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A FORTRAN COMPUTER PROGRAM FOR THE SOLUTION OF MULTI-DIMENSIONAL, TRANSIENT, ABLATION PROBLEMS

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ABSTRACT

A flexible FØRTRAN computer program to determine the temperature history and ablation history of aerodynamically heated flight bodies has been devised. The effect on heat conduction and aerodynamic heating histories of the removal of ablating wall materials is automatically accounted for by the computer program. The program is flexible in that it can accommodate flight body heat conduction inputs in the form of any reasonable combination of geometry and construction materials. The program will accept only one ablative material at any single position on the flight body surface but different ablative materials can be specified for different locations. One section of the program receives flight trajectory, radiation-property, and local aerodynamic flow inputs and provides for the computation of local aerodynamic heating and radiation relief. The other section of the program governs the computation of temperature history throughout the flight body and the thickness history of ablating layers. There is no provision for readjusting vehicle aerodynamics in accordance with body-shape changes. In setting up the program it was assumed that the process of decomposition of the ablative material was concentrated at the surface and that the chemistry of the decomposition could be accounted for by empirically-based effective heats of ablation and ablation surface temperatures instead of chemical reaction equations and associated chemical reaction rate constants. Since the report is to serve as a user's manual, a detailed description of the computer program is provided. The description covers the engineering approach adopted in relation to the general problem of determining temperature and ablation histories in a flight body by numerical methods. This is followed by information on the program structure, flow of program information, and FØRTRAN nomenclature. A

sample problem is posed and step-by-step preparation of the FØRTRAN codi
is explained. Finally, an actual print-out from a computer run for the
problem is displayed and discussed.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

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A FØRTRAN COMPUTER PROGRAM FOR THE SOLUTION OF MULTI-DIMENSIONAL, TRANSIENT, ABLATION PROBLEMS

INTRODUCTION

One of the many considerations in the design of a hypersonic defense missile is the thermal protection system. Ablative systems are attractive in this regard because of their automatic response to aerodynamic heat flux and consequent simplicity compared to transpiration or ducted cooling systems. As a result of this situation, there is a continuing demand for efficient, flexible, and effective ablation design calculation procedures. This demand has been met, in part, by the appearance of a number of ablation computer programs. However, such programs have tended to be oriented toward the re-entry problem and it has seemed that more attention could have been given to constructing programs flexible enough to accept the variety of geometries, materials, and trajectory inputs associated with the hypersonic missile problem. This report presents an ablation computer program for subliming ablators that has been constructed with this flexibility in mind. The report was prepared both as a descriptive exposition of a particular engineering method and as a user's manual. Thus it lays out for the potential user, not only the general engineering techniques, but also the flow of program information and the step-by-step instructions to the person preparing the FØRTRAN coding sheets. Before proceeding further, a quick review of ablation processes is in order.

As is well known, ablation is characterized by the disintegration of a solid material under the combined mechanical and thermal action of a boundary layer of hot gas. In high-speed flight, ablation generally occurs as a combination of physical and chemical processes. The principal physical modes of ablation are:

(a) Melting of a solid surface

(b) Vaporization of a liquid

(c) Sublimation of a solid surface

(d) Fracturing or shearing of solid surface layers

Chemical processes occurring during ablation fall into the following major categories:

(a) Oxidation of solid surface

(b) Oxidation of released gas

(c) Molecular break-down of solid under action of heat (pyrolysis)

In typical ablation processes various combinations of the foregoing reactions usually occur. Some examples are the following:

Quartz - The solid surface melts and is swept along by the air boundary layer while the liquid vaporizes into the boundary layer.

Teflon - The supermolecule (polymer) breaks down in depth, releasing monomer gas and the gas is oxidized at the surface by oxygen from the boundary layer.

Graphite - Oxygen diffuses inward through the boundary layer to support combustion of carbon at the graphite surface.

Phenolic Resin - The supermolecule breaks down in a high-temperature surface layer. Gases are released leaving a porous carbon (char) layer. The released gases react with oxygen which is diffusing inward through the air boundary layer.

In designing the computer program, attention was focused on the case of the pyrolyzing ablator. It was assumed that volume-loss calculations would be initially restricted to the case in which the exposed surface of the ablator undergoes a pyrolyzing process equivalent to a sublimation phase-change. It was

anticipated that more complex ablation processes such as charring could be accommodated at a later date. Meanwhile, however, if surface combustion takes place or if chemical decomposition takes place in depth, the situation is accommodated by assuming the chemical decomposition processes to be concentrated at the surface in the form of a sublimation phase-change having a known effective heat of ablation and a known ablation surface temperature. As a result, the computer program is realistically based on the availability, in the literature, of data on the effective heat of ablation and ablation surface temperature.

The numerical technique is based on the familiar lumped-parameter approach in forward-difference form and is programmed specifically for the IBM 7094 digital computer. The program consists of a number of FØRTRAN and FAP subroutines which are called into action upon command of a FØRTRAN control program. The control program is prepared by the user in accordance with the problem at hand. In a broad sense, the program combines boundary-layer local heat transfer, ablation, and radiation at the surface with multi-dimensional heat conduction beneath the surface of a body in non-steady high speed flight. The program accounts for the effect of in-flight body contour changes on non-steady heat conduction but does not account for the effect of in-flight body contour changes on vehicle aerodynamics. Hence, addition of this feature is planned for sometime in the future. Input data consist of flight trajectory and flight-body details and, in particular, the ablation temperature and a modified form of the effective heat of ablation.

The report is divided into four different sections ranging in content from engineering considerations to a solution of an actual ablation problem. The organizational plan is as follows:

Section 1. Problem Formulation and Governing Equations. This section covers the engineering methods employed.

Section 2. Structure of Program. This section covers the inputs, subprograms, and information flow.

Section 3. The FØRTRAN Control Program. This section describes the content of the principal FØRTRAN statements and gives the program nomenclature.

Section 4. Sample Problem. This section describes the detailed preparation of the FØRTRAN statements on coding sheets, using a specific example.

SECTION 1

PROBLEM FORMULATION AND GOVERNING EQUATIONS

In this section, a typical problem in subliming ablation will be formulated and discussed in order to bring out the engineering techniques adopted. In the section following this one the structure and processes of the computer program itself will be described. The present discussion of engineering techniques culminates in the formulation of a forward-difference numerical procedure. Along the way, various inputs to this numerical procedure are introduced. These inputs are reviewed in Section 2.

In general, the physical problem consists of a flight body whose surface is subjected to aerodynamic heating while also exchanging thermal radiation with the surroundings (i.e., "effective space"). Figure 1 shows schematic diagrams for a typical problem.

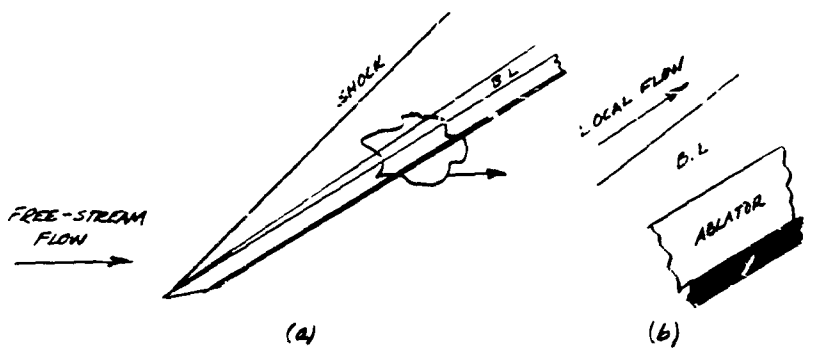


Figure 1. Schematic Diagram of a Typical Ablation Problem

The center of interest in the overall model in Figure 1a is shown as a segment of the boundary layer and wall in Figure 1b. In order to determine local flow conditions (Figure 1b), the aerodynamic problem (Figure 1a) must first be solved. Completion of the aerodynamic phase of the calculations makes it possible to carry

out the second phase which involves the determination of local heat and mass transfer at the exposed surface. The second phase of the calculations can be carried out if the "present-time" local surface temperature has been calculated or the "present-time" ablation surface temperature has been specified on the basis of published ablation data. The third phase of the problem solution makes use of finite-difference equations and carries heat conduction in the wall from "present time" to "future time" by taking a forward step in time.

The overall ablation problem is defined by setting forth body configuration, initial conditions, boundary conditions, and material properties. Problem definition for the region external to the wall surface involves the following items:

(1) Flight body configuration and local flow conditions

(2) Mach number and altitude versus time after launch

(3) Atmospheric properties versus altitude

(4) Transition Reynolds number

(5) Radiation environment

Problem definition for the region at and beneath the wall surface involves the following items.

(1) Wall materials, their arrangement and dimensions

(2) Wall material properties as functions of temperature:

a. Thermal conductivity

b. Density

c. Specific heat

d. Surface emissivity

(3) Additional properties for ablators as functions of $(H_{aw} - H_w)$:

a. The modified effective heat of ablation

b. Ablation surface temperature

(4) Initial wall temperature distribution

(5) Thermal boundary conditions on internal surfaces of the vehicle

Under these conditions it can be shown that the wall surface temperature and ablation rate are determined at every point in flight.

In the example of the flat plate at angle-of-attack (Figure 1a), computations begin with the conversion of upstream flow conditions to the local conditions of the stream external to the boundary layer at the body station under study. Compressible flow charts or air tables are used to determine pressure and Mach number behind the shock using the perfect gas, the thermally perfect gas, or the real gas case as appropriate. Next, the energy equation is used to determine the local temperature. At this stage the local pressure, temperature, and Mach number at the edge of the boundary layer are sufficient to determine the local heat transfer if the present-time local wall surface temperature is known. Fortunately, the latter is always known in a forward-difference numerical method of solution. This completes the determination of local flow conditions. One additional calculation is needed to determine the local Reynolds number.

The local convective heat transfer is based on standard equations of the form

$$\frac{h_H c_p x}{k} = C Re_x^m Pr^n \qquad (1)$$

C, m, and n are determined by the prescribed geometry and by the relative magnitudes of the previously calculated local Reynolds number and the prescribed transition Reynolds number. During ablation, the effect of mass transfer on convection heat transfer must be taken into account. This effect is provided for later on in the formulation of the energy equation for an ablating wall surface element by introducing the transpiration factor β_H. For the present, the enthalpy-based heat transfer coefficient is employed in the relation

$$q_o = h_{H,o}(H_{aw} - H_w) \tag{2}$$

to obtain the ordinary local rate of convective heat flow per unit area to a non-ablating wall.

The convective calculation procedure calls for determining air properties by a modification of Eckert's (1) reference enthalpy (i.e., H*) method. The modification involves the use of numerical constants recommended by Rubesin and Johnson (2) and Sommer and Short (3), respectively, as follows

$$H^* = 0.58\, H_w + 0.42\, (1 + 0.076\, M^2)H \qquad \text{(Laminar)} \tag{3}$$

$$H^* = 0.45\, H_w + 0.55\, (1 + 0.064\, M^2)H \qquad \text{(Turbulent)} \tag{4}$$

A value of T* corresponding to H* is found from a polynomial based on well-accepted air tables of H versus T at a constant pressure of one atmosphere. With T* so determined, an enthalpy-based heat-transfer coefficient is computed using a rearranged form of the standard heat transfer relation containing Pr = 0.72. The relation is

$$h_H = Cx^{m-1}\, (\rho^* u)^m\, (\mu^*)^{1-m}\, (0.72)^{n-1} \tag{5}$$

The Sutherland viscosity relation

$$\mu^* = \mu_o \frac{T^{*3/2}}{T^* + T_c} \tag{6}$$

provides the viscosity.

The adiabatic-wall enthalpy H_{aw} of the boundary-layer air is computed by using a recovery factor of 1.0, 0.85, or 0.9 for the stagnation point, the laminar boundary layer, or the turbulent boundary layer respectively. Local convective (and non-ablative) heat transfer q_o is then computed by use of Equation (2) to complete the convective phase of the calculation.

Radiation from the wall surface to the prescribed radiation environment is computed by means of the standard radiation equation based on a unit area of surface

$$q_{rad} = \sigma F_A F_\varepsilon (T_w^4 - T_{space}^4) \tag{7}$$

Configuration, emissivity factors, and effective space temperature T_{space} used in this equation are prescribed during the problem definition stage and the present-time wall temperature is always known in the forward-difference method.

The variable-property conduction situation in the wall is handled by employing a lumped-parameter equation of non-steady heat flow in more than one dimension. A two-dimensional sketch of a typical lumped-parameter break-up of a wall segment is shown in Figure 2. This view of a wall segment is an enlargement of the segment shown earlier in Figure 1b.

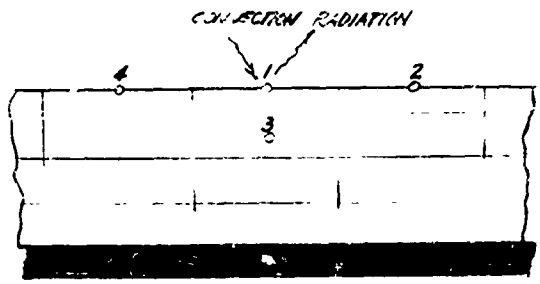


Figure 2. A Two-Dimensional Break-up of a Wall Segment Showing Nodes

In the absence of ablation, convection heat transfer per unit area q_o arrives at area A_1 of element 1 and $q_{rad}A_1$ departs. Additional heat is transferred to element 1 by conduction from other elements i through conductances kA/ℓ, k_2/L, etc. which are called $K_{i,1}$. The net heat transfer to element 1 is equal to the thermal storage in a thermal capacitance $(\rho V c_{p(s)})_1 = C_1$. Thus, if temperatures of elements i at the present time t are denoted by T_i and those at future

time t + Δt are denoted by T_i^+, a forward-difference equation can be written as

$$q_o A_1 + \sum_{i=2}^{4} K_{i,1}(T_i - T_1) - q_{rad} A_1 = C_1 \frac{T_1^+ - T_1}{\Delta t} \tag{8}$$

To prevent temperature overshoot and subsequent oscillations in calculated values, Dusinberre (4) shows that the prescribed time step Δt must be less than a critical time step

$$C_1 / \sum_i K_{i,1} \tag{9}$$

where the $K_{i,1}$ include the respective equivalent conductances for convection and radiation,

$$\frac{q_o A_1}{T_{aw,1} - T_1} \tag{10}$$

and

$$\frac{q_{rad} A_1}{T_1 - T_{space}} \tag{11}$$

, time step sized by Dusinberre's criterion is called a stability time step. When an element is not subjected to convection or radiation the corresponding terms drop out of Equations (8) and (9).

As the calculated temperature of element number 1 (Figure 2) moves toward the ablation temperature of element number 1, overshooting and oscillation must be avoided. It is assumed that the ablation temperature associated with the prescribed material of the protective layer has been specified as a function of heat-transfer driving potential ($H_{aw} - H_w$) or as a constant. Thus, ablation chemistry is accounted for in the calculations empirically, and the need for specific temperature-dependent chemical relations is circumvented. With ablation

temperature specified as a constant or in terms of $(H_{aw} - H_w)$, it is known as the calculations move ahead in flight time. Any overshooting of the ablation temperature $T_{abl,1}$ by surface temperature T_1^+ is prevented by making the time step in equation (8) less than or equal to

$$\frac{C_1(T_{abl,1} - T_1)}{[q_o A_1 + \sum_{i=2}^{4} k_{i,1}(T_i - T_1) - q_{rad}A_1]} \tag{12}$$

In the calculation procedure this criterion is tested along with the stability expression (9) and the smallest of the two time steps is selected. In practice all elements are scanned, and the time step selected is the smallest for all elements.

If surface element 1 is ablating, the ablation processes can be likened to sublimation. Accordingly, the ordinary convective heat transfer toward area A_1 is diminished by the equivalent blocking action, $\dot{m}\beta_H(H_{aw,1} - H_{w,1})$ due to the mass blowing rate $\dot{m}$, and transpiration factor β_H (see Appendix A). Hence q_o in Equation (8) is replaced by

$$q_o - \dot{m}\,\beta_H(H_{aw,1} - H_{w,1}) \tag{13}$$

during ablation. The temperature-dependent ablation chemistry is represented, in the sublimation model, by an enthalpy of sublimation $H_{(sg)}$ and a sublimation temperature T_{abl}. If ablation occurs during a forward time step, the ablating element is held at its present ablation temperature T_{abl} until the completion of the time step. Therefore, during ablation the capacitance term of Equation (8) is replaced by a term which accounts for the mass decrease

$$H_{(sg)} \frac{V_1 - V_1^+}{\Delta t} \rho_1 \tag{14}$$

Since in finite-difference form $\dot{m} = \rho_1(V_1 - V_1^+)/A_1\Delta t$, Equation (8) becomes, upon introduction or Equations (13) and (14) and rearrangement of terms,

$$q_o A_1 + \sum_{i=2}^{4} K_{i,1}(T_i - T_1) - q_{rad}A_1 = \left[H_{(sg)} + \beta_H(H_{aw} - H_w)\right]_1 \rho_1 \frac{V_1 - V_1^+}{\Delta t} \qquad (15)$$

The term in square brackets is called the modified effective heat of ablation. In Appendix A it is shown that

$$H_{(sg)w} + \beta_H(H_{aw} - H_w) = \left\{ \frac{q_o}{\dot{m}} - \int_{T_o}^{T_w} c_{p(s)}dT - \frac{q_{rad}}{\dot{m}} \right\}_{\substack{\text{semi-}\\ \text{infinite}\\ \text{test body}}} \qquad (16)$$

It is clear that there are at least two ways of obtaining the input data needed to fill in the square bracket in Equation (15). They are:

(1) Obtain $H_{(sg)}$ from the chemical literature and β_H from the mass-transfer literature, and evaluate the term directly.

(2) Obtain from the literature on ablation experiments the quantities needed to complete the semi-infinite test body expression in Equation (16).

During ablation calculations, the time step chosen for Equation (15) must not be such that V_1^+ becomes negative, for this would mean more element volume was removed than was available at the beginning of the time step. It follows that the time-step must be less than or equal to

$$\frac{\left[H_{(sg)w} + \beta_H(H_{aw} - H_w)\right]_1 \rho_1 V_1}{q_o A_1 + \sum_{i=2}^{4} K_{i,1}(T_i - T_1) - q_{rad}A_1} \qquad (17)$$

In the final analysis, a time step is chosen after scanning all ablating surface elements to check for the smallest time to ablate away, after scanning all non-ablating surface elements to check for the smallest time to reach ablation temperature, and after scanning all elements to check for the smallest stability time step. The smallest time step dictated by all three criteria must not be exceeded by a given step forward in time.

Figure 3 shows an intermediate stage of ablation. Elements are assumed to be proportioned so that ablation of a given element occurs in one dimension. As a consequence of the effect of volume change on the cross-sectional area and path-length of conduction paths between nodes, adjustments must be made in the K-values of Equations (8), (9), (12), (15), and (17). With reference to Figure 3, the thermal conductance between nodes i and 1 is defined by the relation

$$\frac{1}{K_{i,1}} = \frac{1}{K_{i,il}} + \frac{1}{K_{il}} + \frac{1}{K_{il,1}} \tag{18}$$

where the subscript il denotes the real or imaginary interface between elements i and 1. A typical conductance term is defined by the relation

$$K_{i,il} = \kappa_i \frac{a_i}{L_{i,il}} \tag{19}$$

where a_i is the area normal to the flow or heat in the x-direction. According to Figure 3, a_i must be continually reduced by a factor V_i^+/V_i in order to account for ablation. Also, $\ell_{i,i3}$ must be continually reduced by the same ratio to account for the movement of node i toward interface i3. By means of these adjustments, the $K_{i,1}$ in Equations (8), (9), (15), and (17) are modified to reflect the current status of conduction geometry.

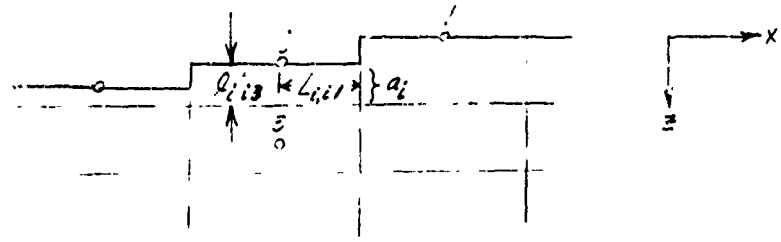


Figure 3. Surface Element Shrinkage Due to Ablation

With regard to the earlier determination of the local convective heat transfer coefficient $h_{H,o}$ it can now be seen that by taking a forward step in time, the calculation always has available for use the local wall surface temperature at the present time. Thus, the reference temperature T* (see Equations (3) and (4)) is computed for conditions at the present time and in the same way, material properties are read from tables of properties by entering the tables at point temperatures corresponding to the present time. Lastly, in the forward difference method, the rate of heat flow to any node (see Equations (8) and (15)) is always based on temperatures at the present time. The method therefore avoids the iteration involved in a formulation calling for heat conduction, convection, radiation or property inputs corresponding to temperature conditions at the end of the time step under consideration.

SECTION 2

STRUCTURE OF PROGRAM

The basic ablation computer program contains, in effect, a set of available thermal capacitors and conductors corresponding to capacitances C and conductances K of the previous section. These are connected by the user who, in writing a control program, brings into play the lumped-parameter equations described in the previous section. Convective, conductive, and/or radiative heating rates are computed for each capacitor in accordance with these equations. Each thermal capacitance is computed from the size and thermal properties supplied as inputs. Prior to the onset of ablation, the program computes transient temperatures, based on the current net heating rate and thermal capacitance, by taking a forward step in time. As already pointed out, the program sizes the time step so as not to allow the temperature of any capacitor to overshoot and cause oscillations in subsequent finite difference calculations and so as not to allow the temperature of any surface element to exceed its ablation temperature. The ablation temperature for each material is an input specified as a function of the difference between the adiabatic wall and wall enthalpies of air. When an element reaches its ablation temperature its temperature is thereafter determined by the local difference between the adiabatic wall and wall enthalpies of air. If the heat input to an ablating element becomes negative the element temperature is again computed from the relation between net heat input and capacitance. While ablation is in progress the time step is sized to prevent the calculated volume decrease of the element from overshooting the element volume available. Also, provision is made to vary the resistances between capacitors (i.e., elements) in accordance with the decrease in surface capacitor volumes due to ablation and to discard capacitors which have ablated away. Contained in the printout of the program are the free stream

aerodynamic conditions, the local flow conditions including the local heat transfer coefficient and adiabatic wall temperature, the capacitor temperatures and temperatures at the interface between the capacitors, the thickness of remaining ablator, the modified effective heat of ablation, and the ablation temperature.

The ablation program has been constructed in two distinct sections; a group of binary subroutines and a FØRTRAN control program. The binary subroutine deck contains, in effect, the reservoir of capacitors and resistors mentioned earlier. It also contains the lumped-parameter equations necessary to compute the various modes of heat transfer, the equations to compute capacitor temperatures, and equations which give it the ability to size the time step according to the three time-step criteria. The geometry being analyzed is taken into account by the user who will be called the FØRTRAN control program writer. The FØRTRAN control program writer, in effect, assembles a network from the reservoir of capacitors and conductors by designating specific index numbers in the calling sequence of the appropriate binary subroutines. By calling other routines he sets initial conditions and provides for computation of heating rates as functions of time, computation of transient temperatures and ablation rates, and computation of properly sized time steps. This feature of being able to construct a problem in the course of calling various subroutines gives the program a great deal of flexibility.

The FØRTRAN control program supplies the input data needed by the subroutines to make the required calculations. These input data are entered into the program via a COMMON statement or through the calling sequence (arguments) of the subroutine CALL statements. Furthermore, a detailed break-down of certain of these input data is given in tabular statements.

Specifically, the FØRTRAN control program consists of the following parts:

I. A DIMENSIØN statement

II. A CØMMØN statement

III. A series of tabular statements

IV. A series of CALL statements

As usual the Part I DIMENSIØN statement sets aside the appropriate number of tabular spaces in the computer and the Part II CØMMØN statement provides the appropriate number of spaces through which, in effect, certain variables can pass from one subroutine to another. A small, but not negligible, amount of information on problem geometry enters the CØMMØN statement. By contrast, the tabular statements of Part III deal almost wholly with details of the problem at hand. Tabular statements must include the following:

1. Mach number versus time
2. Altitude versus time
3. Ambient temperature and pressure versus altitude
4. Local aerodynamic flow conditions (M/M_o versus M_o and P/P_o versus M_o)
5. The effective space temperature versus altitude
6. The emissivity of external surfaces versus temperature
7. A series of coefficients and exponents concerned with the aerodynamic heating equations, plus a transition Reynolds number
8. The initial volumes of all potential ablating capacitors
9. An ablation sequence prescribing the order of capacitor ablation
10. The material density, specific heat, and conductivity as a function of temperature

11. The ablation temperature versus air-enthalpy difference
12. The modified effective heat of ablation versus air-enthalpy difference
13. The capacitor numbers of all initial surface elements

In supplying the foregoing tabular information in numerical form the FØRTRAN control program writer must assign a variable name to each type of entry and identify, by subscripting, each individual numerical entry. With the exception of items 8 and 9, Part III tabular information is transferred to subroutines via the Part IV calling sequences (arguments) of the subroutine CALL statements. This transfer is made possible when the program writer enters tabular variable names in designated positions within the argument of the CALL statements. Items 8 and 9 are entered into the CØMMØN statement and thereby become directly available to the subroutines. In writing the CALL statements of Part IV, the FØRTRAN control program writer draws on a reservoir of capacitors and conductors and assembles them into a network. This step is described in more detail in the next paragraph.

Problem inputs not covered by items 1 to 13 above, are introduced into the CALL statement arguments along with the tabular variables. They appear in the argument as numerical values, unlike the tabular variables which appear as variable names. The numerical inputs in question are:

1. Index numbers of capacitors
2. Initial capacitor temperatures
3. Exposed surface area of capacitor and its Reynolds number reference length
4. Capacitor volume

5. Original area-to-length ratio for resistors and contact resistance values
6. Radiation configuration factors

It is important to note again that the flexibility of the program exists in the reservoir of capacitors and conductors whose index numbers can be called according to the requirements of the geometry of the problem under study. Experience teaches one how best to divide a given heat-transfer model into the elements that ultimately become the capacitors and conductors of the computer program.

Under Part IV of the FØRTRAN control program twelve main subroutines in the binary subroutine deck can be called. They are entitled:

1. ASET	7. CØN
2. TRAJ	8. ACØMCN
3. ATM	9. RAD
4. FØRALT	10. WRITE
5. AAERØ	11. ASTEP
6. ACAP	12. ABL

For some of these subroutines, the order in which the writer of the FØRTRAN control program calls them is critical; for others it is not. To avoid errors, it is suggested that the subroutines be called in the order given above in all cases. Even when one is well versed in the use of the program he will find no particular advantage in changing the order of the CALL statements from that given above. A discussion follows which is intended to provide a brief view of the structure and operation of each subroutine and the overall operation of the program.

The ASET subroutine is a FAP subroutine which sets the initial temperature of each capacitor and defines the beginning and end of flight time. These

settings are chosen by the FØRTRAN control program writer and entered into the argument of the CALL ASET statement.

Subroutine TRAJ is essentially a table look-up FØRTRAN routine which requires as inputs, through its argument, the variable names previously assigned by the control program writer in preparing the tables of Mach number and altitude versus time. The function of TRAJ is to quadratically interpolate in the tables using the current value of time to obtain the current Mach number and altitude. These two items leave the subroutine via the CØMMØN statement and thus become available for later use by the ATM, AAERØ, FØRALT, and WRITE subroutines.

The FØRTRAN subroutine ATM is also a table look-up routine. The control program writer must place the variable names assigned in the tables of static temperature, pressure, and altitude in the argument of ATM when calling the routine. ATM linearly interpolates in the tables using the current altitude, supplied by TRAJ, to obtain the current atmospheric temperature and pressure P_o. Both items are then supplied to AAERØ and WRITE through CØMMØN.

FØRALT is a FØRTRAN subroutine whose function is to quadratically interpolate in the table of effective space temperature versus altitude (using the altitude supplied by TRAJ) to obtain the current space temperature. The routine then assigns this temperature to a particular space node. When calling the routine, the control program writer must include in the argument of the CALL statement, the node index number he desires to represent space and the previously assigned variable names for the effective space temperature and altitude. The space temperature is supplied to RAD and WRITE through a CØMMØN statement.

The AAERØ subroutine is a FAP subroutine. Its primary function is to compute the aerodynamic heating. In order to accomplish this, the AAERØ FAP routine is broken into two FØRTRAN subroutines, AERØA and AAERØB. The control

program writer calls AAERØ which then automatically calls AERØA and AAERØB. The AERØA portion of the AAERØ routine computes an adiabatic wall temperature and an "effective" heat transfer coefficient which excludes a major length dimension termed the reference length. Information needed by AERØA is supplied either through a CØMMØN statement from other subroutines or by the control program writer by properly satisfying the argument when calling the routine. The control program writer must enter in the calling sequence of AAERØ the variable names previously assigned in preparation of:

a. The table giving the transition Reynolds number plus coefficients and exponents needed in the aerodynamic heating equations
b. The two tables giving the local flow conditions, M/M_o, etc.
c. The two tables giving the modified effective heat of ablation and ablation temperature versus enthalpy difference

Also there must be included a series of values for the index number, surface area, and reference length of all those surface capacitors subjected to the aerodynamic flow conditions listed in the calling sequence.

Briefly, the AERØA subroutine operates in the following manner. The ratios of local Mach number to free stream Mach number (M/M_o) and local pressure to free stream pressure (P/P_o) as a function of free stream Mach number are obtained through the argument from the list of tables in the control program. The free stream Mach number M_o computed by TRAJ, is obtained from CØMMØN and a quadratic interpolation is used to obtain the current values of M/M_o and P/P_o. The local Mach number and pressure are obtained by multiplying these ratios by M_o and P_o respectively, where the value of P_o is obtained from ATM through CØMMØN. Next, flight and local Mach numbers are used in an energy equation to convert the temperature ahead of the vehicle to the local temperature of the flow external to

the boundary layer. A local Reynolds number is then computed based on the local temperature, local pressure, local Mach number, and the first reference length given in the AAERØ calling sequence. This Reynolds number is compared with a transition Reynolds number supplied in the list of tables in the control program to determine whether subsequent calculations should be for a laminar or turbulent boundary layer. This Reynolds number is not used, however, to compute the heat transfer coefficient. Instead, a reference enthalpy and adiabatic wall enthalpy are computed. These enthalpies are converted to temperatures by means of a polynomial which has been fitted to conventional temperature-enthalpy data for air at standard atmospheric pressure. The adiabatic wall temperature is placed in CØMMØN. Air properties are then evaluated at the reference temperature, and subsequently combined with the local pressure, local velocity, and coefficients and exponents given in the table listings in the control program, to obtain an "effective" local heat transfer coefficient. Again, the word "effective" is used to indicate that a reference length has not yet been included in the computations. This completes the AERØA calculations and the program automatically proceeds to AAERØB.

The primary function of AAERØB is to compute the aerodynamic heating rate to each capacitor listed in the calling sequence of AAERØ. In order to do this it applies the effective local heat transfer coefficient to each capacitor after obtaining reference lengths from the AAERØ calling sequence, thereby computing a different local heat transfer coefficient for each capacitor. Next, the capacitor "surface area" is obtained from the AAERØ calling sequence, the local adiabatic wall temperature is obtained from AERØA through CØMMØN, and the capacitor "surface temperature" is obtained from ASTEP through CØMMØN from the previous time. AAERØB then has all the information needed to compute the heating rate to each capacitor. This heating rate is then placed in CØMMØN.

A secondary function of AAERØB is to determine the current value of the ablation temperature, TABL, and modified effective heat of ablation, HEFF. In order to do this, it obtains the current value of the enthalpy difference, $H_{aw} - H_w$ from AERØA and uses this current value to quadratically interpolate in the tables of HEFF and TABL versus $H_{aw} - H_w$. As previously mentioned, the variable names assigned to these tables must be written into the AAERØ calling sequence.

The function of the FØRTRAN subroutine ACAP is to compute the thermal capacitance of each capacitor. Tabular values of material density and specific heat are given in the control program as functions of temperature and are entered into the routine by listing the variable names of the tables in the calling sequence. Also, the capacitor volume is entered. The routine determines the current density and specific heat by quadratic interpolation in the tables, using the capacitor temperature obtained through CØMMON from the previous time. The density and specific heat are multiplied by the capacitor volume to obtain the thermal capacitance which is then placed in CØMMØN. One call of subroutine ACAP handles only one capacitor. Therefore, the control program must call ACAP as many times as there are number of capacitors. It is worth noting that by repeatedly calling index numbers in the ACAP subroutine, the FØRTRAN control program writer draws on a reservoir of capacitors and, in essence, defines a set of nodes.

FØRTRAN subroutine CØN is one of the two routines in the program which computes the thermal conductance between nodes and the subsequent conductive heating rate between nodes. By introducing appropriate pairs of capacitor index numbers into the calling sequence of the CØN routine the control program writer draws upon a reservoir of conductors and assembles a node network into a conductor-capacitor configuration approximating the thermal model. This subroutine can be called repeatedly to join together two nodes of non-ablating materials. When CØN is

called, the control program writer lists in the calling sequence the two capacitor numbers being joined, the ratio of area to length between nodes, and the variable names previously assigned in preparing the tables of thermal conductivity versus temperature. The routine takes this information, refers to COMMON for the node temperatures at the end of the previous time step, and computes the heating rate. This heating rate is then added algebraically to the heating rate (if any) previously computed by AAERO. At this stage, therefore, the heating rate stored in COMMON includes both aerodynamic and conductive heating rates on capacitors designated by the program writer. Optionally, the program writer may have conduction heat transfer computed by subroutine ACOMCN as described in the next paragraph.

The FORTRAN subroutine ACOMCN is a routine which computes the thermal resistance between ablative as well as non-ablative capacitors. To obtain the overall thermal resistance between two nodes, three separate resistances are computed; one from the center of one node to the interface, a second across the interface, and a third from the interface to the center of the second node. This feature makes COMCN handy to use in cases where either the material conduction area changes at the interface or it is desired to account for interface resistance. ACOMCN also computes temperatures on each side of the interface and feeds this information through COMMON to the WRITE subroutine. (It should be noted here that all other temperatures are computed by the ASTEP subroutine.) When calling ACOMCN, the FORTRAN control program writer must list the following items in the calling sequence:

a. The index numbers of the two capacitors being joined

b. The area to length ratio from the first node to the interface

c. The area of the interface

d. The area to length ratio from the interface to the second node

e. The variable name previously assigned to the tables of thermal conductivity versus temperature for the material represented by the first node

f. The variable name previously assigned to the tables of thermal conductance versus temperature of the interface

g. The variable name previously assigned to the tables of thermal conductivity versus temperature for the material represented by the second node

Prior to any computations of heating rate or interface temperature, ACØMCN first examines a counter (which is set in the ABL routine) to determine whether either of the two capacitors being joined is ablating. If neither capacitor is ablating, the subroutine computes the interface temperature and heating rate to both capacitors. For this purpose the subroutine obtains the area to length ratios and interface area directly from the calling sequence, the thermal conductivities from the calling sequence, and present capacitor temperatures from CØMMØN. The interface temperature is then computed and placed in CØMMØN. The new increment of heating rate for each of the two indices being joined is added algebraically to the amount already in CØMMØN. However, if after the counter is examined, one or both of the capacitors are found to be ablating, either an area or length between nodes must be adjusted to account for the effect of decreasing element volume. Since each ablation sequence in the control program lists capacitor node index numbers in a column sequence starting at the surface and extending into the ablator, the sequence is examined by the routine to see if both capacitor index numbers appear in a given sequence. If they do, the two capacitors must lie above one another. If only one is found in a given ablation sequence, it follows

that the two capacitors are beside each other. Once the routine has determined the relative location of the capacitors, either the original area or original length is decreased by a factor equal to the ratio of current capacitor volume (obtained from the ABL routine through CØMMØN) to original volume (obtained from a table in the control program through CØMMØN). Once the area to length ratios have been adjusted, the subroutine proceeds in a fashion identical to the non-ablating case.

FØRTRAN subroutine RAD computes the radiation heat transfer rate between the capacitor numbers listed in its calling sequence. The routine obtains the surface area directly from the calling sequence and obtains the surface emissivity from the emissivity-temperature table supplied in the control program whose variable name is also listed in the calling sequence. The wall temperature from the end of the previous time step is used to quadratically interpolate in the table and obtain the current emissivity. The emissivity and wall temperature are combined with the effective space temperature obtained from FØRALT through CØMMØN, to calculate the radiative heating rate on the surface element in question. The net heating rate for each capacitor surface element is then obtained from CØMMØN, altered by the amount of the radiative heating rate, and replaced in CØMMØN.

The sole function of the FAP routine WRITE is to handle the printout of the data. The WRITE subroutine itself calls a FØRTRAN routine entitled PRNTA. PRNTA contains a predetermined printout format which is executed at the flight times specified by the control program writer in the calling sequence of WRITE. At each of the specified flight times, WRITE will print out the following items:

1. Flight time, altitude, free stream Mach number, free stream pressure, and free stream temperature

2. Capacitor temperatures (if they have changed from the initial values specified in the argument of the CALL ASET statement)
3. Contact (interface) temperatures
4. Local flow conditions; Mach number, pressure, temperature, Reynolds number, adiabatic wall temperature, and the "effective" heat transfer coefficient
5. The index number of the capacitor nearest to its ablation temperature and the time needed for it to reach ablation temperature
6. The index number of the capacitor nearest to being completely ablated away and the time to complete ablation
7. The stability time step and the capacitor number associated with it
8. The capacitor number, current volume, modified effective heat of ablation, and ablation temperature for all capacitors currently ablating

In addition to printing out these items at the times called for in the calling sequence, the program will print out any time a capacitor either reaches its ablation temperature or completely ablates away, when ablation is interrupted by a negative heating rate, or when ablation is resumed following a return to a positive heating rate. Such printouts are triggered by a code supplied by the ABL routine.

The function of FØRTRAN subroutine ASTEP is to properly size the time step and compute new capacitor temperatures. All the information needed by ASTEP to perform calculations is obtained from other routines. It has no calling sequence. ASTEP determines three different time steps:

(a). The minimum of the times needed by each surface capacitor to reach its ablation temperature. See expression (12)

(b). The minimum of the times needed by each surface capacitor to reach complete ablation. See expression (17)

(c). The stability time step needed to prevent oscillations in subsequent finite difference calculations. See expression (9)

ASTEP chooses the minimum of (a), (b), and (c) to step ahead in time. Time step (a) is computed using the capacitance supplied by ACAP, the ablation temperature supplied by AAERØB, the wall temperature from the previous time, and the net heating rate computed by AAERØ, ACØMCN, CØN, and RAD. Time step (b) is computed using the density from ACAP, the current volume from ABL, the modified effective heat of ablation from AAERØB, and the net heating rate from AAERØ, ACØMCN, CØN, and RAD. Time step (c) is computed from the capacitance supplied by ACAP and the cumulative thermal resistances computed in AAERØB, CØN, ACØMCN, and RAD. Following selection of the minimum time step, the routine computes new temperatures based on the previous temperature of the capacitor, the net heating rate, the thermal capacitance, and the minimum time step.

The last routine is ABL, a FAP routine which calls the FØRTRAN routine ABL1. The function of ABL1 is to compute the current volume of ablating capacitors and discard those capacitors which have completely ablated away. It also sets a counter so other subroutines will know whether or not a particular capacitor is currently ablating or is completely ablated away. Finally, it changes the surface capacitor when an element completely ablates away so that convection (AAERØ) and radiation (RAD) will be applied to the newly exposed capacitor. When calling the subroutine, the writer must include in the calling sequence the variable names assigned to the numbers of the initial surface capacitors. These variable names and associated capacitor numbers must have been previously defined in the

control program. All other information needed by ABL is obtained through COMMON. The future volume is computed using the present volume, the net heating rate, the minimum time step, the density, and the modified effective heat of ablation.

SECTION 3

THE FØRTRAN CONTROL PROGRAM

The preceding discussion of the computer program has laid the groundwork for giving specific instructions to the user. This section identifies the FØRTRAN control program statements and gives the nomenclature. As noted in the previous section, the FØRTRAN control program consists of:

I. DIMENSIØN statements

II. A CØMMØN statement

III. A series of tabular statements

IV. A series of CALL statements

These statements have the following form and composition:

I. DIMENSIØN Statements

DIMENSIØN F1(I), F1V(J), F2(K),.....

F1(I) - dependent variable table F1, I spaces needed

F1V(J) - independent variable table F1V, J spaces needed

F2(K) - dependent variable table F2, K spaces needed

F2V(L) - independent variable table F2V, L spaces needed

S1(K) - etc.

S1V(K) - etc.

etc.

.

.

It should be emphasized that these variable names are to be devised by the control program writer. Floating point names are to be used.

DIMENSIØN IASEQ(500), V(1000), DUM(4407), IAB(500), VØ(1000), DAMN(4002)

IASEQ(500) - ablation sequence , 500 spaces available

V(1000) - volume of capacitors, 1000 spaces available

DUM(4407) - 4407 dummy spaces

IAB(500) - ablation "on-off" index, 500 spaces available

VØ(1000) - initial volume of potential ablation elements, 1000 spaces available

DAMN(4002) - 4002 dummy spaces

II. CØMMØN Statements

COMMON T, Q, DUM, IAB, IASEQ, VØ, DAMN

T - capacitor temperature

Q - accumulated heating rate being applied to capacitor

DUM - dummy

IAB - defined in part I

IASEQ - defined in part I

VØ - defined in part I

DAMN - dummy

III. Tabular Statements

F1(1) = a a is the first value of the dependent variable in a table named F1

F1(2) = b b is the second value of the dependent variable in a table named F1

F1(n) = k

F1V(1) = n n is the total number of items in table F1

F1V(2) = a' a' is the value of the independent variable corresponding to the dependent variable F1(1)

It should be noted again that these variable names are to be devised by the control program writer.

IV. CALL Statements

1. CALLASET(START, STØP, TEMPIN, I, INDEX1, T1...INDEXI, T(I))

   START - time at beginning of computations

   STØP - time at end of computations

   TEMPIN - temperature at which certain capacitors are to be initialized

   I - number of capacitors not desired to be initialized at TEMPIN

   INDEXI - capacitor numbers whose initial temperature is not desired to be TEMPIN

   T(I) - initial temperature of INDEXI

2. CALLTRAJ(FØFXM,XM,FOFXA,XA)

   FØFXM - variable name given to free stream Mach number table

   XM - variable name given to corresponding flight time table

   FØFXA - variable name given to altitude table

   XA - variable name given to corresponding flight time table

   (The variable names are actually to be entered in the form devised in setting up each table in part III.)

3. CALLATM (FØFXTØ,XTØ,FØFXPØ,XPØ)

   FØFXTØ - variable name given to ambient temperature table

   XTØ - variable name given to corresponding altitude table

   FØFXPØ - variable name given to ambient pressure table

   XPØ - variable name given to corresponding altitude table

4. CALLFØRALT (INDEX, FØFX, X)

   INDEX - number of the capacitor designated to represent space

   FØFX - variable name given to space temperature table (i.e., the table gives the schedule of temperatures to be assigned to INDEX)

   X - variable name assigned to altitude table corresponding to FØFX

5. CALLAAERØ(ID,I,FLØNØS,FLFXLM,XLM,FØFXLP,XLP,ABLT,HDIF1,HEFF,HDIF2, INDEX 1, GEØNØ1, PØSNØ1,.....INDEXI, GEØNØI, PØSNØI)

   ID - aerodynamic block number (a block being a group of surface capacitors all under the influence of the same local flow conditions)

   I - number of surface capacitors in the block

   FLØNØS - variable name given to the table specifying the transition Reynolds number and the coefficients and exponents needed to compute the local heat transfer coefficient

   FØFXLM - variable name given to the table of the local-to-free-stream Mach number ratios

   XLM - variable name given to corresponding free stream Mach number table

FØFXLP - variable name given to the table of local-to-free-stream static pressure ratios

XLP - variable name given to corresponding free stream Mach number table

ABLT - variable name given to the ablation temperature table

HDIF1 - variable name given to corresponding air-enthalpy difference table (HAW - HW)

HEFF - variable name given to the modified effective heat of ablation table

HDIF2 - variable name given to corresponding air-enthalpy difference table

INDEX1 - capacitor number of the first capacitor in the block

GEØNØ1 - surface area of first capacitor

PØSNØ1 - reference length of first capacitor

INDEXI - capacitor number of the last capacitor in the block

GEØNØI - surface area of last capacitor

PØSNØI - reference length of the last capacitor

6. CALLACAP (INDEX,GEØNØ,R,XR,CP,XCP)

INDEX - capacitor number

GEØNØ - capacitor volume

R - variable name given to the table listing the density of the capacitor material

XR - variable name given to the corresponding temperature table

CP - variable name given to the table listing the specific heat of the capacitor material

XCP - variable name given to corresponding temperature table

7. CALLCØN(INDEX1, INDEX2, GEØNØ, FOFX, X)

INDEX1, INDEX2 - identifying numbers of the two capacitors being joined

GEØNØ - the area to length ratio between the two capacitors

FØFX - the variable name assigned to the table giving the thermal conductivity of the material

X - the variable name given to the corresponding temperature table

8. CALLACØMCN(INDEX1, INDEX2, GEØNØ1, GEØNØ2, GEØNØ3, FØFX1, X1, FØFX2, X2, FØFX3, X3)

INDEX1, INDEX2 - identifying numbers of the two capacitors being joined

GEØNØ1 - the ratio of area to length between the node of INDEX1 and the interface

GEØNØ2 - the area of the interface

GEØNØ3 - the ratio of area to length between the interface and the node of INDEX2

FØFX1 - variable name given to the table listing the thermal conductivity of the material represented by INDEX1

X1 - variable name of the table listing the corresponding temperature

FØFX2 - the variable name given to the table listing the interface conductance

X2 - variable name of the corresponding temperature table

FØFX3 - variable name given to the table listing the thermal conductivity of the material represented by INDEX2

X3 - variable name of the corresponding temperature table

9. CALLRAD(INDEX1, INDEX2, GEØNØ, FØFX, X)

INDEX1, INDEX2 - identifying numbers of the two capacitors which exchange heat by radiation

GEØNØ - surface area

FØFX - variable name given to the table listing the surface emissivity

X - variable name given to the table listing the corresponding temperature

10. CALLWRITE (N, TIME1, TIME2,.....TIMEN)

N - number of times at which printout is desired

TIME1,.....TIMEN - specific times at which printout is desired

11. CALLASTEP

This subroutine requires no calling sequence.

12. CALLABL (INDEX1, INDEX2,....INDEXN)

INDEX1, INDEX2,....INDEXN - variable names assigned in control program to each initial surface element

SECTION 4

SAMPLE PROBLEM

From the foregoing discussions of the program structure and subroutine arguments, the reader should now have a general idea of how to construct a FØRTRAN control program to obtain solutions to subliming ablation problems. However, in order to overcome the difficulties inherent in the word description of any computer program, a sample problem will now be solved to demonstrate precisely the use of the computer program.

Pictured in Figure 4 is a sketch of the area to be analyzed. The area encompasses the juncture between a thin skin and a thick ring both of which are protected by .25 inch thick Teflon ablator material. It is desired to find the transient temperatures and ablation rates in the ablator and the transient temperatures in the steel understructure for a Mach 5 low altitude flight. The FØRTRAN coding needed to construct the main control program will be described in detail and, in fact, the coding sheets themselves are included in this section. No attempt will be made to discuss or justify the values chosen for various parameters (transition Reynolds number, ablation temperature, etc.) since the sole purpose of this sample problem is to provide instruction in use of the program.

It is usual practice to divide the area to be analyzed into a network of thermal capacitors before the coding of the FØRTRAN sheets begins. Previous experience in geometry make-up is quite helpful in order to make a good selection of element size. Naturally, for the utmost accuracy the smaller the element size the better. However, since the running time on the computer is increased with decreasing element size, a compromise between accuracy and cost must many times be made. It is sometimes true that the increased accuracy due to a smaller

break-up of the geometry is not measurable. It is in cases such as this that experience is helpful in determining the best element size. The geometry break-up chosen for the sample problem is shown in Figure 5. With the break-up as shown, the solution to this sample problem required 2.5 minutes of IBM 7094 computer time. Had the break-up been twice as fine as that shown, the running time on the computer would not have increased appreciably since most of the computer time was used in converting the FØRTRAN control program to machine language and not in computation. In subdividing the solid, it is generally advisable to hand-calculate a typical stability time step to be sure that the smallest remains greater than 0.05 second. Experience shows that time steps less than 0.05 second can cause excessive consumption of computer time. Once the element sizes have been chosen, a number must be assigned to each element and the volumes of each element and the area-to-length ratios between adjacent elements must be computed. These are then put aside to be included later in the argument of the CALLACAP, CALLACØMCN, and CALLCØN statements. A detailed discussion of the coding sheets now follows. The list of units which must be used with the inputs is given in Table I (Page 52).

The JØB card appearing on Page 1 of the coding sheets is an I.D. card whose form is peculiar to APL. Other systems may require other I.D. cards and this one is shown only for illustrative purposes. The XEQ card, however, is a control card and must appear at the head of any FØRTRAN program. The SAMPLE ABLATION PROBLEM card is a comment card which is not processed by the machine and is used only to clarify the coding. Comment cards will be used liberally throughout the program. The first of the two DIMENSIØN statements describes the variables listed in each particular program. Although this appears at the head of the program, it is usually not completed until the rest of the program has been written and the

names and number of spaces needed for each variable are known. The second DIMENSIØN statement must appear in every job in exactly the form as shown on the first coding sheet. Likewise, the CØMMØN statement must appear in every job exactly as shown on the coding sheet. Since the second DIMENSIØN and the CØMMØN statements are never to be changed, they may be placed on file and need not be re-coded for each job.

The actual coding of the tabular input begins on the second coding sheet. Here the Mach number versus time is given under the assigned variable names F1 and F1V. There are two things to note in this table which are true for each and every set of dependent-independent variable tables written in the control program. First, the first number in the independent variable list (F1V) must be the number of items in the dependent variable (F1) table. This number is needed by the routine which makes the quadratic interpolations in the table. The second item to be noted is how the points describing the Mach number history are specified. In this particular case, a linear variation of Mach number for 5 seconds up to a Mach number of 5 is to be programmed. After 5 seconds, a constant Mach number of 5 is desired. Any time such a sharp break occurs, it is imperative that a number of points extremely close together be specified in the area of this break. This is necessary because quadratic interpolation is automatically used between points given in the table. If enough points are not given in regions where there is a sudden change in the slope of the curves, completely erroneous interpolated results can be obtained. On the third coding sheet, the altitude table (F2) is given. No new corresponding time table is needed since the altitude values were made to coincide with the time table (F1V) given with the Mach number. Thus, later the F1V table will be used with both F1 and F2 in the argument of the CALLTRAJ statement.

Following the trajectory data the ambient atmospheric conditions are listed. The temperature and pressure are specified as a function of altitude. Note once again that the coding effort is reduced by making one altitude table serve both the temperature and pressure tables.

Following the ambient pressure table, the local flow conditions (M/M_o and P/P_o) are specified as a function of free stream Mach number. It might be noted here that unless otherwise stated, the variable names assigned to any of the tables which have been discussed are quite arbitrary as long as floating point names (any beginning with letters other than I, J, K, L, M, and N) are used. For example, the Mach number ratio table F5 could equally well be called S5, F27, or T7.

Following the local pressure ratio table, the effective space temperature versus altitude is listed in tabular form in an identical fashion to the other tables discussed. On Page 6 of the coding sheets, the emissivity of external surfaces is given. In this case it was desired that a constant value of .8 be used rather than a temperature-dependent set of values. Note that since this quantity is a single non-subscripted constant it need not be listed in the DIMENSIØN statement.

The table listing the flow numbers for the aerodynamic heating equations follows next and is the only table which is the same length for every problem. There are invariably six entries in the table and each of these entries has a particular meaning. The first entry must list the transition Reynolds number. The second and third entries give the exponent on the Reynolds number in the Nusselt relation. It should be pointed out that, within the routine, the exponent on the Prandtl number is fixed at 1/3. The fourth and fifth flow numbers give the coefficients of the Nusselt number relation for laminar and

turbulent flow respectively. The values assigned to the second through fifth flow numbers in the sample problem apply to the case of the flat plate. The sixth flow number is set equal to 1 if stagnation point heat transfer is to be computed. At all other times, the sixth flow number must be set equal to zero.

The next table lists the initial volumes of all the potentially ablating capacitors. The variable name used in this list is not arbitrary but must always be VØ. In similar fashion, the sequence of ablating capacitors in the following table must always have IASEQ as its variable name. The first item in this list must specify the number of "columns" of ablating capacitors. For the sample problem this number is 2 (see Figure 5). The second item in the list must specify a number of capacitors in the first column (i.e., 11). Next, the capacitor number assigned to each of the elements in the ablating sequence are listed in order. Note that the first capacitor in the understructure (i.e., 21) (see Figure 5) is the last number to be listed. No particular number sequence need be assigned to the capacitors when formulating the geometry break-up as any combination of numbers, each less than the number 1000, can be handled by the ablation sequence. The fourteenth entry in the sample problem ablation sequence is the number of capacitors (i.e., 11) in the second ablating column. The fifteenth entry starts a list of the capacitors in the second column. If additional columns were present the cycle would be repeated. However, the total length of the table must not exceed 500 entries.

Following the ablation sequence are tables giving the thermal properties of the two materials, Teflon and stainless steel. The form of the tables is identical to those listing the trajectory and atmospheric properties. Note that the density, specific heat, and thermal conductivity must be listed individually. In the case

of stainless steel a table was not used for the density since only a single value was known. This value is given on Page 9 of the coding sheets. Constants may of course, be used in place of tables at any time. Following the listing of the thermal properties, the ablative properties of the materials are given on Page 11. Once again, the tables are in the usual form and a single enthalpy difference table is given to serve both the HEFF and ablation temperature tables.

At the bottom of Page 11, a constant equal to 1 is defined under the variable name of F18. This constant will be found useful later in the argument of some of the subroutine calling statements. A final item specified before the CALL statements are the variable names assigned to the initial surface elements. For the sample problem, element 1 has been assigned the fixed-point variable name INDX1 and element 11 has been assigned the variable name INDX2. This can be seen on Page 12.

As a final note on the tables it should be mentioned that the order in which all the above tables are specified is not critical. They may be placed anywhere between the COMMON statement and the first CALL statement.

The remainder of the program consists of CALL statements. The reader will find it helpful to refer periodically to Section 3 where the calling sequence is defined for each of the routines. Particular attention should be given to the way variable names are placed in the calling sequences and to seeing that they do, indeed, satisfy the requirements described in Section 3.

The first statement in the series is the CALLASET statement (Page 12 of the coding sheets). For the sample problem, CALLASET has been instructed to make computations from 0 to 11 seconds and set all capacitors at an initial temperature of 519°R with the exception of one capacitor, numbered 1000, whose temperature is set at 600°R. The CALLTRAJ statement has in its calling sequence

the variable names which were given previously to the Mach number, altitude, and time tables. Note that this statement has the number 1 in column 5. It is important to include this statement number since the program is instructed to loop back to statement 1 after each time step. The CALLATM statement has in its calling sequence the variable names given to the ambient temperature, pressure, and altitude tables. The CALLFØRALT statement lists the capacitor number 1000 which was chosen as the capacitor to represent space for this problem. It also lists the variable names given to the temperature of space and to the altitude tables.

The CALLAAERØ statements supply information to compute the aerodynamic heating. The reader should refer back to the detailed description of the calling sequence given in Section 3 and to the accompanying definitions of the variable names. In the arguments of the CALLAAERØ statements it is seen that surface areas in the sample problem have been assumed to be 0.0833 square feet and that the reference lengths of INDEX1 and INDEX2 have been assumed to be 0.033 feet and 0.117 feet, respectively.

The CALLACAP statements follow next on Page 12 of the coding forms. Note that there is one statement for each capacitor shown in Figure 5. In the calling sequence of ACAP the hand-calculated volume of each capacitor is entered along with the variable names assigned to the density, specific heat, and temperature tables.

On coding form Page 13 are listed several CALLCØN statements describing the conduction between nonablative capacitors. CALLCØN statements are used in place of CALLACØMCN because of their shorter calling sequence.

The CALLACØMCN statements on Page 14 identify the capacitor pair being joined and give the area-to-length ratio between the first node and the interface.

the interface area, and the area-to-length ratio between the interface and second node. For the sample problem, it was assumed that the interface resistance would be negligible. Therefore, a very large number, $.1 \times 10^{6}$, was used to represent the interface area. The interface unit conductance was then assumed to be equal to 1 and was inserted into the calling sequence by use of the previously defined variable F18. The resulting interface conductance is so large ($.1 \times 10^{9}$) that the interface resistance is effectively zero. Note that since F18 was a constant and not a table, there was no independent variable. A zero was placed in the calling sequence following F18. This was repeated in subsequent ACØNCN sequences. In general, if a constant previously assigned a variable name is to be entered into any calling sequence, its variable name is always listed followed by a zero.

On Page 15 of the coding forms CALLRAD statements are given; one for INDX1 and the other for INDX2. In this problem, 1000 was used as the capacitor number to represent space and therefore appears in the calling sequence of each statement. A surface area of .0833 Ft^2 is given followed by the variable name (F8) assigned to the constant emissivity. It should be noted once again that since a variable named constant is used, the variable name is followed by a zero.

The CALLWRITE statement appears on Page 15 of the coding sheets. It gives the times at which printouts are desired. Care must be taken to insure that the first number in the calling sequence is an accurate count of the number of times at which printout is desired. One should recall from previous discussions that printout will occur automatically at crucial times other than those listed in the argument of the CALLWRITE statement. In order to allow for possible longer running times future printouts were called for up to 30 seconds even though the

sample problem was set to run only 11 seconds. The CALLASTEP statement following on Page 16 of the coding sheets requires no calling sequence and, therefore, no discussion. The final call statement is the CALLABL statement. This calling sequence must contain the variable names given to the initial surface elements. For this sample problem the names INDX1 and INDX2 were assigned to the initial surface elements. The next statement, the GØ TØ 1 statement, will cause the program to go back to the CALLTRAJ statement after each time step and proceed with new computations for the new flight time. The program is completed with an END card which is required in all FØRTRAN jobs.

After the data on the coding sheets 1 through 16 have been converted to information on punched cards, the resulting control program deck is combined with the deck of binary subroutines for running on the computer. The decks of binary subroutines are available upon request from the authors.

Figure 6 presents a section of printout taken from the sample problem at a flight time of 3.6 seconds. For the most part, the printout is self-explanatory but a few words of clarification will be given.

The units of the variables in the printout are:

Time	- Seconds
Altitude	- Feet
Pressure	- Pounds per square foot
Temperature	- °F
H prime	- $Btu \cdot (Ft)^{\alpha}/Ft^2 \cdot Sec \cdot °F$
Current Volume (VC)	- Ft^3
Effective heat of ablation (EFFHV)	- Btu/lb

The thermal capacitor numbers and their associated temperatures are listed if the temperatures have changed from their initial values. Additional contact temperature,

are given on both sides of the interface between those capacitor previously joined by CALLACØMCN statements. The local flow properties are listed according to an ID number which corresponds to the ID number in each CALLAAERØ statement. Thus, to find the capacitor numbers to which each set of flow conditions applies, one must refer back to a CALLAAERØ statement containing the proper ID number.

Figures 7 and 8 graphically present results from the sample problem. In Figure 7 the ablator thickness versus time for the two ablating "columns" is given. The ablation rates are considerably different because the problem was deliberately set up with boundary layer transition occurring between the two columns. Thus, ablation under both laminar and turbulent flow is present. Figure 8 presents temperature-time results for the external surface (at the location of element 1) and the steel understructure. It is seen that the surface temperature continues to rise after the onset of ablation at 3.4 seconds. This is caused by the changing enthalpy difference across the boundary layer and the fact that the ablation temperature is a function of the enthalpy difference.

The example problem chosen is an extreme case which demonstrates the capability of the computer program to deal with a substantial differential in local ablation rates and large local differences in the thermal mass of the structure. Therefore, it should be re-emphasized that the effect of body contour changes on vehicle aerodynamics is not accounted in the computer program. On the other hand, in cases where body contour changes do not substantially affect vehicle aerodynamics the present computer program can be used effectively to integrate the thermal analysis of ablatively protected structures having complex interconnected conducting paths.

As a final note on the program, Table II has been prepared in order to show the upper limit on program capacity.

REFERENCES

1. Eckert, E.R.G., Survey of Boundary Layer Heat Transfer at High Velocities and High Temperatures, WADC TR 59-624, April 1960.

2. Rubesin, M. W. and Johnson, H. A., A Critical Review of Skin-Friction and Heat-Transfer Solutions of the Laminar Boundary Layer of a Flat Plate, Trans. ASME Vol. 71, No. 4, 1949.

3. Sommer, S. C., Short, B. J., Free-Flight Measurements of Skin Friction of Turbulent Boundary Layers with High Rates of Heat Transfer at High Supersonic Speeds, J. Aero. Sci., Vol. 23, 1956.

4. Dusinberre, G. M., Numerical Analysis of Heat Flow, McGraw-Hill, New York, 1949.

5. Adams, M. C., Recent Advances in Ablation, ARS Journal, Sept. 1959.

6. Allen, R. W., Ablation and Transpiration - Part I, APL/JHU EM-3906, October 8, 1964.

NOMENCLATURE

a - Elemental planar surface, located in conductive medium and orientated in direction normal to direction of heat flow but aligned with x-direction on ablation element

A - Elemental planar surface, located in conductive medium and orientated in direction normal to direction of heat flow but aligned with z-direction (in or out of exterior surface) of ablation element

C - A constant

C_i - Capacitance of element i

c_p - Specific heat of a gas at constant pressure

$c_{p(s)}$ - Specific heat of a solid material

F_A - A radiation configuration factor based on geometry

F_ϵ - A radiation configuration factor based on emissivity

h_H - Convective heat transfer coefficient based on enthalpy difference

$h_{H,o}$ - Convective heat transfer coefficient based on enthalpy difference in the absence of mass release from surface

H_{aw} - Enthalpy of air in contact with an adiabatic wall surface

$H_{aw,i}$ - Enthalpy of air in contact with the adiabatic surface of element i

$H_{(g)w}$ - Enthalpy of gaseous wall material at wall surface temperature and pressure conditions

H - Static enthalpy of air at local-flow conditions

$H_{(s)o}$ - Enthalpy of solid wall material at initial condition

$H_{(sg)}$ - Enthalpy of sublimation

$H_{(sg)w}$ - Enthalpy of sublimation for the wall surface temperature condition

H_w - Enthalpy of air in contact with a non-adiabatic wall surface

$H_{w,i}$ - Enthalpy of air in contact with the non-adiabatic surface of element i

H^* - Reference enthalpy of air defined by Equations (3) and (4)

k_i - Thermal conductivity of element i at its temperature condition

k - Thermal conductivity of air

K - Thermal conductance

$K_{i,1}$ - Thermal conductance between node i and node 1

$K_{i,i1}$ - Thermal conductance between node i and interface between element i and element 1

ℓ - Elemental length of conductive path directed normal to adjacent aerodynamically heated wall surface

$\ell_{i,i3}$ - Elemental length of conductive path directed normal to adjacent aerodynamically heated wall surface and running between node i and the interface between element i and element 3

L - Elemental length of conductive path directed parallel to adjacent aerodynamically heated wall surface

$L_{i,i1}$ - Elemental length of conductive path directed parallel to adjacent aerodynamically heated wall surface and running between node i and the interface between element i and element 1

M_o - Free-stream Mach number

M - Mach number of local flow

m - A constant

$\dot{m}$ - Mass flow rate of ablator across unit area of the control surface

n - A constant

P - Local static pressure

P_o - Free-stream static pressure

Pr - Prandtl number

q_o - Non-ablative convective heat flow per unit time and unit wall-surface area

q_{rad} - Radiation heat flow per unit time and unit wall-surface area

Re - Reynolds number

T - Absolute temperature

T_c - A constant used in Sutherland's Viscosity Law

T_o - Absolute initial temperature of solid material

T_{aw} - Absolute temperature of the air in contact with an adiabatic wall surface

$T_{aw,i}$ - Absolute temperature of the air in contact with the adiabatic wall surface of element i

T_w - Absolute temperature of a non-adiabatic wall surface

T_{space} - Absolute temperature of effective radiation space

T_{abl} - Absolute temperature of an ablating surface

$T_{abl,i}$ - Absolute temperature of the ablating element i

T_i - Present-time absolute temperature of element i

T_i^+ - Future-time absolute temperature of element i

T^* - The absolute temperature corresponding to reference enthalpy H^* at 1 atm.

$t, \Delta t$ - Time, time increment

u - Local velocity external to boundary layer

V_i - Present-time volume of element i

V_i^+ - Future-time volume of element i

x - Distance from leading edge

θ_H - Transpiration factor based on enthalpy difference

μ^* - Air absolute viscosity evaluated at T^*

μ_c - A constant in Sutherland's Viscosity Law

ρ_1 - Density of element 1

ρ^* - Air density evaluated at T^*

σ - Stefan-Boltzmann Constant

TABLE I

UNITS OF COMPUTER PROGRAM INPUT VARIABLES

VARIABLE	UNITS
Altitude	Ft
Temperature	$^{\circ}R$
Pressure	Lb_f/Ft^2
Volume	Ft^3
Density	Lb_m/Ft^3
Specific Heat	$Btu/Lb_m{}^{\circ}R$
Thermal Conductivity	$Btu \cdot Ft/Ft^2 \cdot hr \cdot {}^{\circ}R$
Modified Effective Heat of Ablation (HEFF)	Btu/Lb_m
Area	Ft^2
Length	Ft

Fig. 4 SKETCH OF AREA OF ANALYSIS FOR SAMPLE PROBLEM

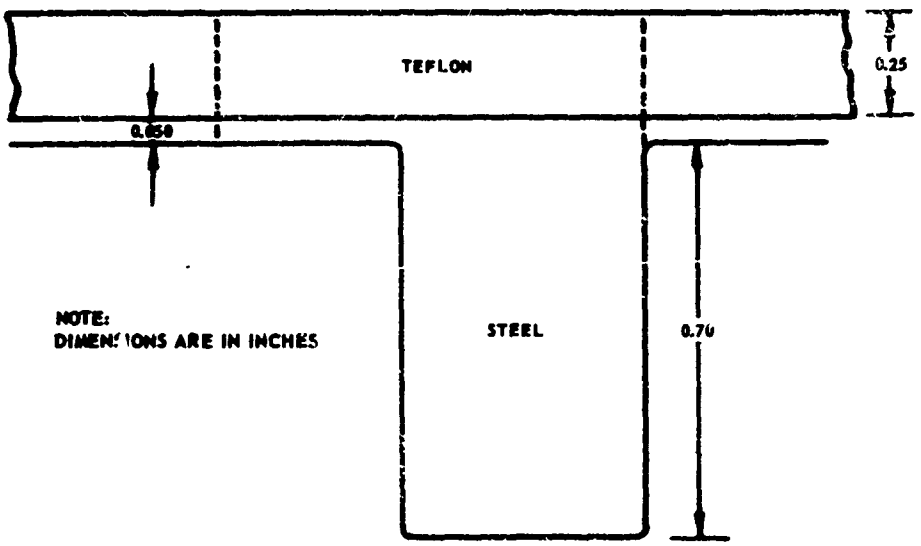
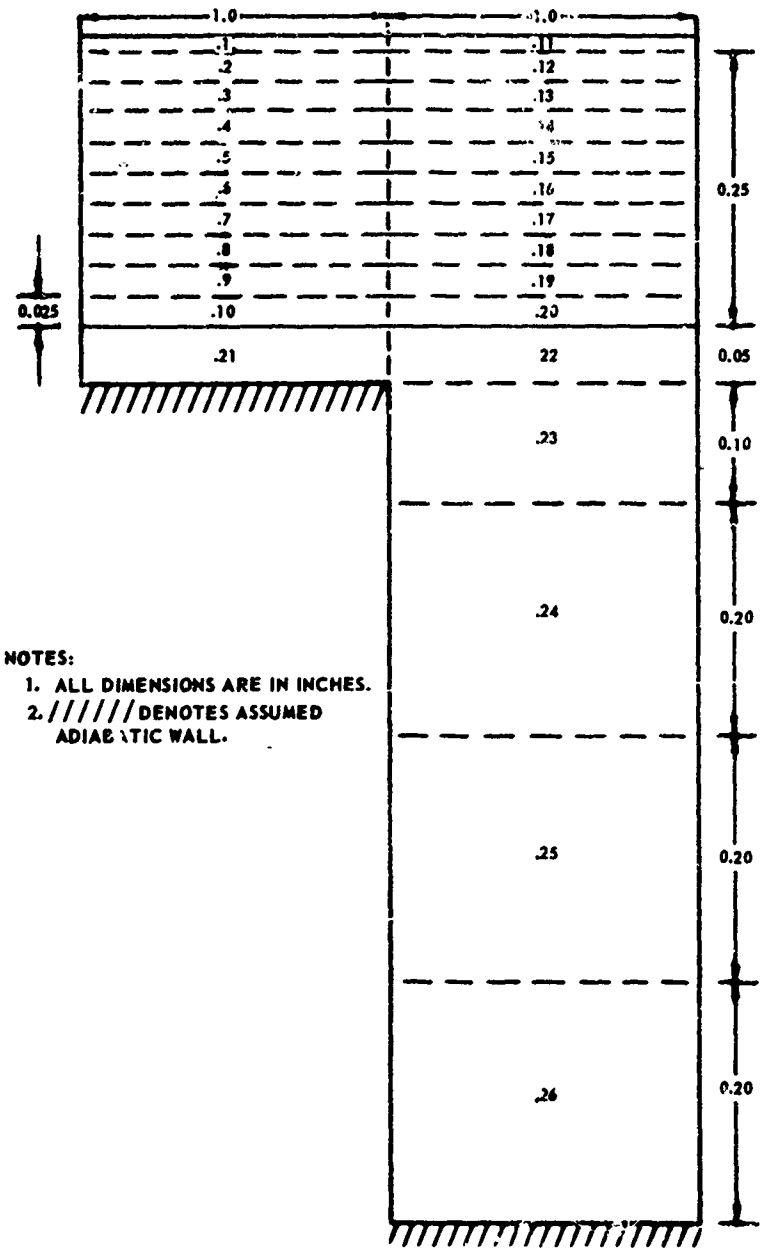


Fig. 5 BREAKUP OF GEOMETRY FOR SAMPLE PROBLEM



NOTES:
1. ALL DIMENSIONS ARE IN INCHES.
2. ////// DENOTES ASSUMED ADIABATIC WALL.

CAPACITOR NO. 11
VC 0.17408000E-03
EPFNV 0.78647784E+03
TABL 0.76459102E+03

TIME= 0.38568860E+01 ALTITUDE= 0.5922E+03 MACH= 0.3597E+01 AMBIENT PRESSURE= 0.2072E+04 AMBIENT TEMPERATURE= 0.5663E+02

THERMAL CAPACITOR TEMPERATURES

1=	928.	2=	120.	3=	66.	4=	60.	5=	59.	6=	59.	7=	59.	11=	765.	12=	131.	13=	73.
14=	66.	15=	59.	16=	59.	17=	59.	1000=	141.										

CONTACT TEMPERATURES

1,	2=	278.;	278.	2,	3=	94.;	94.	3,	4=	63.;	63.	4,	5=	59.;	59.	5,	6=	59.;	59.
6,	7=	59.;	59.	7,	8=	59.;	59.	8,	9=	59.;	59.	9,	10=	96.;	59.	11,	12=	417.;	417.
12,	13=	134.;	134.	13,	14=	67.;	67.	14,	15=	59.;	59.	15,	16=	59.;	59.	16,	17=	59.;	59.
17,	18=	59.;	59.	18,	19=	59.;	59.	19,	20=	59.;	59.	10,	21=	59.;	59.	20,	22=	59.;	59.
1,	11=	667.;	667.	2,	12=	156.;	156.	3,	13=	70.;	70.	4,	14=	60.;	60.	5,	15=	59.;	59.
6,	16=	59.;	59.	7,	17=	59.;	59.	8,	18=	59.;	59.	9,	19=	59.;	59.	10,	20=	59.;	59.
21,	22=	59.;	59.																

LOCAL FLOW

ID	MACH NO.	PRESSURE	TEMPERATURE	REYNOLDS NO.	TAW	HPRIME
1	2.82	0.7057E+04	312.	0.1246E+07	1150.	0.9709E-02
2	2.82	0.7057E+04	312.	0.4416E+07	1197.	0.1190E-00

TIME TO BEGINNING OF ABLATION FOR CAPACITOR NO. 1 = 0.58028349E+00
TIME TO COMPLETE ABLATION FOR CAPACITOR NO. 11 = 0.20548635E+01
CRITICAL INDEX NO. = 11 STABILITY TIME STEP = 0.23389363E-00

CAPACITOR NO. 11
VC 0.26349311E-03
EPFNV 0.80685060E+03
TABL 0.87274023E+03

TIME= 0.48083824E+01 ALTITUDE= 0.6473E+03 MACH= 0.4008E+01 AMBIENT PRESSURE= 0.2066E+04 AMBIENT TEMPERATURE= 0.5633E+02

THERMAL CAPACITOR TEMPERATURES

1=	731.	2=	169.	3=	75.	4=	61.	5=	59.	6=	59.	7=	59.	8=	59.	11=	780.	12=	256.
13=	92.	14=	62.	15=	59.	16=	59.	17=	59.	1000=	141.								

CONTACT TEMPERATURES

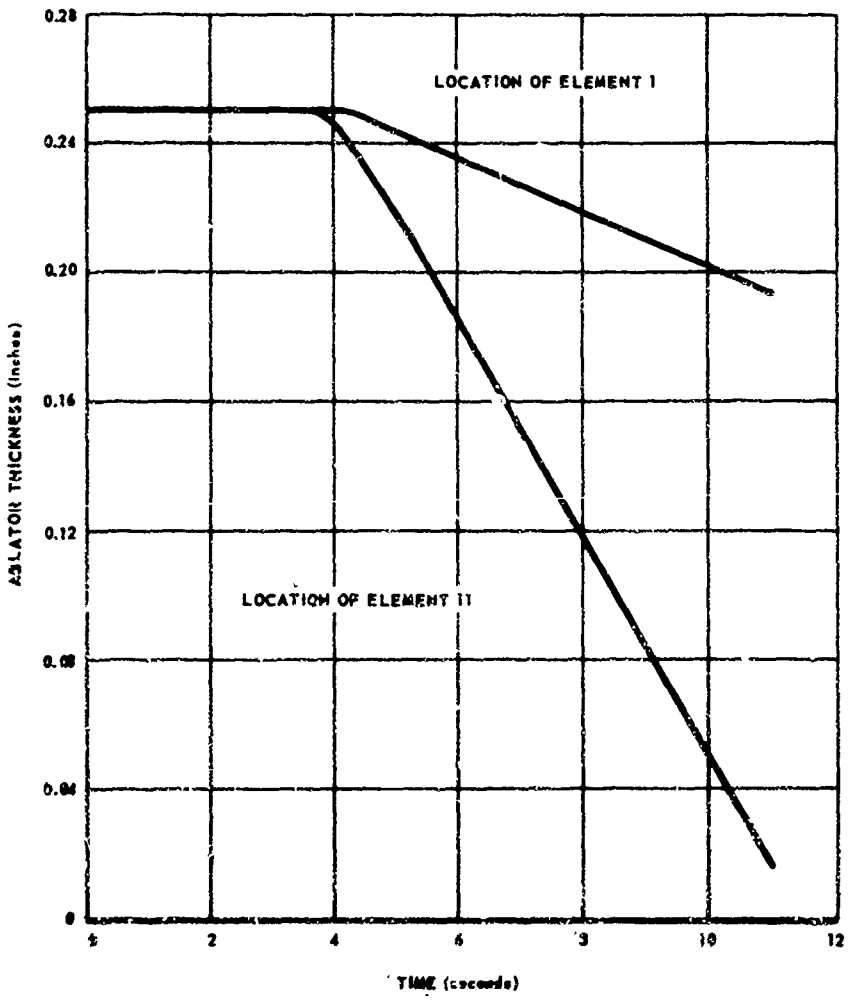
1,	2=	383.;	383.	2,	3=	123.;	123.	3,	4=	68.;	68.	4,	5=	60.;	60.	5,	6=	59.;	59.
6,	7=	59.;	59.	7,	8=	59.;	59.	8,	9=	59.;	59.	9,	10=	59.;	59.	11,	12=	498.;	498.
12,	13=	177.;	177.	13,	14=	77.;	77.	14,	15=	61.;	61.	15,	16=	59.;	59.	16,	17=	59.;	59.
17,	18=	59.;	59.	18,	19=	59.;	59.	19,	20=	59.;	59.	10,	21=	59.;	59.	20,	22=	59.;	59.
1,	11=	782.;	782.	2,	12=	213.;	213.	3,	13=	83.;	83.	4,	14=	62.;	62.	5,	15=	59.;	59.
6,	16=	59.;	59.	7,	17=	59.;	59.	8,	18=	59.;	59.	9,	19=	59.;	59.	10,	20=	59.;	59.
21,	22=	59.;	59.																

LOCAL FLOW

ID	MACH NO.	PRESSURE	TEMPERATURE	REYNOLDS NO.	TAW	HPRIME
1	2.81	0.7631E+04	353.	0.1404E+07	1421.	0.1070E-01
2	2.81	0.7631E+04	353.	0.4978E+07	1480.	0.1356E-00

TIME TO BEGINNING OF ABLATION FOR CAPACITOR NO. 1 = 0.11103449E-00
TIME TO COMPLETE ABLATION FOR CAPACITOR NO. 11 = 0.78824279E+00

Fig. 7 SAMPLE PROBLEM ABLATOR THICKNESS VERSUS TIME



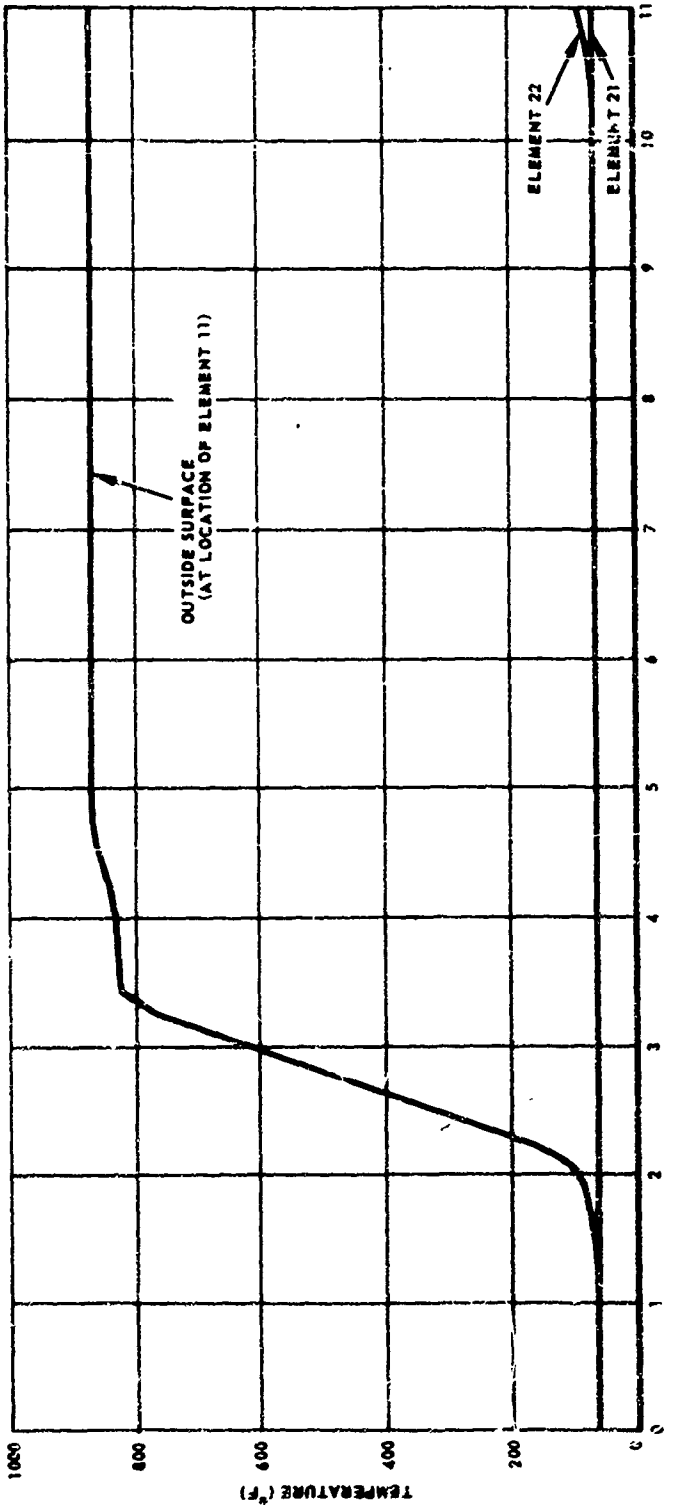


Fig. 8 SAMPLE PROBLEM TEMPERATURE RESULTS

APPENDIX A

THE MODIFIED EFFECTIVE HEAT OF ABLATION

Figure A1 has been prepared in order to show two typical pyrolization processes, and a typical temperature distribution in the boundary layer and ablator. Figure Ala illustrates a combined sublimation-oxidation process while Figure Alb depicts charring ablation. With reference to the temperature distribution, Figure Alc, it can be assumed either that the ablator has been suddenly injected into a hot-gas stream and is experiencing a transient surface temperature rise, or that ablation has steadied out such that the temperature profile shown is of a fixed shape and magnitude with respect to the moving surface. As is well known, one of the principal features of ablation is the reduction in inward convective heat flux through the boundary layer by the outward flow of released gas. This release of gas into the boundary layer is similar in its effect on the boundary layer to the release from a transpiration cooled wall. Therefore, the blocking effectiveness of the release is commonly characterized by a transpiration factor β_H.

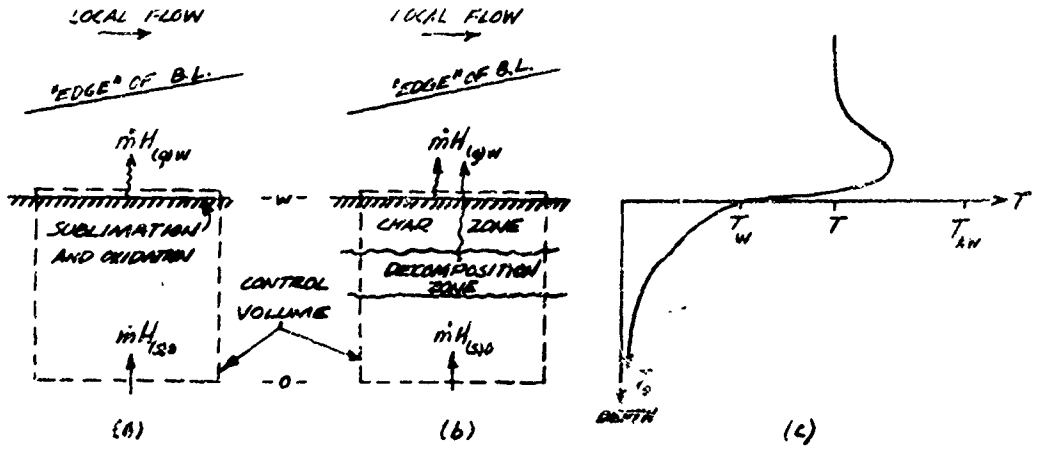


Figure A1. Two Modes of Ablation and a Typical Temperature Distribution

In the case of the steady ablation process the fundamental steady one-dimensional energy equation on the control volume of Figure A1a, which extends deep into the steadily ablating semi-infinite body, is

$$\frac{q_o}{\dot{m}} = H_{(g)w} - H_{(s)o} + \hat{s}_H(H_{aw} - H_w) + \frac{q_{rad}}{\dot{m}} \qquad \text{(A1)}$$

Effective Heat of Ablation	Enthalpy Rise of Ablator	Blocking Term	Net Outward Surface Radiation

where q_o denotes ordinary unblocked convective heat flux to a wall whose surface temperature is equal to that of the ablating surface. With reference to equation (A1) it can be seen that a purely experimental effective heat of ablation can be obtained in the laboratory by applying a given level of $(H_{aw} - H_w)$ and by measuring q_o to a non-ablating calorimeter model, whose surface temperature is equal to the ablator surface temperature, and by measuring mass loss rate $\dot{m}$ of the ablating model in the same stream. The experimentally determined quotient $q_o/\dot{m}$ will correctly represent the right-hand side of equation (A1) if

(a) Calorimeter radiation matches that of the ablator, or if q_o is corrected in the case of a mis-match.

(b) The ablation model is thick enough to simulate a semi-infinite body.

(c) The run is steady or is corrected for any unsteady periods.

(d) The supply air is clean.

(e) Air pressure effects on degradation chemistry simulate the in-flight case.

By comparison to the foregoing direct experimental methods, the indirect experimental method of determining $q_o/\dot{m}$ involves selecting a level of $H_{aw} - H_w$ and suitable

experimental values of other quantities on the right-hand side of Equation (A1). In the particular case of a subliming ablator, $H_{(g)w} - H_{(s)o}$ can be calculated from the relation

$$H_{(g)w} - H_{(s)o} = H_{(sg)w} + \int_{T_o}^{T_w} c_{p(s)} dT \tag{A2}$$

provided the ablation wall surface temperature T_w is known. The enthalpy-based transpiration factor β_H is available in the literature (5) covering the laminar and turbulent boundary layers. However, calculation of the radiation term $q_o/\dot{m}$ is not straight-forward because it involves the unknown ablation rate $\dot{m}$. The alternate expression for $q_o/\dot{m}$ due to Adams (5)

$$\frac{q_o}{\dot{m}} = \frac{H_{(g)w} - H_{(s)o} + \beta_H (H_{aw} - H_w)}{1 - \frac{q_{rad}}{q_o}} \tag{A3}$$

results from a rearrangement of the terms of Equation (A1). Still, however, the calculation of q_{rad}/q_o is not straight-forward because it involves the unknown heating rate q_o. No attempt will be made to resolve this problem here. For further discussion, see Reference 6.

In the present ablation program an equivalent surface-ablation energy property was needed. It was defined as the sum of the sublimation enthalpy change and the blocking term. By substituting Equation (A2) into Equation (A1) one finds this sum to be related to the effective heat of ablation in the following way

$$H_{(sg)w} + \beta_H (H_{aw} - H_w) = \left(\frac{q_o}{\dot{m}} - \int_{T_o}^{T_w} c_{p(s)} dT - \frac{q_{rad}}{\dot{m}} \right)_{\substack{\text{semi-infinite} \\ \text{test body}}} \tag{A4}$$

Since the right-hand side of equation (A4) is a modified form of the ordinary effective heat of ablation $q_o/\dot{m}$ it is called the modified effective heat of ablation. When obtaining the modified effective heat of ablation from the literature one must exercise good judgement with regard to factors (a) - (e) cited above.

Coding Sheets

PROGRAMMER R.P. SUESS / R.W. ALLEN

PROBLEM NUMBER 1210

FORTRAN CODING FORM

PAGE 2 OF 12 PAGES

DATE

IDENTIFICATION

C FOR COMMENT

FORTRAN STATEMENT

```
      JOB     12.0,P,SUESS,B,3000
      XEQ
C     SAMPLE ABLATION PROBLEM
      DIMENSION F1(9),F1V(10),F2(9),F3(6),F3V(7),F4(6),F5(7),F5V(8),F6(7
     1),F7(3),F7V(4),F9(6),F10(6),F10V(7),F11(6),F12(6),F14(6),F14V(7),
     2F15(6),F16(6),F16V(7),F17(6)
      DIMENSION IASEQ(500),V(1000),DUM(4407),IAB(1000),V0(1000),
     1DAMN(4002)
      COMMON T,G,DUM,IAB,IASEQ,V0,DAMN
```

PROGRAMMER _____

PROBLEM NUMBER _____

FORTRAN CODING FORM

PAGE 2 OF _____ PAGES

DATE _____

IDENTIFICATION _____

73 80

C FOR COMMENT

STATEMENT NUMBER | CONTINUATION

FORTRAN STATEMENT

```
C     FLIGHT TRAJECTORY
C     MACH NUMBER VERSUS TIME
      FIV(1)=0.00
     1    2.00
     2    4.00
     3    4.90
     4    4.99
     5    5.00
     6    5.00
     7    5.00
     8    5.00
     9    5.00
C
      FIV(1)=0.
     1    0.00
     2    2.00
     3    4.00
     4    4.90
     5    4.99
     6    5.00
     7    5.00
     8    5.01
     9    5.50
      FIV(10)=30.
```

PROGRAMMER

PROB. OR NUMBER

FORTRAN CODING FORM

PAGE 3 OF PAGES

DATE

IDENT. 73 80

C FOR COMMENT

STATEMENT NUMBER | CONTINUATION

FORTRAN STATEMENT

```
      ALTITUDE
      F2(1) = 0.20
              2  3.3
              3  6.6
              4  8.16
              5  8.32
              6  8.35
              7  3.35
              8  9.15
     1        9     5000.
      TEMPERATURE ATMOSPHERIC CONDITIONS - STANDARD DAY
      F3(1) = 519.
              2  515.
              3  512.
              4  509.
              5  504.
     1        6     501.
      F3V(1) = 6.
              2  0.0
              3  1000.
              4  2000.
     1        5     3000.
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 4 OF ____ PAGES

DATE

IDENTIFICATION

C FOR COMMENT

STATEMENT NUMBER

CONTINUATION

FORTRAN STATEMENT

```
      F3V(6)=4000.
      F3V(7)=5000.

C     AMBIENT PRESSURE
      F4(1)=2116.
            2 2041.
            3 1968.
            4 1897.
            5 1828.
      VVVVVVV1761.

C     LOCAL FLOW CONDITIONS VERSUS FREE STREAM MACH NUMBER
C     MACH NUMBER RATIO
      F5(1)=1.000
            2 0.625
            3 0.460
            4 0.715
            5 0.750
            6 0.725
      VVVVVV0.700

      F5V(1)=7.
            2 0.000
            3 1.615
      VVVV4VV1.770
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 5 OF _____ PAGES

DATE

IDENTIFICATION

C FOR COMMENT

STATEMENT NUMBER | FORTRAN STATEMENT

```
      ESV(5) = 2.00
             6   3.00
             7   4.00
      VVVVAVV5.00

C     PRESSURE RATIO
      F6(1) = 1.00
             2   2.22
             3   2.14
             4   2.20
             5   2.83
             6   3.69
      VVV7VV3.76

C     EFFECTIVE SPACE TEMPERATURE VERSUS ALTITUDE
      F7(1) = 600.
      F7(2) = 604.
      F7(3) = 608.

      E7V(L) = 3.
             2   0.00
             3   2500.
      VVVV4VV5000.
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 6 OF _____ PAGES

DATE

IDENTIFICATION

73 80

C FOR COMMENT

STATEMENT NUMBER | CONTINUATION

FORTRAN STATEMENT

```
C     EMISSIVITY OF EXTERNAL SURFACES
      FB = .8

C     FLOW NUMBER FOR AERODYNAMIC HEATING EQUATION
      F9(1)  2.0E06
             2.5000
             3.8000
             4.3E00
             5.0.0245
             6.0.00000

C     INITIAL VOLUMES OF POINTAL ABLATING CAPACITOR
      V0(1) = .17HE-03
             2
             3
             4
             5
             6
             7
             8
             9
      V0(10) = .17HE-03
            10
            11
            12
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 2 OF PAGES

DATE

IDENTIFICATION

C FOR COMMENT

STATEMENT NUMBER

CONTINUATION

FORTRAN STATEMENT

```
      V(13) = .17453E-03
C     SEQUENCE OF ADJACENT ELEMENTS
      IASEQ(1) = 2
      IASEQ(10) = 8
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 5 OF PAGES

DATE

IDENTIFICATION 73 80

C FOR COMMENT

STATEMENT NUMBER

FORTRAN STATEMENT

```
      IASEQ(15)=11
     1          16,12
     1          17,13
     1          18,14
     1          19,15
     2          20,16
     2          21,17
     2          22,18
     2          23,19
     2          24,20
     2          25,21
C
C    THERMAL PROPERTIES OF TELFLON
C    DENSITY
      FIO(1)=1,25
     2          1,1,1,5
     5          10,5
     7          9,7
     C          8,7
     G          7,8
C
      FIOV(1)=6
     2          5.00
     3          7.00
     9          9.00
```

PROGRAMMER

PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 2 OF PAGES

DATE

IDENTIFICATION

C FOR COMMENT

STATEMENT NUMBER

CONTINUATION

FORTRAN STATEMENT

```
      FIOV(S)=1100.
     &      1300.
     &      1500.

C     SPECIFIC HEAT
      F.I.(1)  .2300
            2  .2513
            3  .2800
            4  .3100
            5  .3300
     &      .3645

C     THERMAL CONDUCTIVITY
      FI2(1)=.1488
            2  .1768
            3  .2010
            4  .2337
            5  .2713
     &      .3045

C     THERMAL PROPERTIES OF 303 STAINLESS STEEL
C     DENSITY
      F.I.3.=S.O.I.

C     SPECIFIC HEAT
```

PROGRAMMER

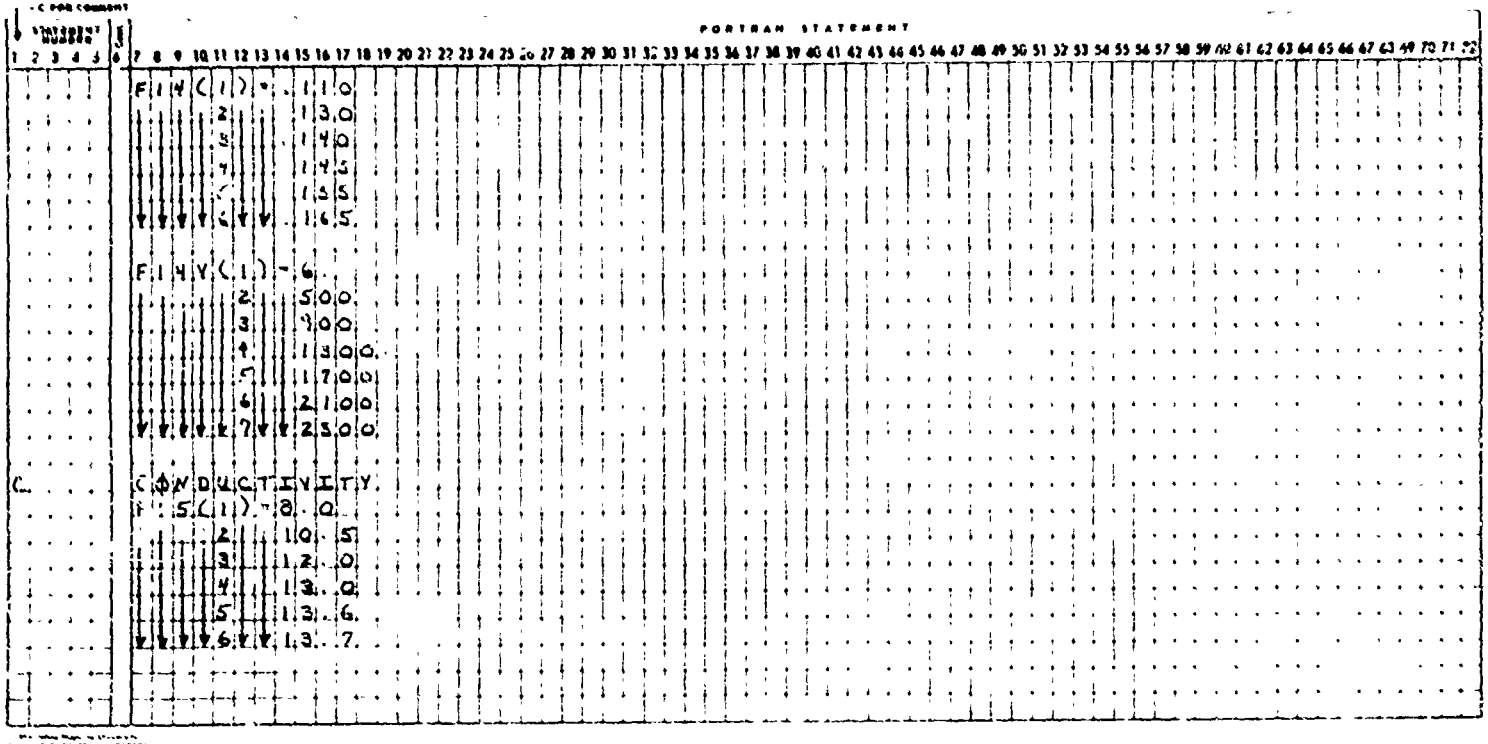
PROBLEM NUMBER

FORTRAN CODING FORM

PAGE 10 OF PAGES

DATE

IDENTIFICATION



FORTRAN CODING FORM

PROGRAMMER

PROBLEM NUMBER

PAGE 11 OF PAGES

DATE

IDENTIFICATION 73 80

```
C     ABLATION TEMPERATURE OF TEFLON VERSUS ENTHALPY DIFFERENCE
      F16(1)=1260.
            2    1310.
            3    1360.
            4    1410.
            5    1460.
            6    1510.

      F16V(1)=6.
             2    250.
             3    500.
             4    750.
             5    1000.
             6    1250.
             7    1500.

C     MODIFIED HEFF FOR TEFLON
      F17(1)=825.
            2    1000.
            3    1175
            4    1250.
            5    1375.
            6    1500.

      F 8 1 0
```

PROGRAMMER

PROBL M NUMBER

FORTRAN CODING FORM

PAGE 12 OF PAGES

DATE

IDENTIFICATION 73 80

C FOR COMMENT

STATEMENT NUMBER

FORTRAN STATEMENT

```
C     SETTING OF INITIAL SURFACE LEVELS
      INDX1 = 1
      INDX2 = 111

      CALL ASET(0.0,11.0,519.,1,1000,6000.)
     1CALL TRAJ(F1,F.1V,F2,F1V)
      CALL ATM(F2,F3V,F4,F3V)
      CALL FORALT(1000.0,F7,F7V)
      CALL AERO0(1,1,F9,F5,F5V,F6,F5V,F16,F16V,F17,F16V,INDX1,,0B33,,0331)
      CALL AERO0(2,1,F9,F5,F5V,F6,F5V,F16,F16V,F17,F16V,INDX2,,0B33,,1117)
      CALL CAP(1,.17YE-03,F10,F10V,F11,F10V)
```

PROGRAMMER

PROGRAM NUMBER

FORTRAN CODING FORM

PAGE 12 OF

DATE

IDENTIFICATION 73 80

FORTRAN STATEMENT

```
      CALLACAP(9,.174E-03,F10,F10V,F11,F10V)
      CALLACAP(10,.174E-03,F10,F10V,F11,F10V)
               11
               12
               13
               14
               15
               16
               17
               18
               19
               20
               21,.348E-03,F13,0,F14,F14V)
               22,.348E-03,
               23,.696E-03,
               24,.39E-03,
               25,1.39E-03,
               26,1.39E-03,

      CALL [illegible](22,23,.15,.33,F15,F14V)
               23,.37,.6,.660,
               25,.5,.000,
               2[illegible],.5,.000,
```

PROGRAMMER

PUNCH ON NUMBER

FORTRAN CODING FORM

PAGE 17 OF PAGES

DATE

IDENTIFICATION

C FOR COMMENT

STATEMENT NUMBER

FORTRAN STATEMENT

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72

```
      CALLACΦmcN(1,2,F0.
                 2,3,
                 3,
                 4
                 5,6,
                 6,7,
                 7,8,
                 8,)
      CALLACΦmcN(9,10,80
      CALLACΦmcN(11,12,80
                 12,13,
                 13,14,
                 14,15,
                 15,16,
                 16,17,
                 17,18,
                 18,19,
                 19,20,
      CALLACΦmcN(1C,1,,6C
      CALLACΦmcN(21,22,80
```

FORTRAN CODING FORM

PROGRAMMER

PROBLEM NUMBER

PAGE 45 OF PAGES

DATE

IDENTIFICATION

```
      CALL ACOMCN(1, 11, .050, 1E09, .050, F12, F10V, F18, 0, F12, F10V)
                  2, 12,
                  3, 13,
                  4, 14,
                  5, 15,
                  6, 16,
                  7, 17,
                  8, 18,
                  9, 19,

      CALL ACOMCN(10, 20, .050, 1E09, .050, F12, F10V, F18, 0, F12, F10V)
      CALL ACOMCN(21, 22, .100, 1E09, .100, F15, F14V, F18, 0, F15, F14V)

      CALL RAD(INDX1, 1000, .0833, F8, 0)
      CALL RAD(INDX2, 1000, .0833, F8, 0)

      CALL WRITE(41, 0., .5, 1., 1.5, 2., 2.5, 3., 3.5, 4., 4.5, 5., 5.5, 6., 6.5, 7., 7
     15, 8., 8.5, 9., 9.5, 10., 11., 12., 13., 14., 15., 16., 17., 18., 19., 20., 21., 22
     1., 23., 24., 25., 26., 27., 28., 29., 30.)
```

PROGRAMMER

PUNCH RUN NUMBER

FORTRAN CODING FORM

PAGE /6 OF P-665

DATE

IDENTIFICATION 73 80

C FOR COMMENT

STATEMENT NUMBER

FORTRAN STATEMENT

```
      CALLASTSP
      CALLAGL(INDX(1,1),1,LX,...)
      GO TO 2
      END
```

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