50000	5124.94845	7925.45674
100.00000	27.00000	5125.84840	7937.02159
100.00000	27.50000	5126.69835	7947.58244
100.00000	28.00000	5127.49830	7957.13929
100.00000	28.50000	5128.24825	7965.69214
100.00000	29.00000	5128.94820	7973.24199
100.00000	29.50000	5129.59815	7979.78884
100.00000	30.00000	5130.19810	7985.33269
100.00000	30.50000	5130.74805	7989.87354
100.00000	31.00000	5131.24800	7993.41139
100.00000	31.50000	5131.69795	7995.94724
100.00000	32.00000	5132.09790	7997.48109
100.00000	32.50000	5132.44785	7998.01294
100.00000	33.00000	5132.74780	7998.54379
100.00000	33.50000	5133.00775	7999.07464
100.00000	34.00000	5133.22770	7999.60549
100.00000	34.50000	5133.40765	7999.13634
100.00000	35.00000	5133.54760	7998.66719
100.00000	35.50000	5133.64755	7998.19804
100.00000	36.00000	5133.70750	7997.72889
100.00000	36.50000	5133.72745	7997.25974
100.00000	37.00000	5133.70740	7996.79059
100.00000	37.50000	5133.64735	7996.32144
100.00000	38.00000	5133.54730	7995.85229
100.00000	38.50000	5133.40725	7995.38314
100.00000	39.00000	5133.22720	7994.91399
100.00000	39.50000	5132.99715	7994.44484
100.00000	40.00000	5132.72710	7993.97569
100.00000	40.50000	5132.40705	7993.50654
100.00000	41.00000	5132.04700	7993.03739
100.00000	41.50000	5131.64695	7992.56824
100.00000	42.00000	5131.20690	7992.09909
100.00000	42.50000	5130.72685	7991.62994
100.00000	43.00000	5130.20680	7991.16079
100.00000	43.50000	5129.64675	7990.69164
100.00000	44.00000	5129.04670	7990.22249
100.00000	44.50000	5128.40665	7989.75334
100.00000	45.00000	5127.72660	7989.28419
100.00000	45.50000	5127.00655	7988.81504
100.00000	46.00000	5126.24650	7988.34589
100.00000	46.50000	5125.44645	7987.87674
100.00000	47.00000	5124.60640	7987.40759
100.00000	47.50000	5123.72635	7986.93844
100.00000	48.00000	5122.80630	7986.46929
100.00000	48.50000	5121.84625	7985.99914
100.00000	49.00000	5120.84620	7985.52899
100.00000	49.50000	5119.80615	7985.05884
100.00000	50.00000	5118.72610	7984.58869
100.00000	50.50000	5117.60605	7984.11854
100.00000	51.00000	5116.44600	7983.64839
100.00000	51.50000	5115.24595	7983.17824
100.00000	52.00000	5114.00590	7982.70809
100.00000	52.50000	5112.72585	7982.23794
100.00000	53.00000	5111.40580	7981.76779
100.00000	53.50000	5110.04575	7981.29764
100.00000	54.00000	5108.64570	7980.82749
100.00000	54.50000	5107.20565	7980.35734
100.00000	55.00000	5105.72560	7979.88719
100.00000	55.50000	5104.20555	7979.41704
100.00000	56.00000	5102.64550	7978.94689
100.00000	56.50000	5101.04545	7978.47674
100.00000	57.00000	5100.40540	7977.99659
100.00000	57.50000	5099.72535	7977.51644
100.00000	58.00000	5099.00530	7977.03629
100.00000	58.50000	5098.24525	7976.55614
100.00000	59.00000	5097.44520	7976.07599
100.00000	59.50000	5096.60515	7975.59584
100.00000	60.00000	5095.72510	7975.11569
100.00000	60.50000	5094.80505	7974.63554
100.00000	61.00000	5093.84500	7974.15539
100.00000	61.50000	5092.84495	7973.67524
100.00000	62.00000	5091.80490	7973.19509
100.00000	62.50000	5090.72485	7972.71494
100.00000	63.00000	5089.60480	7972.23479
100.00000	63.50000	5088.44475	7971.75464
100.00000	64.00000	5087.24470	7971.27449
100.00000	64.50000	5086.00465	7970.79434
100.00000	65.00000	5084.72460	7970.31419
100.00000	65.50000	5083.40455	7969.83404
100.00000	66.00000	5082.04450	7969.35389
100.00000	66.50000	5080.64445	7968.87374
100.00000	67.00000	5079.20440	7968.39359
100.00000	67.50000	5077.72435	7967.91344
100.00000	68.00000	5076.20430	7967.43329
100.00000	68.50000	5074.64425	7966.95314
100.00000	69.00000	5073.04420	7966.47299
100.00000	69.50000	5071.40415	7965.99284
100.00000	70.00000	5069.72410	7965.51269
100.00000	70.50000	5068.00405	7965.03254
100.00000	71.00000	5066.24400	7964.55239
100.00000	71.50000	5064.44395	7964.07224
100.00000	72.00000	5062.60390	7963.59209
100.00000	72.50000	5060.72385	7963.11194
100.00000	73.00000	5058.80380	7962.63179
100.00000	73.50000	5056.84375	7962.15164
100.00000	74.00000	5054.84370	7961.67149
100.00000	74.50000	5052.80365	7961.19134
100.00000	75.00000	5050.72360	7960.71119
100.00000	75.50000	5048.60355	7960.23104
100.00000	76.00000	5046.44350	7959.75089
100.00000	76.50000	5044.24345	7959.27074
100.00000	77.00000	5042.00340	7958.79059
100.00000	77.50000	5039.72335	7958.31044
100.00000	78.00000	5037.40330	7957.83029
100.00000	78.50000	5035.04325	7957.35014
100.00000	79.00000	5032.64320	7956.86999
100.00000	79.50000	5030.20315	7956.38984
100.00000	80.00000	5027.72310	7955.90969
100.00000	80.50000	5025.20305	7955.42954
100.00000	81.00000	5022.64300	7954.94939
100.00000	81.50000	5020.04295	7954.46924
100.00000	82.00000	5017.40290	7953.98909
100.00000	82.50000	5014.72285	7953.50894
100.00000	83.00000	5012.00280	7953.02879
100.00000	83.50000	5009.24275	7952.54864
100.00000	84.00000	5006.44270	7952.06849
100.00000	84.50000	5003.60265	7951.58834
100.00000	85.00000	5000.72260	7951.10819
100.00000	85.50000	4997.80255	7950.62804
100.00000	86.00000	4994.84250	7950.14789
100.00000	86.50000	4991.84245	7949.66774
100.00000	87.00000	4988.80240	7949.18759
100.00000	87.50000	4985.72235	7948.70744
100.00000	88.00000	4982.60230	7948.22729
100.00000	88.50000	4979.44225	7947.74714
100.00000	89.00000	4976.24220	7947.26699
100.00000	89.50000	4973.00215	7946.78684
100.00000	90.00000	4969.72210	7946.30669
100.00000	90.50000	4966.40205	7945.82654
100.00000	91.00000	4963.04200	7945.34639
100.00000	91.50000	4959.64195	7944.86624
100.00000	92.00000	4956.20190	7944.38609
100.00000	92.50000	4952.72185	7943.90594
100.00000	93.00000	4949.20180	7943.42579
100.00000	93.50000	4945.64175	7942.94564
100.00000	94.00000	4942.04170	7942.46549
100.00000	94.50000	4938.40165	7941.98534
100.00000	95.00000	4934.72160	7941.50519
100.00000	95.50000	4931.00155	7941.02504
100.00000	96.00000	4927.24150	7940.54489
100.00000	96.50000	4923.44145	7940.06474
100.00000	97.00000	4919.60140	7939.58459
100.00000	97.50000	4915.72135	7939.10444
100.00000	98.00000	4911.80130	7938.62429
100.00000	98.50000	4907.84125	7938.14414
100.00000	99.00000	4903.84120	7937.66399
100.00000	99.50000	4899.80115	7937.18384
100.00000	100.00000	4895.72110	7936.70369

GEOMETRY (HEATED INTERNAL SURFACE ELEMENT #1)									
I	VOL	MAT	CON	12	A/L	13	A/L		
1	0.00	1.	1.	2.	17.895E0	0.0	0.00		
2	0.00	0.00	0.00						
3	1.5973E-4	1.	1.0	3.0	9.6919E0	0.0	0.00		
4	0.00	0.00	0.00						
5	1.7709E-4	1.	1.0	4.0	1.0693E1	0.0	0.00		
6	0.00	0.00	0.00						
7	1.9445E-4	1.	1.0	5.0	1.1693E1	0.0	0.00		
8	0.00	0.00	0.00						
9	2.1181E-4	1.	1.0	6.0	1.2693E1	0.0	0.00		
10	0.00	0.00	0.00						
11	2.2917E-4	1.	1.0	7.0	1.3693E1	0.0	0.00		
12	0.00	0.00	0.00						
13	2.4653E-4	1.	1.0	8.0	9.9585E0	0.0	0.00		
14	0.00	0.00	0.00						
15	5.4514E-4	1.	1.0	9.0	8.3401E0	0.0	0.00		
16	0.00	0.00	0.00						
17	6.1459E-4	1.	1.0	10.	9.3411E0	0.0	0.00		
18	0.00	0.00	0.00						
19	6.8403E-4	1.	1.0	11.	1.0342E1	0.0	0.00		
20	0.00	0.00	0.00						
21	7.5348E-4	1.	1.0	12.	1.1343E1	0.0	0.00		
22	0.00	0.00	0.00						
23	8.2292E-4	1.	1.0	13.	1.2343E1	0.0	0.00		
24	0.00	0.00	0.00						
25	8.9236E-4	1.	1.0	14.	1.3344E1	0.0	0.00		
26	0.00	0.00	0.00						
27	9.6181E-4	1.	1.0	15.	1.4344E1	0.0	0.00		
28	0.00	0.00	0.00						
29	1.0312E-3	1.	1.0	16.	1.5345E1	0.0	0.00		
30	0.00	0.00	0.00						
31	1.1007E-3	1.	1.0	17.	1.6345E1	0.0	0.00		
32	0.00	0.00	0.00						
33	1.1701E-3	1.	1.0	18.	1.7266E1	0.0	0.00		
34	0.00	0.00	0.00						
35	1.2396E-3	1.	1.0	0.0	0.00	0.0	0.00		
36	0.00	0.00	0.00						

SURFACE AREA AND RADIUS DATA FOR A9A03 #1
SURFACE ELEMENT AREA(FT**2) RADIUS(FT)
1 .03625 .03625

Appendix C

SAMPLE PROBLEM PRINTOUT

A portion of the sample problem printout is presented in this appendix. The first page contains data read into the main procedure via GET statements and READ subroutines. The next five pages contain thermochemical tables for ATJ-S graphite and air, and are followed by two tables defining the model geometry. The remaining pages present typical printouts at 0.2 second, 0.221 second, and 0.232 second. The time-dependent output is divided into aerodynamic heating data, surface energy balance information, thermal capacitor temperatures, and critical time step data.

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WTS= 1: TR1(1)=3025. WDER(1)=2 TR1(7)=1274. WDER(2)=3
TR1(3)=961. WDER(3)=4 TR1(4)=795. WDER(4)=5
TR1(5)=699. WDER(5)=5 TR1(6)=540. WDER(6)=7
TR1(7)=587. WDER(7)=6 TR1(8)=557. WDER(8)=9
TR1(9)=544. WDER(9)=10 TR1(10)=542. WDER(10)=11
TR1(11)=542. WDER(11)=11

MATERIAL 1: MEAT OF VARIETU/FT=3) MELT TEMP DENSITY
1 4.0026+03 0.00 1.110E+02

THE DATA FOR REACTN STATEMENT 4 1:
THERMAL PROPERTIES OF ATJ - 5 RMC CP SAME AS PICO

TEMP DEG R	SMOCP	K	FMSS	ARSON
0.000	14.820	59.000	0.000	0.000
500.000	15.990	72.200	0.000	0.000
960.000	33.300	51.700	0.000	0.000
1460.000	42.950	41.200	0.000	0.000
1960.000	46.950	37.100	0.000	0.000
2460.000	52.400	24.200	0.000	0.000
2960.000	54.400	24.000	0.000	0.000
3460.000	55.250	17.100	0.000	0.000
3960.000	55.800	15.400	0.000	0.000
4460.000	54.600	16.400	0.000	0.000
4960.000	57.500	17.700	0.000	0.000
5460.000	54.400	18.700	0.000	0.000
5960.000	55.400	18.700	0.000	0.000

THE DATA FOR REACTN STATEMENT 4 1
HEATING PARAMETERS APC - ATJ STUPE

TIME	SEC SMTH	ACTM	CONV CM	P LOC	QUMW
0.000	1287.000	0.000	3.940	100.001	0.000
0.100	1287.000	0.000	3.900	100.001	0.000
10.000	1287.000	0.000	3.940	100.001	0.000
13.000	1287.000	0.000	3.960	100.001	0.000
15.000	1287.000	0.000	3.960	100.001	0.000

THE ENTHALPY VALUES IN THE THERMOCHEMICAL DATA HAVE BEEN REFERENCED TO 529.00 DEGREES RANKINE.

CALCULATED VALUES OF SURFACE MATERIAL ENTHALPY

TEMP - 2	ENTHALPY
0.001	-91.216
500.000	-9.006
960.000	99.120
1460.000	249.885
1960.000	476.499
2460.000	704.429
2960.000	944.457
3460.000	1191.024
3960.000	1447.038
4460.000	1495.304
4960.000	1527.511
5460.000	4.26.243
5960.000	6442.054

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ENTHALPY DATA FOR AT-J-S AND AIR			
P LOCAL	BETA	T WALL	W WALL
100.00000	1.00000	534.74	1.7400000000
100.00000	0.00000	1798.20	3.2400000000
100.00000	0.00000	1600.00	2.8650000000
100.00000	0.00000	1980.00	1.8671000000
100.00000	0.00000	2070.00	-1.7711000000
100.00000	0.00000	2160.00	-6.2837000000
100.00000	0.00000	2250.00	-4.2800000000
100.00000	0.00000	2340.00	-1.1121000000
100.00000	0.00000	2430.00	-2.7430000000
100.00000	0.00000	2520.00	9.1879000000
100.00000	0.00000	2610.00	1.5255000000
100.00000	0.00000	2700.00	3.7466170000
100.00000	0.00000	2790.00	1.8454000000
100.00000	0.00000	2880.00	2.1103500000
100.00000	0.00000	2970.00	2.4143700000
100.00000	0.00000	3060.00	2.5790400000
100.00000	0.00000	3150.00	2.8577700000
100.00000	0.00000	3240.00	2.0226370000
100.00000	0.00000	3330.00	2.8714000000
100.00000	0.00000	3420.00	0.7578510000
100.00000	0.00000	3510.00	-1.2359620000
100.00000	0.00000	3600.00	-3.0020070000
100.00000	0.00000	3690.00	-1.7504050000
100.00000	0.00000	3780.00	-1.4717040000
100.00000	0.00000	3870.00	-1.9077600000
100.00000	0.00000	3960.00	-2.3539240000
100.00000	0.00000	4050.00	-2.8009130000
100.00000	0.00000	4140.00	-3.2630130000
100.00000	0.00000	4230.00	-3.7293700000
100.00000	0.00000	4320.00	-4.1867220000
100.00000	0.00000	4410.00	-4.6519590000
100.00000	0.00000	4500.00	-5.1184440000
100.00000	0.00000	4590.00	-5.5844700000
100.00000	0.00000	4680.00	-6.0553070000
100.00000	0.00000	4770.00	-6.5251460000
100.00000	0.00000	4860.00	-6.9949400000
100.00000	0.00000	4950.00	-7.4646800000
100.00000	0.00000	5040.00	-7.9343600000
100.00000	0.00000	5130.00	-8.4040000000
100.00000	0.00000	5220.00	-8.8736800000
100.00000	0.00000	5310.00	-9.3433100000
100.00000	0.00000	5400.00	-9.8128900000
100.00000	0.00000	5490.00	-10.2824200000
100.00000	0.00000	5580.00	-10.7519000000
100.00000	0.00000	5670.00	-11.2213300000
100.00000	0.00000	5760.00	-11.6907100000
100.00000	0.00000	5850.00	-12.1600400000
100.00000	0.00000	5940.00	-12.6293200000
100.00000	0.00000	6030.00	-13.0985500000
100.00000	0.00000	6120.00	-13.5677300000
100.00000	0.00000	6210.00	-14.0368600000
100.00000	0.00000	6300.00	-14.5059400000
100.00000	0.00000	6390.00	-14.9749700000
100.00000	0.00000	6480.00	-15.4439500000
100.00000	0.00000	6570.00	-15.9128800000
100.00000	0.00000	6660.00	-16.3817600000
100.00000	0.00000	6750.00	-16.8505900000
100.00000	0.00000	6840.00	-17.3193700000
100.00000	0.00000	6930.00	-17.7881000000
100.00000	0.00000	7020.00	-18.2567800000
100.00000	0.00000	7110.00	-18.7254100000
100.00000	0.00000	7200.00	-19.1939900000
100.00000	0.00000	7290.00	-19.6625200000
100.00000	0.00000	7380.00	-20.1310000000
100.00000	0.00000	7470.00	-20.5994300000
100.00000	0.00000	7560.00	-21.0678100000
100.00000	0.00000	7650.00	-21.5361400000
100.00000	0.00000	7740.00	-22.0044200000
100.00000	0.00000	7830.00	-22.4726500000
100.00000	0.00000	7920.00	-22.9408300000
100.00000	0.00000	8010.00	-23.4089600000
100.00000	0.00000	8100.00	-23.8770400000
100.00000	0.00000	8190.00	-24.3450700000
100.00000	0.00000	8280.00	-24.8130500000
100.00000	0.00000	8370.00	-25.2809800000
100.00000	0.00000	8460.00	-25.7488600000
100.00000	0.00000	8550.00	-26.2166900000
100.00000	0.00000	8640.00	-26.6844700000
100.00000	0.00000	8730.00	-27.1522000000
100.00000	0.00000	8820.00	-27.6198800000
100.00000	0.00000	8910.00	-28.0875100000
100.00000	0.00000	9000.00	-28.5550900000
100.00000	0.00000	9090.00	-29.0226200000
100.00000	0.00000	9180.00	-29.4901000000
100.00000	0.00000	9270.00	-29.9575300000
100.00000	0.00000	9360.00	-30.4249100000
100.00000	0.00000	9450.00	-30.8922400000
100.00000	0.00000	9540.00	-31.3595200000
100.00000	0.00000	9630.00	-31.8267500000
100.00000	0.00000	9720.00	-32.2939300000
100.00000	0.00000	9810.00	-32.7610600000
100.00000	0.00000	9900.00	-33.2281400000
100.00000	0.00000	9990.00	-33.6951700000
100.00000	0.00000	10000.00	-34.1621500000

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2.00000	2200.00	-1.304954E+02	1.104172E+02
2.00000	2300.00	-2.964621E+02	1.314848E+02
2.00000	2400.00	-1.413813E+02	1.344008E+02
2.00000	2500.00	-8.533650E+01	1.373238E+02
2.00000	2600.00	-2.978988E+01	1.398001E+02
2.00000	2700.00	-4.513403E+00	1.429275E+02
2.00000	2800.00	1.652786E+00	1.467674E+02
2.00000	2900.00	1.232927E+01	1.492752E+02
2.00000	3000.00	9.197253E+01	1.575557E+02
2.00000	3100.00	1.064914E+02	1.557871E+02
2.00000	3200.00	1.232930E+02	1.590872E+02
2.00000	3300.00	1.427455E+02	1.624571E+02
2.00000	3400.00	1.652671E+02	1.658983E+02
2.00000	3500.00	1.913422E+02	1.694125E+02
2.00000	3600.00	2.215312E+02	1.730012E+02
2.00000	3700.00	2.564632E+02	1.765575E+02
2.00000	3800.00	2.969500E+02	1.804040E+02
2.00000	3900.00	3.438610E+02	1.842796E+02
2.00000	4000.00	3.855974E+02	1.877429E+02
2.00000	4100.00	4.122415E+02	1.907911E+02
2.00000	4200.00	4.407268E+02	1.934826E+02
2.00000	4300.00	4.711379E+02	1.970164E+02
2.00000	4400.00	5.037371E+02	2.002914E+02
2.00000	4500.00	5.385444E+02	2.034378E+02
2.00000	4600.00	5.757568E+02	2.067264E+02
2.00000	4700.00	6.154505E+02	2.100005E+02
2.00000	4800.00	6.572007E+02	2.136255E+02
2.00000	4900.00	6.756155E+02	2.169166E+02
2.00000	5000.00	7.052778E+02	2.202678E+02
2.00000	5100.00	7.362727E+02	2.237706E+02
2.00000	5200.00	7.685667E+02	2.273207E+02
2.00000	5300.00	8.023101E+02	2.309450E+02
2.00000	5400.00	8.375349E+02	2.346179E+02
2.00000	5500.00	8.743045E+02	2.383492E+02
2.00000	5600.00	9.115701E+02	2.420485E+02
2.00000	5700.00	9.492478E+02	2.458249E+02
2.00000	5800.00	9.871699E+02	2.497307E+02
2.00000	5900.00	1.016303E+03	2.537667E+02
2.00000	6000.00	1.053933E+03	2.581954E+02
2.00000	6100.00	1.092573E+03	2.596902E+02
2.00000	6200.00	1.132421E+03	2.631187E+02
2.00000	6300.00	1.174610E+03	2.666731E+02
2.00000	6400.00	1.221390E+03	2.696714E+02
2.00000	6500.00	1.270051E+03	2.725037E+02
2.00000	6600.00	1.320642E+03	2.759466E+02
2.00000	6700.00	1.373248E+03	2.786702E+02
2.00000	6800.00	1.427949E+03	2.818599E+02
2.00000	6900.00	1.495128E+03	2.838918E+02
2.00000	7000.00	1.567214E+03	2.858179E+02
2.00000	7100.00	1.657379E+03	2.768279E+02
2.00000	7200.00	1.764499E+03	2.444477E+02
2.00000	7300.00	1.925679E+03	2.197946E+02
2.00000	7400.00	2.075702E+03	1.958017E+02
2.00000	7500.00	2.237411E+03	1.744558E+02
2.00000	7600.00	2.411708E+03	1.544370E+02
2.00000	7700.00	2.599609E+03	1.384916E+02
2.00000	7800.00	2.862135E+03	1.233963E+02
2.00000	7900.00	3.020437E+03	1.094156E+02
2.00000	8000.00	3.255749E+03	9.794411E+01
2.00000	8100.00	3.633204E+03	2.353209E+00

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2.00000	1200.00	4.054243E+03	-2.965652E+01
2.00000	1300.00	4.344815E+03	-4.397217E+01
2.00000	1400.00	4.644223E+03	-7.807010E+01
2.00000	1500.00	4.952750E+03	-1.238785E+02
2.00000	1600.00	5.269527E+03	-2.464773E+02
2.00000	1700.00	5.594332E+03	-4.399523E+02
2.00000	1800.00	5.927441E+03	-7.335791E+02
2.00000	1900.00	6.268625E+03	-1.170319E+03
2.00000	2000.00	6.617344E+03	-2.443448E+03

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personally by request.

ENTHALPY DATA FOR ATJ-S AND AIR

P LOCAL	WALL TEMP	M WALL	3 CMW
500.00000	500.00	1.700000000	-1.670000000
500.00000	600.00	3.240000000	1.645000000
500.00000	700.00	2.465000000	3.342000000
500.00000	800.00	1.987000000	7.270000000
500.00000	900.00	-1.771000000	3.019000000
500.00000	1000.00	-6.283000000	6.723000000
500.00000	1100.00	-4.707000000	1.299000000
500.00000	1200.00	-2.743000000	1.401000000
500.00000	1300.00	0.107000000	1.525000000
500.00000	1400.00	4.310000000	1.920000000
500.00000	1500.00	6.175000000	2.165000000
500.00000	1600.00	5.664000000	2.640000000
500.00000	1700.00	6.167000000	2.527000000
500.00000	1800.00	4.630000000	2.720000000
500.00000	1900.00	7.071000000	2.093000000
500.00000	2000.00	7.391000000	3.052000000
500.00000	2100.00	3.401000000	1.505000000
500.00000	2200.00	4.574000000	-2.680000000
500.00000	2300.00	7.080000000	-2.610000000
500.00000	2400.00	9.503000000	-1.010000000
500.00000	2500.00	1.017000000	-1.627000000
500.00000	2600.00	1.057000000	-1.850000000
500.00000	2700.00	1.104000000	-2.702000000
500.00000	2800.00	1.137000000	-2.720000000
500.00000	2900.00	1.167000000	-3.185000000
500.00000	3000.00	1.182000000	-3.637000000
500.00000	3100.00	1.207000000	-4.092000000
500.00000	3200.00	1.215000000	-4.549000000
500.00000	3300.00	1.227000000	-5.007000000
500.00000	3400.00	1.240000000	-5.460000000
500.00000	3500.00	1.254000000	-5.927000000
500.00000	3600.00	1.270000000	-6.384000000
500.00000	3700.00	1.284000000	-6.839000000
500.00000	3800.00	1.300000000	-7.285000000
500.00000	3900.00	1.310000000	-7.743000000
500.00000	4000.00	1.324000000	-8.193000000
500.00000	4100.00	1.347000000	-8.634000000
500.00000	4200.00	1.373000000	-9.066000000
500.00000	4300.00	1.400000000	-9.489000000
500.00000	4400.00	1.427000000	-9.903000000
500.00000	4500.00	1.454000000	-10.308000000
500.00000	4600.00	1.481000000	-10.704000000
500.00000	4700.00	1.508000000	-11.091000000
500.00000	4800.00	1.535000000	-11.469000000
500.00000	4900.00	1.562000000	-11.838000000
500.00000	5000.00	1.589000000	-12.198000000
500.00000	5100.00	1.616000000	-12.549000000
500.00000	5200.00	1.643000000	-12.891000000
500.00000	5300.00	1.670000000	-13.224000000
500.00000	5400.00	1.697000000	-13.548000000
500.00000	5500.00	1.724000000	-13.863000000
500.00000	5600.00	1.751000000	-14.169000000
500.00000	5700.00	1.778000000	-14.466000000
500.00000	5800.00	1.805000000	-14.754000000
500.00000	5900.00	1.832000000	-15.033000000
500.00000	6000.00	1.859000000	-15.303000000
500.00000	6100.00	1.886000000	-15.564000000
500.00000	6200.00	1.913000000	-15.816000000
500.00000	6300.00	1.940000000	-16.059000000
500.00000	6400.00	1.967000000	-16.293000000
500.00000	6500.00	1.994000000	-16.518000000
500.00000	6600.00	2.021000000	-16.734000000
500.00000	6700.00	2.048000000	-16.941000000
500.00000	6800.00	2.075000000	-17.139000000
500.00000	6900.00	2.102000000	-17.328000000
500.00000	7000.00	2.129000000	-17.508000000
500.00000	7100.00	2.156000000	-17.679000000
500.00000	7200.00	2.183000000	-17.841000000
500.00000	7300.00	2.210000000	-17.994000000
500.00000	7400.00	2.237000000	-18.138000000
500.00000	7500.00	2.264000000	-18.273000000
500.00000	7600.00	2.291000000	-18.400000000
500.00000	7700.00	2.318000000	-18.518000000
500.00000	7800.00	2.345000000	-18.627000000
500.00000	7900.00	2.372000000	-18.728000000
500.00000	8000.00	2.399000000	-18.820000000
500.00000	8100.00	2.426000000	-18.904000000
500.00000	8200.00	2.453000000	-18.979000000
500.00000	8300.00	2.480000000	-19.046000000
500.00000	8400.00	2.507000000	-19.105000000
500.00000	8500.00	2.534000000	-19.156000000
500.00000	8600.00	2.561000000	-19.200000000
500.00000	8700.00	2.588000000	-19.236000000
500.00000	8800.00	2.615000000	-19.265000000
500.00000	8900.00	2.642000000	-19.287000000
500.00000	9000.00	2.669000000	-19.302000000
500.00000	9100.00	2.696000000	-19.310000000
500.00000	9200.00	2.723000000	-19.312000000
500.00000	9300.00	2.750000000	-19.308000000
500.00000	9400.00	2.777000000	-19.298000000
500.00000	9500.00	2.804000000	-19.282000000
500.00000	9600.00	2.831000000	-19.260000000
500.00000	9700.00	2.858000000	-19.232000000
500.00000	9800.00	2.885000000	-19.198000000
500.00000	9900.00	2.912000000	-19.158000000
500.00000	10000.00	2.939000000	-19.113000000

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2.69897	2200.00	-5.304954E+02	1.106172E+02
2.69897	2300.00	-2.964627E+02	1.216454E+02
2.69897	2400.00	-1.417813E+02	1.244009E+02
2.69897	2500.00	-6.533650E+01	1.273238E+02
2.69897	2600.00	-2.978986E+01	1.308991E+02
2.69897	2700.00	-4.513403E+00	1.420275E+02
2.69897	2800.00	1.452766E+00	1.440674E+02
2.69897	2900.00	1.232927E+01	1.492762E+02
2.69897	3000.00	9.197255E+01	1.525557E+02
2.69897	3100.00	1.053458E+02	1.557053E+02
2.69897	3200.00	1.206547E+02	1.589258E+02
2.69897	3300.00	1.381867E+02	1.622100E+02
2.69897	3400.00	1.582647E+02	1.656215E+02
2.69897	3500.00	1.812674E+02	1.690335E+02
2.69897	3600.00	2.076115E+02	1.724755E+02
2.69897	3700.00	2.377915E+02	1.759307E+02
2.69897	3800.00	2.723350E+02	1.796776E+02
2.69897	3900.00	3.114116E+02	1.839064E+02
2.69897	4000.00	3.552354E+02	1.871005E+02
2.69897	4100.00	4.041523E+02	1.910453E+02
2.69897	4200.00	4.478723E+02	1.944387E+02
2.69897	4300.00	4.756541E+02	1.975117E+02
2.69897	4400.00	5.052232E+02	2.004324E+02
2.69897	4500.00	5.369475E+02	2.030746E+02
2.69897	4600.00	5.694153E+02	2.057255E+02
2.69897	4700.00	6.153054E+02	2.117797E+02
2.69897	4800.00	6.421926E+02	2.136212E+02
2.69897	4900.00	6.711615E+02	2.159071E+02
2.69897	5000.00	7.024571E+02	2.206244E+02
2.69897	5100.00	7.359260E+02	2.239005E+02
2.69897	5200.00	7.695748E+02	2.276494E+02
2.69897	5300.00	8.121045E+02	2.310340E+02
2.69897	5400.00	8.554434E+02	2.345841E+02
2.69897	5500.00	8.762759E+02	2.383908E+02
2.69897	5600.00	9.056605E+02	2.421562E+02
2.69897	5700.00	9.422075E+02	2.449545E+02
2.69897	5800.00	9.758131E+02	2.484163E+02
2.69897	5900.00	1.009375E+03	2.539195E+02
2.69897	6000.00	1.044738E+02	2.544731E+02
2.69897	6100.00	1.081241E+03	2.603905E+02
2.69897	6200.00	1.117686E+03	2.640715E+02
2.69897	6300.00	1.156131E+03	2.674691E+02
2.69897	6400.00	1.194912E+03	2.713498E+02
2.69897	6500.00	1.235875E+03	2.748021E+02
2.69897	6600.00	1.276644E+03	2.787355E+02
2.69897	6700.00	1.372901E+03	2.819099E+02
2.69897	6800.00	1.366103E+03	2.854491E+02
2.69897	6900.00	1.415003E+03	2.890933E+02
2.69897	7000.00	1.465005E+03	2.927477E+02
2.69897	7100.00	1.517612E+03	2.967544E+02
2.69897	7200.00	1.576875E+03	2.997096E+02
2.69897	7300.00	1.538452E+03	3.032960E+02
2.69897	7400.00	1.705315E+03	3.037843E+02
2.69897	7500.00	1.803635E+03	2.879788E+02
2.69897	7600.00	1.912336E+03	2.729995E+02
2.69897	7700.00	2.021678E+03	2.587027E+02
2.69897	7800.00	2.144486E+03	2.453277E+02
2.69897	7900.00	2.270925E+03	2.325638E+02
2.69897	8000.00	2.404818E+03	2.204439E+02
2.69897	8100.00	2.545606E+03	2.080035E+02

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1 = 4202.5 2 = 2565.2 3 = 616.3 4 = 501.3 5 = 335.3 6 = 239.3 7 = 180.3 8 = 127.3
9 = 97.3 10 = 86.3 11 = 82.3

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

CRITICAL INDEX NO. = 6, TIME STEP = 1.030076E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.20800E-01 SECONDS.

REC ENTH	RHO U CH	P LOCAL	CM/CH	LEWIS #	BLOWING PARAM	SPACE TEMP R
1.28700E+03	3.95967E+00	1.00001E+02	1.00000E+00	1.00000E+00	4.00000E-01	1.00000E-04

MODE	Q CONV	Q COND	Q CHM TOT	Q CHM TOT	Q COND TOT	Q RAD IN	Q RAD OUT	Q SENS TOT	IN RAD TOT	OUT RAD TOT	M DOT	REC RATE	CHM/CH	MASS LOST	REFLECTION	M WALL	ACCUM Q ERR	Q NET	CM
1	2.91155E+03	7.41412E+02	1.63341E+01	5.85615E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	5.48599E-01	7.01127E-02	1.39673E-02	1.39673E-02	1.50908E-03	5.01604E+02	-2.58346E-03	-2.2072E+00	3.70711E+00

TIME (SEC):
2.20800E-01

1 = 3934.0 2 = 2541.9 3 = 1041.9 4 = 572.0 5 = 369.3 6 = 244.1 7 = 198.7 8 = 137.7
9 = 102.6 10 = 88.4 11 = 83.0 12 = 80.9 13 = 80.4

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

CRITICAL INDEX NO. = 6, TIME STEP = 1.030076E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.31740E-01 SECONDS.

REC ENTH	RHO U CH	P LOCAL	CM/CH	LEWIS #	BLOWING PARAM	SPACE TEMP R
1.28700E+03	3.95967E+00	1.00001E+02	1.00000E+00	1.00000E+00	4.00000E-01	1.00000E-04

MODE	Q CONV	Q COND	Q CHM TOT	Q CHM TOT	Q COND TOT	Q RAD IN	Q RAD OUT	Q SENS TOT	IN RAD TOT	OUT RAD TOT	M DOT	REC RATE	CHM/CH	MASS LOST	REFLECTION	M WALL	ACCUM Q ERR	Q NET	CM
1	2.92529E+03	7.39757E+02	1.63341E+01	5.85615E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	6.48308E-01	7.00951E-02	2.10230E-02	2.10230E-02	1.51602E-01	5.01604E+02	-1.63727E-03	1.41602E-01	3.70556E+00

TIME (SEC):
2.31740E-01

1 = 3922.1 2 = 2545.2 3 = 1111.4 4 = 617.2 5 = 393.1 6 = 275.8 7 = 208.1 8 = 142.5
9 = 103.6 10 = 89.7 11 = 83.5 12 = 81.1 13 = 80.4 14 = 80.3

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

CRITICAL INDEX NO. = 6, TIME STEP = 1.119476E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.5453E-01 SECONDS.

REC ENTH	RHO U CH	P LOCAL	CM/CH	LEWIS #	BLOWING PARAM	SPACE TEMP R
1.28700E+03	3.95967E+00	1.00001E+02	1.00000E+00	1.00000E+00	4.00000E-01	1.00000E-04

MODE	Q CONV	Q COND	Q CHM TOT	Q CHM TOT	Q COND TOT	Q RAD IN	Q RAD OUT	Q SENS TOT	IN RAD TOT	OUT RAD TOT	M DOT	REC RATE	CHM/CH	MASS LOST	REFLECTION	M WALL	ACCUM Q ERR	Q NET	CM
1	2.92529E+03	7.39757E+02	1.63341E+01	5.85615E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	6.48308E-01	7.00951E-02	2.10230E-02	2.10230E-02	1.51602E-01	5.01604E+02	-1.63727E-03	1.41602E-01	3.70556E+00

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NOMENCLATURE

A	area
ALPHA_w	absorptivity of the surface evaluated at T_w
CH	heat transfer Stanton number ($q_{\text{conv}}/\rho_e U_e \Delta H$)
C_m	mass transfer Stanton number ($m_d/\rho_e U_e \Delta Z$)
c_p	specific heat
e	natural logarithm base
F	radiation view factor
$h_{a,w}, h_{a,2}$	the sensible enthalpies above T_{ref} of an ablative material evaluated at T_w and T_2 , respectively
h_r	sensible recovery enthalpy
h_w	sensible gas enthalpy at the wall
$\Delta H_{i,w}$	chemical enthalpy change of each diffusing specie i due to reactions with the ablative material. $\Delta H_{i,w}$ is evaluated at T_w , and equals $H_{i,w} - \bar{H}_{rg,w}$
H	total enthalpy above T_{ref} (i.e., $H = \text{sensible} + \text{chemical enthalpies}$)
$H_{a,w}$	total enthalpy above T_{ref} of solid ablative materials evaluated at T_w
$\bar{H}_{dg,w}$	average total enthalpy above T_{ref} of gases diffusing to the surface, evaluated at T_w
$\bar{H}_{e,w}$	average total enthalpy above T_{ref} of gases at the thermal temperature boundary layer edge, evaluated at T_w
H_r	total recovery enthalpy above T_{ref}

$H_{i,w}$	total enthalpy above T_{ref} of gaseous specie i diffusing to the surface, evaluated at T_w
$H_{rg,w}$	average total enthalpy (above T_{ref}) of the reacted gases at the surface, evaluated at T_w
K_{i-j}	thermal conductivity between elements i and j
L_{i-j}	distance from element i to element j
m_a	ablative mass loss rate per unit area
m_d	mass flow rate per unit area of all gases diffusing to the surface
m_i	mass flow rate per unit area of gaseous species i diffusing to the surface
m_{mech}	mechanical erosion mass loss
m_{rg}	mass flow rate per unit area of all reacted gases leaving the surface via diffusion and mass transfer
N	number of species diffusing to the wall
P_L	local pressure
q_a	chemical heating rate per unit area due to ablative material reacting at the surface
q_{chem}	chemical heating rate per unit area ($q_{chem} = q_d + q_a$)
q_{cond}	conduction heat transfer rate per unit area
q_{conv}	convection heating rate per unit area
q_d	chemical heating rate per unit area due to diffusing gases reacting at the surface
q_{in}	total heating rate per unit area due to laser heating and/or other radiative heating

q_{las}	incident laser heating rate per unit area
$q_{rad\ in}$	heating rate per unit area due to radiation to the surface
$q_{rad\ out}$	heat loss rate per unit area due to radiation from the surface
q_{sens}	heating rate per unit area required to raise the sensible energy of the solid ablative material from T_2 to T_w
Q_{vap}	heat of vaporization (Btu/lb)
T_{ref}	reference temperature at which chemical and sensible enthalpies are zero (T_{ref} is often set at $536^\circ R$)
T_{sp}	space temperature, to which the surface radiates
T_w, T_2, T_3	temperature at the wall and at interior nodes 2 and 3
U_e	velocity parallel to the surface at the boundary layer edge
V	element volume
VIEW	view factor for the incident laser beam
$Z_{i,e}, Z_{i,w}$	diffusion mass transfer potentials of specie i evaluated at the boundary layer edge and at the wall respectively (these potentials are discussed in Ref. 5)
α	blowing coefficient, $\frac{2\lambda_m}{\rho_e U_e C_H}$
β	ablation to diffusion mass loss ratio defined as $\beta = \frac{m_a}{\rho_e U_e (C_m)_b}$
ϵ_w	thermal emissivity of the surface evaluated at T_w

λ	an empirical constant known as the "blowing parameter" (usually $\lambda = 0.5$ for laminar flow and $\lambda = 0.4$ for turbulent flow)
ρ	material density
ρ_e	density at the boundary layer edge
σ	Stefan-Boltzman constant
τ_a, τ_b, τ_c	times at three consecutive time steps (a, b, and c)

Subscripts

a	ablative material
b	corrected for blowing
d	diffusion
dg	diffusion gas
e	boundary layer edge
i	specie i diffusing to the wall
rg	radiating gas
r	recovery condition
w	wall
2-5	from node 2 to node 5

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