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AUTHORITY

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AERODYNAMIC HEATING AND ABLATION COMPUTER PROGRAM (HEATAB)

William J. Moulds
J. D. Young
Lt USAF

TECHNICAL REPORT NO. AFWL-TR-66-105
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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico
AERODYNAMIC HEATING AND ABLATION COMPUTER PROGRAM

(HEATAB)

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FOREWORD

This report was prepared under Project 627A, Program Element 6.44.06.12.4, Weapon System 627A.

Inclusive dates of research were January 1966 through May 1966. This report was submitted by the authors 18 August 1966.

The authors wish to thank Mrs. Barbara G. Deimer and Jerome L. Hitchcock for their assistance in the preparation of this program and report.

This report has been reviewed and is approved.

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Chief, Electronics Branch

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Chief, Development Division
ABSTRACT

An Aerodynamic Heating and Ablation Computer Program (HEATAB) is presented to establish a means by which heat transfer problems may be solved with minimum effort. This program computes the boundary layer conditions, time-temperature distribution in a body, the ablation recession rate, and weight loss. The program was written in Fortran IV for the CDC 6600 computer.
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SECTION I
INTRODUCTION

This program is an outgrowth of a need for aerodynamic heating and ablation analysis of hypersonic reentry vehicles. The present design requirements for advanced systems of high performance reentry vehicles have resulted in a severe thermal environment around the nose and conical surfaces of the vehicles. The most popular, self-regulating type of heat protection system, the ablating heat shield, will produce a surface erosion and nose blunting. Large shape changes, which will influence the aerodynamic performance of the vehicle during flight, may be produced. This vehicle shape change for an ablation-type system is important from a systems standpoint in determining the actual performance of the vehicle during flight. Equally important from a systems standpoint is the determination of boundary-layer parameters for R-F transmission as well as temperature-time profiles in the vehicle for temperature-sensitive instruments.

It is our hope that this report will help the nonthermodynamicist understand his problem and solve it with minimum effort. The equations of heat transfer are general in that they apply to most axially symmetric vehicles of any composite skin structure. The vehicle skin is assumed to be made of discrete layers of material whose properties may vary from layer to layer. The existing computer program is specific in that the equations have been applied to a sharp-nosed, conical vehicle. With a thorough understanding of thermodynamic principles, as applied to a conical vehicle, and with a basic knowledge of computer programming, the reader should be able to adapt this program to any vehicle.
SECTION II
BACKGROUN AND THEORY

1. Background

Advances in hypersonic atmospheric flight have resulted in environments of extremely high temperatures. Boundary layer temperatures in excess of 10,000°F are characteristic of vehicles entering the atmosphere at hypersonic speeds. As a result, the thermal barrier is at present the major obstacle to the safe reentry of vehicles. The term "thermal barrier" refers primarily to the problems associated with the dissipation of the vehicle energy to the surrounding air. For sharp bodies at hypersonic speeds, most of the dissipation occurs in the boundary layer. The viscous stresses within the boundary layer exert shearing work on the fluid and raise its temperature appreciably. This work, called aerodynamic heating, also raises the surface temperatures of bodies within this environment.

In hypersonic flight, it becomes obvious that capacitance or mass heat sink protection, though simple, is an impossible means of coping with the extremely high total heat input associated with hypervelocity reentry vehicles. Consequently, other means of cooling or protecting for operating beyond heat sink limitations must be used. One convenient means for meeting this form of environmental protection is by the method of ablation cooling.

The ablative process is illustrated in figure 1. The ablation process works in the following manner: (1) the material or ablator acts as a heat sink, (2) when the critical or melting temperature of the ablator is reached, a thin layer of the material at the surface will begin successively to melt, vaporize, depolymerize, or decompose chemically, (3) as the material vaporizes, the gaseous products of decomposition enter into the boundary layer. Being relatively cool, as compared to the boundary-layer air, the injected gas forms a thin but effective film that greatly reduces the heat transfer to the vehicle surface.

Experiments have verified that, in high-speed flow, the magnitude and direction of the flow at the surface does not depend on the difference between the wall temperature and the free-stream temperature as in low-speed flow, but
rather on the difference between the wall temperature and the adiabatic wall temperature. To correlate experimental data, it is convenient to define the unit surface heat rate (reference 1) for high-speed flow as

\[
\dot{q}_c/A = -\dot{h} \left(T_{AW} - T_W\right)
\]

where

\[
\begin{align*}
\dot{q}_c/A &= \text{heating rate BTU/sec - ft}^2 \\
\dot{h} &= \text{convective heat transfer coefficient -BTU/ft}^2 \text{ - sec}^{-1} \text{ - °R} \\
T_{AW} &= \text{adiabatic wall temperature - °R} \\
T_W &= \text{vehicle wall temperature - °R} \\
A &= \text{local wetted area - ft}^2
\end{align*}
\]

It is important in the selection of a suitable material for thermal protection by the ablative process that the products of decomposition have a high specific heat. This in turn produces a high effective mean specific heat of the gas-air mixture in the boundary layer and a high Prandtl number. It is also desirable that the ablator have a low thermal conductivity. This will decrease heat conducted to the interior of the vehicle.
2. Heat Transfer Coefficient

In conventional analysis of heat transfer by forced convection, the nature of the flow can be described by the Reynolds number, which is a dimensionless measure of the ratio of inertial to viscous forces. In high speed flow, at least two additional parameters must be considered. These are Mach number and Prandtl number. The parameter Mach number (AMACH) describes the influence of compressibility on heat transfer and flow phenomena and is defined as the ratio of the gas or flight velocity VEL to the local or ambient speed of sound VS. The Prandtl number, Pr, is defined as the ratio of heat storage to heat conduction of a gas.

The heat transfer coefficient (reference 2) is related to the flow properties through the relation

\[ \text{Nu}(Pr)^{-1/3} = C(Re)^a \]

where

- Nu = Nusselt number = \( he \times K \)
- he = effective heat transfer coefficient
- X = distance from the nose - ft
- k = thermal conductivity of air - BTU/ft - sec - °R
- Pr = Prandtl number = \( \frac{C_p \mu}{K} \)
- C = specific heat of air - BTU/lb - °R
- \( \mu \) = viscosity of air - lb - sec/ft²
- Re = Reynolds number = \( \rho Vx/\mu \)
- \( \rho \) = density of air - lb - sec²/ft⁴
- V = Boundary-layer edge velocity - ft/sec
- C = 0.0296 for turbulent flow (reference 1)
- 0.354 for laminar flow
- a = 0.8 for turbulent flow (reference 1)
- 0.5 for laminar flow
Good correlation with experimental data is obtained if the gas properties are evaluated at the reference temperature and the velocity is taken as the boundary-layer edge velocity. For the case of mass addition, the properties of the injected gas are used to compute the Prandtl number and Nusselt number.

3. Unsteady Heat Conduction

This section presents a means of applying the Schmidt graphical method for solving an unsteady heat conduction problem. A thorough discussion of this method can be found in any general text on heat transfer (references 1 and 3) and will not be attempted here. This method is quite flexible and difficult boundary conditions can be handled easily.

The graphical method is widely used in industry because it gives a running picture of the changing temperature distribution; its details can be delegated to relatively untrained personnel, and mistakes, if they occur, are quickly discovered. However, for precise computations, especially when variations of physical properties of material with temperature are important, as in the ablation process, a numerical method should be used instead of a graphical method. Numerical methods are especially convenient when a computer is available, since the steps involved in a numerical solution can be programmed without difficulty.

The numerical method for solving unsteady-state conduction problems differs from that used to solve steady-state problems. In the latter cases, the temperature distribution in a body can be obtained for a network of points in a solid by solving a system of residual equations. In unsteady-state systems, the initial temperature distribution is known, but its variation with time must be determined. It is, therefore, necessary to deduce the temperature distribution at some future time from a given distribution at an earlier time.

To illustrate the numerical method, it is first necessary to transform the Fourier conduction equation (a partial differential equation that is second order in space and first order in time) for the unsteady temperature distribution in a heat-conducting solid into a finite difference form.

\[
\frac{\Delta T}{\Delta t} = \frac{\alpha}{(\Delta x)^2} \frac{\Delta^2 T}{\Delta x^2}
\]

the subscript denotes the differentiation variable. Letting \( n \) denote position and \( K \) time, \( \Delta T \) can be written as

5
In a similar manner

\[ \Delta _{x} T = T_{n+1,k} - T_{n,k} \]

The expression \( \Delta _{x} ^{2} T \) thus becomes

\[ \Delta _{x} ^{2} T = T_{n+1,k} - 2T_{n,k} + T_{n-1,k} \]

Substituting these expressions into the Fourier equation gives

\[ T_{n,k+1} - T_{n,k} = \frac{\alpha \Delta t}{(\Delta x)^{2}} \left( T_{n+1,k} - 2T_{n,k} + T_{n-1,k} \right) \]

The temperature throughout a wall or slab can now be computed for any later time if the initial distribution is known. A Schmidt plot demonstrates the temperature profile versus time in a semi-infinite slab (figure 2).

Figure 2. Schmidt Plot in an Infinitely Thick Wall
A constant wall temperature is assumed in the graphical example but a varying wall temperature can be handled with equal ease. By letting the wall temperature vary with time, the distribution at each point within the body can be computed for each time increment.

4. Vehicle Thermal Model

To determine the time-temperature profile in the vehicle skin, the Fourier conduction equation was written as a finite difference equation and solved numerically. This method is a further adaptation of the Schmidt graphical method (reference 3). The wall is divided into a number of lamina with known thickness, specific heat, and thermal conductivity and with a known initial temperature distribution. Figure 3 illustrates the model with its associated nomenclature.

\[
T_{n,k+1} = T_{n,k} + \frac{\Delta t}{(Ax)^2} \left( T_{n+1,k} - 2T_{n,k} + T_{n-1,k} \right)
\]

Figure 3. Model for Wall Temperature Profile and Ablation Recession Calculations

The difference equation to compute the temperature at position \( n \) at time \( k+1 \) is
In this form, the properties cannot vary from layer to layer. If the properties vary from layer to layer, the above equation must be written in the form

\[ T_{n,k+1} = T_{n,k} + \Delta \tau \left[ \alpha_{n-1} \frac{\Delta T}{\Delta X_{n-1}} \left( T_{n-1,k} - T_{n,k} \right) - \alpha_n \frac{\Delta T}{\Delta X_n} \left( T_{n,k} - T_{n+1,k} \right) \right] \]

It is useful to replace the thermal diffusivity by its defined equivalent

\[ \alpha = \frac{K}{\rho C_p} \]

This step allows one to easily recognize certain groups of terms as the heat conducted through each lamina and permits the convective heat flux to be used in solving for the wall temperature. The equation for the wall temperature is

\[ T_{n-1,k+1} = T_{n-1,k} + \frac{\Delta \tau}{\rho C_p \Delta X_{n-1}} \left[ h_e (T_{AW} - T_{n-1,k}) \right] - \frac{\Delta \tau K}{\rho C_p \Delta X_{n-1}} \left( T_{n-1,k} - T_{n,k} \right) \]

The backface boundary condition can be specified in several ways. If internal heating (or cooling) is present, the backface temperature may be held constant or allowed to vary in a specified manner. A conservative assumption is that no heat flows through the last lamina. This assumption will cause somewhat more ablation and higher temperatures than would be encountered with a cooled backface or other heat sink material.

5. Mass Loss and Surface Recession

Two mechanisms are involved in the loss of ablation material. These mechanisms are: (1) mass loss due to oxidation, and (2) mass loss due to sublimation. The oxidation is controlled by the diffusion of oxygen to the reacting carbon and the sublimation is controlled by local pressure and temperature. A detailed discussion of the theory of ablation material and decomposition of reaction is not the intent of this report, so only the results will be presented. For a more detailed discussion, see references 4 and 5.
For laminar flow, the diffusion mass loss rate is given by

\[ \dot{M}_D = \frac{\dot{q}_c + \dot{q}_{HGR}}{K_1 + K_2 \left( h - C_{PBL} \frac{T_W}{T_{RL}} \right)} \]

and for turbulent flow, the equation is

\[ \dot{M}_D = \frac{\dot{q}_c + \dot{q}_{HGR}}{K_1 + K_2 \left( h - C_{PBL} \frac{T_W}{T_{RL}} \right)} \]

where the constants \( K_1 \) and \( K_2 \) can be interpreted as the intercept and slope respectively on an effective heat of ablation versus enthalpy difference (between recovery and wall conditions) plot.

- \( \dot{q}_c \) = heat rate - BTU/ft\(^2\) - sec
- \( \dot{q}_{HGR} \) = heat rate for hot gas radiation - BTU/ft\(^2\) - sec
- \( h \) = recovery enthalpy in boundary layer - BTU/lb
- \( C_{PBL} \) = specific heat in boundary layer - BTU/lb - °R
- \( T_W \) = wall temperature - °R

\[ \dot{q}_{HGR} = \sigma \left( T_{GAS} \right)^4 GE - (T_W)^4 ALPG \]

where
- \( \sigma \) = Stephan-Boltzmann constant, \( 4.8 \times 10^{-13} \) BTU/sec-ft\(^2\) - °R\(^4\)
- \( T_{GAS} \) = gas temperature - °R
- \( GE \) = gas emissivity at temperature \( T_{GAS} \)
- \( T_W \) = wall temperature - °R
- \( ALPG \) = absorptivity of gas at temperature \( T_W \)

The total mass loss rate is given by
\[ \dot{M}_W = \dot{M}_D \left[ 1 + 2.64 \times 10^6 (PBL)^{-0.67} \exp \left( - \frac{11.05 \times 10^6}{TW} \right) \right] \]

where

\[ PBL = \text{boundary-layer edge pressure} - \text{lbs/ft}^2 \] (reference 6)

The surface recession rate is calculated by

\[ \dot{S} = \frac{\dot{M}_W}{\rho} \]

where \( \rho \) is the ablation material virgin density. To determine the total recession, \( \dot{S} \) is summed after each calculation for a new trajectory point.

6. Calculation of Total Weight Loss Rate

After the local instantaneous and total recession rates have been computed, the local weight loss rate is calculated by determining the volume reduction of the body and multiplying by the material density. It is assumed in this calculation that the recession is uniform over the region of interest. Total weight loss rate is obtained by summing the local rates.
SECTION III
PROGRAM DESCRIPTION

1. Introduction

This section discusses and presents the basic program (HEATAB) with stagnation point modification (STAGG) for a sharp-nose, conical vehicle. The program was written in FORTRAN IV for the CDC 6600 computer. Only a general flow chart is given. The flow within individual blocks is easily followed from the program listing (Appendixes I and II).

2. HEATAB Description

The basic sequence of calculations is shown on the flow chart of HEATAB, figure 4. After entry into the program, the first steps are the reading of input data and the defining of constants. Descriptive initial conditions are printed to identify the case being run.

Time is the independent variable and its computation marks the entry to the computational loop of the program. The flight conditions, atmospheric properties, and layer index are now determined. A number of methods can be used to input the flight trajectory such as subroutine, punched card, or magnetic tape. The atmospheric properties are computed by subroutines. \( K \) is a subscript that indicates the layer for which computation is being performed. The initial value for \( K \) is 1. \( \text{IND}(K) \) is used to indicate to the computer to use virgin or char properties. If \( T(K) \) is less than the char temperature, \( \text{IND}(K) \) will route the computer to virgin material physical properties. Similarly, if \( T(K) \) is greater than the char temperature, then char properties will be computed.

The next sequence of calculations determines the recovery temperature, boundary-layer edge conditions, and Reynolds number. Following these calculations, it is determined if ablation is occurring or has occurred. Based on this determination, the correct Prandtl number is computed. Based on the outcome of the decision regarding the existence of turbulent flow, the appropriate recovery factor, heat transfer coefficient, dynamic temperature, adiabatic wall temperature, and gas temperature are calculated. The resulting output of this sequence is the heat flux to the body.
Computing the wall temperature distribution is the function of the next sequence of computations. Again the decision regarding charring and ablating is made and the appropriate physical properties are selected. The temperature $T_W(1)$ is computed as a function of the adiabatic wall temperature and $T_W(2)$. The temperatures below the surface are next computed as functions of the old adjacent temperatures.

If the wall is ablating, mass is being lost from the vehicle and the wall will recede. The mass loss rate is computed in this sequence, along with the recession rate and new layer thickness. The new thickness is used the next time the temperature calculations are made. The printing of output data marks the completion of one cycle of computation. As a new cycle is started, a decision is made based on the vehicle's altitude. If the altitude for the new time is positive, computation continues; if the altitude is negative, a normal exit is made and computation ends.

3. **STAGG Description**

This section contains a description of the STAGG version of the aerodynamic heating and ablation program. STAGG is a modification of the basic program that can be used to calculate heat transfer rates on the stagnation point of sharp-nosed vehicles. Heat transfer rates and temperature profiles are calculated by the existing HEATAB equations, using local properties, but the constant in the heat transfer coefficient and Reynolds number for transition from laminar to turbulent flow has been redefined. The constants as defined by Lees' theory (reference 7) and Blausius' skin friction coefficient for point cone heat flux are

$$C = 0.778 \text{ for laminar flow}$$
$$0.0348 \text{ for turbulent flow}$$

Another difference between HEATAB and STAGG is the addition of nose blunting equations.

In the determination of nose blunting, it is assumed that the initial nose shape of particular interest, for which STAGG was written, was a sphere-cone and, after ablation, the final shape was a sphere-cone. Experimental evidence has shown that the final eroded shape could be approximated by a sphere-cone having a small deviation from a sphere. The reference sphere-cone configuration after erosion is obtained by placing a spherical surface tangent to a cone parallel to the original surface but displaced by the erosion on the cone and
and located axially at a position on the vehicle center line in accordance with the erosion at the stagnation point. (See figure 5.)

The experimental evidence of nose-shape change of reentry vehicles, as previously noted, can be represented by a sphere-cone shape which deviates from a spherical shape by an amount less than 10 percent of the final nose radius. The final eroded nose radius at zero angle of attack, therefore, can be obtained in terms of the stagnation point erosion and cone erosion as shown in equation

\[ R = R_0 + \frac{1}{1 - \sin \theta_c} \left[ \sin \theta_c \int_{t_0}^{t} \left( \frac{\dot{q}_c}{\rho_\infty} \right)_s \, dt - \int_{t_0}^{t} \left( \frac{\dot{q}_c}{\rho_\infty} \right)_c \, dt \right] \]

The integral represents the erosion at a given time during a flight for the locations at the stagnation point (S) and a point on the cone (C) at a location of wetted length of about five times the nose radius.

It is now possible to evaluate the final nose radius for a given application. Let

\[ \dot{T} = \int_{t_0}^{t} \left( \frac{\dot{q}_c}{\rho_\infty} \right)_s \, dt \]
\[ \dot{C} = \int_{t_0}^{t} \left( \frac{\dot{q}_c}{\rho_\infty} \right)_c \, dt \]

\[ . \cdot R = R_0 + \frac{1}{1 - \sin \theta_c} \left[ \sin \theta_c \, \dot{T} - \dot{C} \right] \]

where

- \( R_0 \) = original nose radius – ft
- \( R \) = instantaneous nose radius – ft
- \( \theta_c \) = cone half-angle – radians
TDOT = instantaneous stagnation point recession rate - ft/sec
CDOT = instantaneous cone recession rate - ft/sec
SECTION IV
BOUNDARY LAYER TRANSITION

The problem of transition from laminar to turbulent boundary layer flow has always been a troublesome one for the aeronautical engineer. The standard approach has usually been to design conservatively, that is, for turbulent flow. In general, the transition Reynolds number has been found to depend upon the local Mach number, which has been observed in the analysis of boundary layer transition on a series of flight vehicles. Transition on blunt spherical nose vehicles with low edge of boundary layer Mach numbers appears to occur at Reynolds number of $1.5 \times 10^5$, while on sharp bodies where the edge of the boundary layer Mach numbers approach 10, Reynolds numbers as high as $2.0 \times 10^6$ have been observed prior to transition. Thus, for untested vehicle configurations, it is necessary to investigate the relationship of the Mach number and the Reynolds number in both the high and low Mach number regions. It should be noted that flight data on sharp bodies indicates that, generally, transition does not occur instantaneously over the entire vehicle so that it may travel several thousand feet between the onset of transition and the establishment of a fully turbulent boundary layer. These criteria have been summarized by Heuk in reference 8.

The approach of this report is to apply the sharp and blunt body transition Reynolds numbers simultaneously. Therefore, the sharp body criterion is described by the expression

$$Re_{tran} = 2.0 \times 10^6$$

where the Reynolds number is that from a wetted length of one foot to the extreme aft end of a conical vehicle.

The blunt body criterion is applied when either of the following two Reynolds numbers are reached:

$$Re_{tran} = 1.5 \times 10^5$$ on the spherical nose

$$Re_{tran} = 5.0 \times 10^5$$ on the conical portion aft of the spherical nose for a wetted length of five times the nose radius

The above criteria has been found to correlate with experimental data.
APPENDIX I

HEATAB Program Listing
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<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Computes</th>
<th>Versus</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTUDE</td>
<td>Alt, Altitude of Vehicle</td>
<td>Time</td>
</tr>
<tr>
<td>CCPP</td>
<td>CC, Char Specific Heat of Lamina K of Ablator</td>
<td>TW(K)</td>
</tr>
<tr>
<td>CTCPC</td>
<td>CT, Char Thermal Conductivity of Lamina K of Ablator</td>
<td>TW(K)</td>
</tr>
<tr>
<td>DENS</td>
<td>Rho, Density of Air</td>
<td>Alt</td>
</tr>
<tr>
<td>GASE</td>
<td>GE, Ablative Gas Emissivity</td>
<td>TG</td>
</tr>
<tr>
<td>GASTC</td>
<td>GTC, Ablative Gas Thermal Conductivity</td>
<td></td>
</tr>
<tr>
<td>GCPB</td>
<td>GCP, Ablative Gas Specific Heat</td>
<td>P</td>
</tr>
<tr>
<td>PRESS</td>
<td>PE, Atmospheric Pressure</td>
<td>Alt</td>
</tr>
<tr>
<td>QVST</td>
<td>Q, Dynamic Pressure</td>
<td>Time</td>
</tr>
<tr>
<td>SPCh</td>
<td>SPC, Cone Surface Pressure Coefficient</td>
<td>AMACH</td>
</tr>
<tr>
<td>TCAT</td>
<td>TCA, Thermal Conductivity of Air</td>
<td>TR</td>
</tr>
<tr>
<td>TEMPA</td>
<td>Temp, Ambient Temperature</td>
<td>Alt</td>
</tr>
<tr>
<td>VCPPC</td>
<td>VC, Virgin Specific Heat of Lamina K of Ablator</td>
<td>TW(K)</td>
</tr>
<tr>
<td>VELOC</td>
<td>Vel, Velocity of Vehicle</td>
<td>Time</td>
</tr>
<tr>
<td>VISCO</td>
<td>Vis, Viscosity of Ambient Air</td>
<td>Alt</td>
</tr>
<tr>
<td>VISCOT</td>
<td>VISG, Ablative Gas Viscosity</td>
<td>TR</td>
</tr>
<tr>
<td>VSD</td>
<td>VS, Velocity of Sound</td>
<td>Alt</td>
</tr>
<tr>
<td>VTCPC</td>
<td>VT, Virgin Thermal Conductivity of Lamina K of Ablator</td>
<td>TW(K)</td>
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</tbody>
</table>

*This listing of subroutines common for HEATAB and STAGG.*
**LIST OF SYMBOLS FOR HEATAB**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACP(K)</td>
<td>Specific heat of ablator (char or virgin), BTU/lb - °R</td>
</tr>
<tr>
<td>AJ</td>
<td>778.184, Joule's constant</td>
</tr>
<tr>
<td>AKL1</td>
<td>Ablator constants for mass loss. Can be interpreted as the intercept and slope respectively on an effective heat of ablation versus enthalpy difference plot for laminar flow.</td>
</tr>
<tr>
<td>AKL2</td>
<td>Same as above, except for turbulent flow</td>
</tr>
<tr>
<td>AKT</td>
<td>Same as above, except for turbulent flow</td>
</tr>
<tr>
<td>AKT2</td>
<td></td>
</tr>
<tr>
<td>ALPG</td>
<td>Absorptivity of ablative gas</td>
</tr>
<tr>
<td>ALT</td>
<td>Altitude of vehicle, ft</td>
</tr>
<tr>
<td>AMACH</td>
<td>Mach number of vehicle</td>
</tr>
<tr>
<td>ANR</td>
<td>Computed Reynolds number</td>
</tr>
<tr>
<td>ARHO(K)</td>
<td>Density of ablator at lamina K (char or virgin), lbs/ft³</td>
</tr>
<tr>
<td>ATC(K)</td>
<td>Thermal conductivity of ablator at lamina K (char or virgin), BTU/ft-sec-°R</td>
</tr>
<tr>
<td>CPA</td>
<td>Specific heat of air, BTU/lb-°R</td>
</tr>
<tr>
<td>DE(K)</td>
<td>Instantaneous lamina thickness, ft</td>
</tr>
<tr>
<td>DEL(K)</td>
<td>Original lamina thickness, ft</td>
</tr>
<tr>
<td>DELT</td>
<td>Time step, sec</td>
</tr>
<tr>
<td>DMD</td>
<td>Diffusion controlled oxidation mass loss</td>
</tr>
<tr>
<td>DTR</td>
<td>Dynamic temperature rise, °R</td>
</tr>
<tr>
<td>E</td>
<td>2.7183</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational acceleration, ft/sec²</td>
</tr>
<tr>
<td>GCP</td>
<td>Ablation gas specific heat, BTU/lb-°R</td>
</tr>
<tr>
<td>GTC</td>
<td>Ablation gas thermal conductivity, BTU/ft-°R-sec</td>
</tr>
<tr>
<td>GVIS</td>
<td>Boundary layer air viscosity, lb-sec/ft²</td>
</tr>
<tr>
<td>HE</td>
<td>Convective heat transfer coefficient, BTU/ft²-sec-°R</td>
</tr>
<tr>
<td>IND(K) = 0</td>
<td>Lamina K of ablator is virgin</td>
</tr>
<tr>
<td>IND(K) = 1</td>
<td>Lamina K of ablator is char</td>
</tr>
<tr>
<td>JIND = 0</td>
<td>Outermost lamina not ablating</td>
</tr>
<tr>
<td>JIND = 1</td>
<td>Outermost lamina is ablating</td>
</tr>
<tr>
<td>NAL</td>
<td>Number of ablative laminas</td>
</tr>
<tr>
<td>NP1</td>
<td>Number which refers to bond lamina</td>
</tr>
<tr>
<td>NP2</td>
<td>Number which refers to aluminum skin</td>
</tr>
<tr>
<td>P</td>
<td>Boundary layer pressure, Atmospheric</td>
</tr>
<tr>
<td>PE</td>
<td>Ambient pressure, psi</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>PBL</td>
<td>Boundary layer edge pressure, psi</td>
</tr>
<tr>
<td>PR</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>PXE</td>
<td>Dummy variable</td>
</tr>
<tr>
<td>Q</td>
<td>Dynamic pressure, psf</td>
</tr>
<tr>
<td>QDOTC</td>
<td>Convective heat rate, BTU/ft²-sec</td>
</tr>
<tr>
<td>QDOTR</td>
<td>Hot gas radiation heat rate, BTU/ft²-sec</td>
</tr>
<tr>
<td>RE</td>
<td>Transition Reynolds number</td>
</tr>
<tr>
<td>RF</td>
<td>Recovery factor</td>
</tr>
<tr>
<td>RHO</td>
<td>Ambient density of air, lb-sec²/ft³</td>
</tr>
<tr>
<td>RHOC</td>
<td>Char ablator density, lb/ft³</td>
</tr>
<tr>
<td>RHOV</td>
<td>Virgin ablator density, lb/ft³</td>
</tr>
<tr>
<td>S</td>
<td>Instantaneous ablator wall recession rate</td>
</tr>
<tr>
<td>SDOT</td>
<td>Total ablator wall recession, ft</td>
</tr>
<tr>
<td>SIGMA</td>
<td>Stephan-Boltzmann constant</td>
</tr>
<tr>
<td>SPC</td>
<td>Cone surface pressure coefficient</td>
</tr>
<tr>
<td>TAW</td>
<td>Adiabatic wall temperature, °R</td>
</tr>
<tr>
<td>TCA</td>
<td>Thermal conductivity of air, BTU/ft-°R-sec</td>
</tr>
<tr>
<td>TEM</td>
<td>Initial temperature of laminas, °R</td>
</tr>
<tr>
<td>TEMP</td>
<td>Ambient temperature, °R</td>
</tr>
<tr>
<td>TG</td>
<td>Ablation gas temperature, °R</td>
</tr>
<tr>
<td>TIME</td>
<td>Elapsed time, sec</td>
</tr>
<tr>
<td>TM</td>
<td>Total mass from ablation</td>
</tr>
<tr>
<td>TMDOT</td>
<td>Instantaneous mass loss rate</td>
</tr>
<tr>
<td>TMELT</td>
<td>Temperature at which ablation starts, °R</td>
</tr>
<tr>
<td>TR</td>
<td>Reference temperature, °R</td>
</tr>
<tr>
<td>TR(K)</td>
<td>Temperature of lamina K, °R</td>
</tr>
<tr>
<td>VEL</td>
<td>Tangential velocity of vehicle, ft/sec</td>
</tr>
<tr>
<td>VIS</td>
<td>Viscosity of ambient air, lb-sec/ft²</td>
</tr>
<tr>
<td>VISC</td>
<td>Ablative gas viscosity, lb-sec/ft²</td>
</tr>
<tr>
<td>VS</td>
<td>Velocity of sound, ft/sec</td>
</tr>
<tr>
<td>X</td>
<td>Wetted length from nose to station on cone, ft</td>
</tr>
<tr>
<td>WT</td>
<td>Instantaneous weight loss rate</td>
</tr>
</tbody>
</table>
PROGRAM HEATAR(INPUT,OUTPUT)

AERODYNAMIC HEATING ON CONE

DIMENSION TW(50),IND(50),ACP(50),ARHO(50),DFL(50),DF(50)
READ 1,AKL1,AKL2,AKT1,AKT2,ALG,APL,SCMA,NAL,NP1,NP2,F,TEMP.
1ARHO(NP1),ARHO(NP2),ACP(NP1),ACP(NP2),DEL(NP1),
2DEL(NP2),DEL(NP1),DF(NP2),DEL,RE,VEL,TEM,CPA,ROV,
3RHOC,TEM,TOL,X
1 FORMAT(ASNECESSARY)
DO 2 N=1,NP2
TW(N)=TM
2 IND(N)=0
DO 3 N=1,NAL
DEL(N)=TOL
3 DE(N)=TOL
SDOT=0.
JIND=0
TIME=-DELT
TAW=TEMP
PRINT 4
4 FORMAT(HEADINGSASNECESSARY)
100 TIME=TIME+DELT
DO 6 N=1,NAL
AN=N
IF (AN*DELT(1) - SDOT) 6,8,8
6 CONTINUE
PRINT 7
7 FORMAT(10OVFRHEAT/)
GO TO 200
8 K=N
TR=TEMP*58*(TW(K)-TEMP)+19*(TAW-TEMP)
CALL ALTUDE(ALT,TIME)
CALL VSD(VS,ALT)
CALL VELOCI(VEL,TIME)
AMACH=VEL/VS
CALL TFMPA(TMP,A(T))
CALL RHOF(RHO,ALT)
CALL VSF(VIS,ALT)
CALL TCA(TCA,TR)
CALL VSF(TVIS,TR)
CALL SPCM(SCP,AMACH)
CALL GVS(GVS,TIME)
CALL PRESS(P,E,ALT)
PPL=SPC*Q+PF
P=PPL/!16,2
15 IF(JIND.EQ.0)GO TO 9
CALL GCPR(GCP,P)
CALL GASTC(GTC,GCP)
PR=GCP*GVS/GTC
GO TO 10
9 P=CPA*VIS/GTC
10 AND=VEL*X*PHO/VIS
11 IF(ANP.GT.RF)GO TO 12
12 RF=PR**5
RF=.57*G/G**.33*ANP**.3
GO TO 13
HF=.0296*TCA/X*PR**.3*ANR**.2
DTR=VEL**2*/(2*G*AJ*CPA)
TAW=TEMP+RF+DTP
TG=TEMP+OTR
CALL GASF(GE,TG)
ALPG=.022*(TG/TMELT)**4.5
QDOTC=HE*(TAW-TW(K))*DELT
IF(IND(K).EQ.1) GO TO 17
IF(TW(K).GE*TME)*TMELT) GO TO 17
15
TWK=TW(K)
CALL VTCPC(VT,TWK)
CALL VDCPC(VC,TWK)
ATC(K)=VT
ACP(K)=VC
ARHO(K)=PHOV
IF(K.EQ.1) GO TO 18
Tw(K)=TW(K)+DELT*(ATC(K-1)/ARHO(K-1))-(ACP(K-1))**2)*
1(TW(K-1)-TW(K)+ATC(K)/ARHO(K))**2*(TW(K)-TW(K+1))
IF(TW(K).LT.TMELT) GO TO 31
16
TW(K)=TMELT-1
GO TO 17
17
TWK=TW(K)
CALL CTCPCCC(T,TWK)
CALL CCP(CC,TWK)
ACP(K)=CC
ATC(K)=CT
ARHO(K)=PHOC
IND(K)=1
18
TW(K)=TW(K)+DFLT/(ACP(K)*ARHO(K))**DE (K)**(HE*(TAW-TW(K))-
ATC(K)/DE (K)**(TW(K)-TW(K+1)))*
IF(TW(K).GE*TME)*TMELT) GO TO 21
19
JIND = 0
GO TO 21
20
TW(K)=TMELT
IND(K)=1
JIND=1
CALL GCCP(GCP,P)
QDOTR=SIGMA*(GEG**4-ALPG*TMELT**4)*DELT
IF(QDOTR)22,22,23
22
QDOTP=0.
23
IF(ANP.GT.RF) GO TO 25
24
DMD=(QDOTC+QDOTR)/(AKL1+AKL2*(GCP*TAW-CPA*TMELT))
GO TO 26
25
DMD=(QDOTC+QDOTR)/(AKT1+AKT2*(GCP*TAW-CPA*TMELT))
26
PXE=1.05+04/TMELT
TMDOT = DMD*(1. + 2.64E+09/(PBL**67**XR**PXE))
TM=TM+TMDOT
SDOT=TM/PHOV
S=TMDOT/PHOV
WT=3.1416+2.*R**2*S*PHOV
DO 29 N=1,NAL
29
CONTINUE
PPINT 7
GO TO 200
30
DE(N)=DFL(N)-(<SDOT-(N-1)-6FL(1)))
[END(N)=1
IF(N.EQ.1)GO TO 31
DE(N-1)=0.0
K=K+1
IF(K.LE.NAL)GO TO 14
TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*(TW(K-1)-TW(K))**2)*ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*(TW(K)-TW(K+1))
K=K+1
TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*)
PRINT 5,TIME,ALT,VEL,ANR,TAW,TEMP,HE,QDTC,WT,TM,TG,SDOT,
5 FORMAT(1S NECESSARY )
IF(ALT)200,200,100
200 CONTINUE
END
APPENDIX II

STAGG Program Listing
**LIST OF SYMBOLS FOR STAGG**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDOT</td>
<td>Instantaneous cone recession rate, ft/sec</td>
</tr>
<tr>
<td>PHI</td>
<td>See figure 5</td>
</tr>
<tr>
<td>R</td>
<td>Radius of spherical nose, ft</td>
</tr>
<tr>
<td>TCAE</td>
<td>Time cone ablation ends</td>
</tr>
<tr>
<td>TCAS</td>
<td>Time cone ablation starts</td>
</tr>
<tr>
<td>THETC</td>
<td>Cone half-angle, rad</td>
</tr>
</tbody>
</table>
PROGRAM STAGG (INPUT, OUTPUT)

C STAGNATION HEATING

DIMENSION TW(50), IND(50), ATC(50), ACP(50), ARH0(50), DEL(50), DE(50)
READ 1, A1, AKL1, AKL2, AKT1, AKT2, I, GVIS, SIGMA, NAL, N1, NP2, E, TMELT,
1* ARH0(NP1), ARH0(NP2), ATC(NP1), ATC(NP2), ACP(NP1), ACP(NP2), DEL(NP1),
2* DEL(NP2), DE(NP1), DE(NP2), DEL, P, THTC, PHI, RE, VEL, TEMP, CPA, RH0V,
3* RH0C, TCA9, TEM, TOL, TCAF

1 FORMAT ( AS NECESSARY )
   DO 2 N = 1, NP2
   TW(N) = TEM
2 IND(N) = 0
   DO 3 N = 1, NAL
   DEL(N) = TOL
3 DE(N) = TOL
   CDOT = 0*
   SDOT = 0*
   JIND = 0
   TIME = -DFLT
   X = 0.1745*P*PHI
   TAW = TRMP
   PRINT 4
4 FORMAT ( HEADINGS AS NECESSARY )
   TIME = TMF + DELT
   DO 6 N = 1, NAL
   AN = N
   IF (AN = DEL(1) - SDOT) 6, 8, 8
6 CONTINUE
   PRINT 7
7 FORMAT ( 10H OVERHEAT/ )
   GO TO 100
8 K = N
   TR = TEMP + .58*(TW(K) - TEMP) + 19*(TAW - TEMP)
   CALL ALTDE (ALT, TIME)
   CALL VSD(VS, ALT)
   CALL VELOC (VEL, TIME)
   AMACH = VFL/VS
   CALL TEMP (TEMP, ALT)
   CALL RHOF (RH0, ALT)
   CALL VISCO (VIS, ALT)
   CALL TCAT (TCA, TR)
   CALL VSCOT (VISG, TR)
   CALL SPCM (SPC, AMACH)
   CALL OVLST (O, TIME)
   CALL RFTS (RE, ALT)
   PBL = SPC*Q + PE
   P = PBL/2116.2
   IF (JIND, EQ, 0) GO TO 9
   CALL GCQR (GCP, P)
9 CALL GARTC (GTC, GCP)
   PP = GCP*GVIS/GTC
   GO TO 10
10 PP = CPA*VIS/GTC
11 ANP = VEL**X/RHO/VIS
   IF (ANP, GE, 0) GO TO 12
12 IF = PP**E
   HE = .779*TCA/X*PP**E*37*ANP**E
   GO TO 13

30
HE = .0296 * TCA / X * PP**.33 * ANR**.8
DTR = VEL**2 / (2 * G * AJ * CPA)
TAW = TEMP + RF * DTR
TG = TEMP + DTR
CALL GASF(GF, TG)
ALPG = .022 * (TG/ TMELT)**.45
QDOTC = HF * (TAW - TW(K)) * DELT
IF(IND(K) * FO*1) GO TO 17
IF(TW(K) * GE * TMELT) GO TO 17
TWK = TW(K)
CALL VTCPC(VT, TWK)
CALL VCPPC(VC, TWK)
ATC(K) = VT
ACP(K) = VC
ARHO(K) = PHOV
IF(K = EO*1) GO TO 18
TW(K) = TW(K) + DELT * (ATC(K) / (ARHO(K-1) * ACP(K-1) * DE (K-1)**2)*
I(TW(K-1) - TW(K)) - ATC(K) / (ARHO(K) * ACP(K) * DE (K)**2) * (TW(K) - TW(K+1)) )
IF(TW(K) * LE * TMELT) GO TO 31
TW(K) = TMFLT - 1.
GO TO 31
TWK = TW(K)
CALL CTCPP(CT, TWK)
CALL CCP(CC, TWK)
ACP(K) = CC
ATC(K) = CT
ARHO(K) = PHOC
IND(K) = 1
TW(K) = TW(K) + DELT * (ACP(K) * ARHO(K) * DE (K)) * (HE * (TAW - TW(K))) -
I(ATC(K) / DE (K) * (TW(K) - TW(K+1)))
IF(TW(K) * GE * TMELT) GO TO 21
JIND = 0
GO TO 31
TWK = TMFLT
IND(K) = 1
JIND = 1
CALL GCPP(GCP, P)
QDOTR = SIGMA * (G * TG**4 - ALPG * TMELT**4) * DELT
IF(QDOTR) 22, 22 ??
QDOTR = 0.
IF(ANR = GT * K., 25)
DMD = (QDOTC + QDOTR) / (AKL1 + AKL2 * (GCP * TAW - CPA * TMELT))
GO TO 26
DMD = (QDOTC + QDOTR) / (AKT1 + AKT2 * (GCP * TAW - CPA * TMELT))
PE = 11.05E+04 / TMELT
TMDOT = DMD * (1. + 2.64E+09 / (PBL**.67 * F**PE))
TM = TM + TMDOT
SOT = TM / PHOV
STMDOT = PHOV
WT = 3.1416 * 2.0 ** 25 * PHOV
IF(TIMFLT * TCAS OR TIME * GT * TCAE) GO TO 28
DFAN = 27, DDOT
FORMAT(F11.5)
DMD = 1 / (1. - SIN(THETC) * SIN(THETC) * SDOT)
X = 0.01745 * R * PHI
31
DO 29 N=1*NAL
  BN=N
  IF (BN*DEL(1) - SDOT) 29,30,30
29  CONTINUE
  PRINT 7
  GO TO 200
30  DF(N)=DFL(N)-(SDOT-(N-1)*DEL(1))
    IND(N)=1
    IF (N.EQ.1) GO TO 31
    DE(N-1)=0.0
31  K=K+1
    IF (K.LE.NAL) GO TO 14
    TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*(TW(K-1)-TW(K))
    K=K+1
    TW(K)=TW(K)+DELT*(ATC(K-1)/(ARHO(K-1)*ACP(K-1)*DE(K-1)**2)*\(TW(K-1)-TW(K))
    PRINT 5,TIME,ALT,VEL,ANR,TAW,TEMP,HE,ODOTC,WT,TM,TG,SDOT,R,
    FORMAT( AS NECESSARY )
    IF (ALT)200,200,100
200  CONTINUE
END
APPENDIX III

HEATAB 3 Listing
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HEATAB 3, Version of HEATAB

HEATAB 3, a modification and extension of the basic HEATAB program, calculates the total ablation mass loss rate for a conical reentry vehicle. The body is divided into a number of segments, or stations, and the heating rate at each station is computed. In addition to the input data required in HEATAB, the fore and aft radii and slant lengths of each body segment must be supplied to the computer. This input into the program is identified by the comment statement "Additional Vehicle Data." Computation of the skin temperature profile is identical to the method used in HEATAB, except that this calculation is made for each x-station for each trajectory point.

To compute the total mass loss rate, the following procedure is used. The weight loss rate per unit area is first computed then the instantaneous and total recessions are calculated. Using these numbers and the initial radii and slant length of the particular segment of interest, the mass loss rate per unit area is multiplied by the appropriate surface area to give a local integrated mass loss rate. Summing these local rates over the body results in the total weight loss rate.

As written, the HEATAB 3 output will give, for each time interval, an output of trajectory conditions and body conditions. The trajectory conditions are items such as altitude, velocity, and Mach number. Body conditions listed for each x-station are Reynolds number, weight loss rate per unit area, wall recession, and wall temperature.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW(I,J)</td>
<td>Layer temperature at lamina I and station J</td>
</tr>
<tr>
<td>IND(I,J)</td>
<td>0 = virgin material, 1 = char material</td>
</tr>
<tr>
<td>JIND(I)</td>
<td>0 = not ablating, 1 = ablating</td>
</tr>
<tr>
<td>VCP(I,J)</td>
<td>Virgin specific heat</td>
</tr>
<tr>
<td>VTC(I,J)</td>
<td>Virgin thermal conductivity</td>
</tr>
<tr>
<td>VRHO(I,J)</td>
<td>Virgin density</td>
</tr>
<tr>
<td>DEL(I,J)</td>
<td>Original lamina thickness</td>
</tr>
<tr>
<td>DE(I,J)</td>
<td>Instantaneous lamina thickness</td>
</tr>
<tr>
<td>SDOT</td>
<td>Total recession of wall</td>
</tr>
<tr>
<td>XI(J)</td>
<td>Location of x-station, ft</td>
</tr>
<tr>
<td>RS(J)</td>
<td>Smaller radius of cone segment for a particular x-station</td>
</tr>
<tr>
<td>RL(J)</td>
<td>Larger radius of cone segment for a particular x-station</td>
</tr>
<tr>
<td>SL(J)</td>
<td>Slant height at station X</td>
</tr>
<tr>
<td>WT(J)</td>
<td>Instantaneous weight loss rate at station X, lb/sec</td>
</tr>
<tr>
<td>TM(J)</td>
<td>Total weight flux at station X, lb/ft^2-sec</td>
</tr>
<tr>
<td>TMELT</td>
<td>Ablation temperature, °R</td>
</tr>
<tr>
<td>RE</td>
<td>Transition Reynolds number</td>
</tr>
<tr>
<td>DELT</td>
<td>Time step, sec</td>
</tr>
<tr>
<td>TEMP</td>
<td>Ambient temperature at altitude, ALT</td>
</tr>
<tr>
<td>TAW</td>
<td>Adiabatic wall temperature, °R</td>
</tr>
<tr>
<td>SIGMA</td>
<td>Stephan-Boltzmann constant</td>
</tr>
<tr>
<td>GVIS</td>
<td>Ablation gas viscosity</td>
</tr>
<tr>
<td>AKL1</td>
<td>(See HEATAB Symbol Listing)</td>
</tr>
<tr>
<td>AKL2</td>
<td>(See HEATAB Symbol Listing)</td>
</tr>
<tr>
<td>AKT1</td>
<td>(See HEATAB Symbol Listing)</td>
</tr>
<tr>
<td>AKT2</td>
<td>(See HEATAB Symbol Listing)</td>
</tr>
<tr>
<td>CHA</td>
<td>Cone half-angle</td>
</tr>
<tr>
<td>NOFX</td>
<td>Number of x-stations</td>
</tr>
<tr>
<td>TIME</td>
<td>Time, sec</td>
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<tr>
<td>ALT</td>
<td>Altitude, ft</td>
</tr>
<tr>
<td>AMACH</td>
<td>Mach number</td>
</tr>
<tr>
<td>VELS</td>
<td>Acoustic velocity, ft/sec</td>
</tr>
<tr>
<td>RHO</td>
<td>Ambient density, slugs/ft^3</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>VIS</td>
<td>Ambient viscosity</td>
</tr>
<tr>
<td>SPC</td>
<td>Cone surface pressure coefficient</td>
</tr>
<tr>
<td>VEL</td>
<td>Velocity, ft/sec</td>
</tr>
<tr>
<td>Q</td>
<td>Dynamic pressure lb/ft²</td>
</tr>
<tr>
<td>TCA</td>
<td>Air thermal conductivity</td>
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<tr>
<td>VISG</td>
<td>Air viscosity</td>
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<tr>
<td>PE</td>
<td>Ambient pressure, lb/ft²</td>
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<tr>
<td>CPA</td>
<td>Specific heat of air</td>
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<tr>
<td>PBL</td>
<td>Boundary layer edge pressure, lb/ft²</td>
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<tr>
<td>P</td>
<td>Boundary layer pressure, atms</td>
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<tr>
<td>GCP</td>
<td>Ablation gas specific heat</td>
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<tr>
<td>GTC</td>
<td>Ablation gas thermal conductivity</td>
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<tr>
<td>PR</td>
<td>Prandtl number</td>
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<tr>
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<td>Reynolds number</td>
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<tr>
<td>RF</td>
<td>Recovery factor</td>
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<tr>
<td>HE</td>
<td>Convective heat transfer coefficient</td>
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<tr>
<td>DTR</td>
<td>Dynamic temperature rise</td>
</tr>
<tr>
<td>TG</td>
<td>Gas temperature</td>
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<tr>
<td>GE</td>
<td>Gas emissivity</td>
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<tr>
<td>ALPG</td>
<td>Absorbtivity at gas</td>
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<tr>
<td>QDOTC</td>
<td>Convective heat flux</td>
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<tr>
<td>TWK</td>
<td>Dummy variable used in subroutines</td>
</tr>
<tr>
<td>VT</td>
<td>Dummy variable (virgin thermal conductivity)</td>
</tr>
<tr>
<td>VC</td>
<td>Dummy variable (virgin specific heat)</td>
</tr>
<tr>
<td>CC</td>
<td>Dummy variable (char specific heat)</td>
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<tr>
<td>CT</td>
<td>Dummy variable (char thermal conductivity)</td>
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<tr>
<td>QDOTR</td>
<td>Hot gas radiation heat flux</td>
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<tr>
<td>DMD</td>
<td>Diffusion controlled oxidation mass loss</td>
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<tr>
<td>PXE</td>
<td>Dummy variable in ThDOT equation</td>
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<tr>
<td>TMDOT</td>
<td>Mass loss rates in sublimation region</td>
</tr>
<tr>
<td>CDOT</td>
<td>Instantaneous recession</td>
</tr>
<tr>
<td>WDOT</td>
<td>Integrated weight loss rate, lb/sec</td>
</tr>
</tbody>
</table>
HEATAB III

JDVOOO, 6100, 50000, YOUNG, 5791, WLDE, 2241.
KON, 75000, 30000

HEATAB3

1. PROGRAM HEATAB3(INPUT, OUTPUT)
2. AERODYNAMIC HEATING FOR R/V
3. THIS MODIFICATION OF HEATAB GIVES THE AERATION MASS LOSS RATE
4. FOR A RE-ENTERING BODY.
5. DIMENSION TW(6,10), JIND(10), VCP(6,10), VTC(6,10), VRHO(6,10), DELE(6,10), DE(6,10), SDGT(10), XI(10), RS(10), RL(10), SL(10), WT(10)
6. 2*TM(10)
7. CONSTANTS DEFINED
8. PI = 3.14159
9. E = 2.718
10. TMELT = 6760s
11. RE = 1.0
12. DELT = 0.05
13. TEMP = 298.2
14. TAV = TEMP
15. G = 32.160
16. AJ = 77.3
17. SIGMA = 4.98F17
18. CVIS = 4.429E-5
19. AKL1 = 5370
20. AKTL = 4240
21. AKL2 = 5.37
22. AKT2 = 4.77
23. PRINT 501

501 FORMAT(1H1)
1. IDENTIFICATION CARD
2. READ 502

502 FORMAT(ROH
3. PRINT 502
4. INPUT - ONE HALF ANGLE, NUMBER OF X-STATIONS, X-STATIONS
5. READ 503, CHA, NOFX, (XI(I)), I = 1, NOFX
6. 503 FORMAT(F10.4, 5X, 15, 5F10.4, 5F10.4)
7. PRINT 504, CHA, NOFX, (XI(I)), I = 1, NOFX
8. 504 FORMAT(2, 1H1, ONE HALF ANGLE = , F8.2, 5X, 2B3, NUMBER OF X-STATIONS = (5X, F10.3)
9. DO 1, J = 1, NOFX
10. JIND(J) = 0
11. VCP(5, J) = .315
12. VCP(6, J) = .208
13. VTC(5, J) = .74E-04
14. VTC(6, J) = .03694
15. VRHO(5, J) = 91.7
16. VRHO(6, J) = 169.
17. DO 11 = 1, 6
18. TW(1, J) = 544.
19. 11 IND(1, J) = 0
20. ADDITIONAL VEHICLE DATA
21. READ 505, (PL(I), J = 1, NOFX)
22. READ 505, (RS(I), J = 1, NOFX)
23. READ 505, (SL(I), J = 1, NOFX)
24. 505 FORMAT(8F10.5)
25. DO 95 = 1, 3
DO 95 J=1,NCFX
   DEL(I,J) = .0033
95   DF(I,J) = .0033
DO 96 I = 1,NCFX
   DFL(4,I) = .00941
   DE(4,I) = .00941
   DFL(5,I) = .00333
   DE(5,I) = .00333
   DEL(6,I) = .005
96   DF(6,I) = .005

C INPUT - TIME, ALTITUDE, AND MACH NUMBER FROM TRAJECTORY
500 FORMAT(3F10.2)
   IF (TIME-20.50) 1000,1000,403
1000 CALL VELSF(VELS,ALT)
   CALL TEMPAT(TEMP,ALT)
   CALL RHOF(RHO,ALT)
   CALL VISCOT(VISC,ALT)
   CALL SPY(SPC,AMACH)
   VEL=VELS*AMACH
   O = .5*RHO*VEL**2
517 PRINT 507, TIME+ALT, VEL, AMACH, O
507 FORMAT(3X,7HTIME = ,F7.2,5X,11HALTITUDE = ,F10.2,5X,11HVELOCITY
   1= ,F9.2,5X,10HMACH NO = ,F5.2,5X,19HDYNAMIC PRESSURE = ,E12.6/)
   2X,7HSTATION,6X,15HREYNOLDS NUMBER,5X,26HFWIGHT LOSS RATE (LBS/SEC
   3),5X,15HTOTAL RECESSIION,5X,16H WALL TEMPERATURE)

C CALCULATE FOR EACH Y-STATION
DO 401 LEN = 1,NCFX
   X = X(I,LEN)
   IF (SDOT(LEN) = .0033) 6,7,7
6   K=1
   GO TO 15
7   IF(SDOT(LEN) = .01666) 8,9,9
   K=2
   IND(K,LEN) = 1
   GO TO 15
8   IF(SDOT(LEN) = .02499) 10,11,11
9   K=3
   IND(K,LEN) = 1
   GO TO 15
10  IF(SDOT(LEN) = .0341) 12,13,13
11  K=4
   IND(K,LEN) = 1
   GO TO 15
12  PRINT 14
13  FORMAT(* OVERHFAT*)
   GO TO 403
15  TR=TEMP+.58*(TW(K,LEN)-TEMP)+.19*(TAW-TEMP)
   CALL TCAT(TCA,TR)
   CALL VISCOT(VISC,TR)
   PE=2116.2*F**(-.42*E09F-05*ALT)
   CR=**2/3
   PRL = E09C00+PE
   P=PEL/2116.2
   IF(JIND(LEN)=F0.0) GO TO 16
   CALL GDP*(GCP,P)
   GTC=4.4*PE-05*(GCP+.207)
DP = GCD * r.V
GO TO 17
16 PR = CP * VISG / TCA
17 ANR = VFL * X * PHO / VIS
IF (ANR < PE) 18 R10
18 RF = PR ** 5
HE = 8575 / TCA * X * PR ** 33 * ANR ** 5
GO TO 20
19 RF = PR ** 33
HE = 0.0298 / TCA * X * PR ** 33 * ANR ** 5
20 DTR = VEL * 2 / (2 * G * AJ * CPA)
TAW = TEMP + RF * DTR
TG = TEMP + DTR
IF (TG = 8500) 22 21 21
21 GE = 0.2169
GO TO 23
22 GE = 0.05 + F** (-61144E-03 * TG)
23 ALPG = 0.8 + (G / TMELT) ** 45
ODOTC = HE * (TAW - TW(K, LEN)) / DELT
IF (IND(K, LEN) * EQ 1) GO TO 26
24 IF (TW(K, LEN) = TMELT) 25 26 26
25 TW = TW(K, LEN)
CALL VTCP(VT, TWK)
CALL VCP(VC, TWK)
VTC(K, LEN) = VT
VCP(K, LEN) = VC
VRHO(K, LEN) = 90.4
IF (K != EQ 1) GO TO 27
TW(K, LEN) = TW(K, LEN) + DELT * (VTC(K, LEN) / VRHO(K, LEN))
1 * DE(K, LEN) ** 2 * (TW(K, LEN) - TW(K, LEN) - VTC(K, LEN) / VRHO(K, LEN)
2 * VCP(K, LEN) * DE(K, LEN) ** 2 * (TW(K, LEN) - TW(K, LEN))
50 IF (TW(K, LEN) = TMELT) 36, 51, 51
51 TW(K, LEN) = TMELT + 1
GO TO 36
26 TW = TW(K, LEN)
CALL CTCP(CT, TWK)
CALL GCPP(GC, TWK)
VCP(K, LEN) = CC
VTC(K, LEN) = CT
VRHO(K, LEN) = 74.8
27 TW(K, LEN) = TW(K, LEN) / (VCP(K, LEN) * VRHO(K, LEN) * DE(K, LEN))
1 * HE(Y(T
1AW - TW(K, LEN)) / VTC(K, LEN) / DE(K, LEN) * (TW(K, LEN) - TW(K, LEN))
28 IF (TW(K, LEN) = TMELT) 172, 29, 29
29 JIND(LEN) = 0
GO TO 36
29 TW(K, LEN) = TMELT
1A7(K, LEN) = 1
JIND(LEN) = 1
CALL GCPP(GC, P)
OOPR = 15MA * (GF * TG ** 4 + ALPG * TMELT ** 4) * DELT
1F (OOPR) 31, 31, 32
31 OOPR = 0
32 IF (ANR < PE) 33, 31, 34
33 DMD = (OOPR + DMD) / (AKL1 + AKL2 * (GCP * TAW = CPA * TMELT))
GO TO 35
34 DMD = (OOPR + DMD) / (AKT1 + AKT2 * (GCP * TAW = CPA * TMELT))
35 EY = 11.4 + .04 / TMELT
TDOT = CMD 1 2.6469/(RCL**.67**F**PX))
TM(LFN)=TM(LFN)+TDOT
SDOT(LFN)=TM(LFN)/74
CDOT = TDOT/74
WT(LFN)=IF(DOT(LFN)+PS(LFN)-2*SDOT(LFN)) * CDOT*90.4 * SL(LFN)
JND(LFN)=1
IF(SDOT(LFN)*0.02)=3.54,54
IF(SDOT(LFN)=0.1666)=5.56,56
IF(SDOT(LFN)=0.2499)=7.58,58
DE(4,LEN)=DEL(4,LEN)-(SDOT(LEN)-DE(1,LEN))
GO TO 36
DE(3,LEN)=DEL(3,LEN)-(SDOT(LEN)-2*DE(1,LEN))
GO TO 36
DE(2,LEN)=DEL(2,LEN)-(SDOT(LEN)-DE(1,LEN))
GO TO 36
DE(1,LEN)=DEL(1,LEN)-SDOT(LEN)
IF(KGT4)=GO TO 37
GO TO 24
TW(5,LEN)=TW(5,LEN)+DELT*(VTC(4,LEN)/(VRHO(4,LEN)*VCP(4,LEN)*DE(4,LEN)**2) * (TW(4,LEN)-TW(5,LEN))
VTC(5,LEN)/(VRHO(5,LEN)*VCP(5,LEN)*DE(5,LEN)**2) * (TW(5,LEN)-TW(6,LEN))
TW(6,LEN)=TW(6,LEN)+DELT*(VTC(5,LEN)/(VRHO(5,LEN)*VCP(5,LEN)*DE(5,LEN)**2) * (TW(6,LEN)-TW(6,LEN))
41 PRINT .509,10,AND,W(T(LEN)),SDLAT(T(LEN)),TW(1,LEN)
401 CONTINUE
WDOT = WDOT + W(T(LEN))
C CALCULATE TOTAL WEIGHT LOSS RATE
DO 402 LL = 1,NOFX
WDOT = WDOT + W(T(LLL))
402 CONTINUE
PRINT 500,ALT,VEL,WDOT
S8A FORMAT(2X,1SHFOR AN ALTITUDE OF 190223.23FEET AND A VELOCITY OF 1F10.2,32HFT/SEC, THE WEIGHT LOSS RATE IS 1F6.3,8HBLBS/SEC
GO TO 500
403 CONTINUE
41
REFERENCES


AERODYNAMIC HEATING AND ABLATION COMPUTER PROGRAM (HEATAB)

January 1966-May 1966

Moulds, William J.; Young, J. D., Lt, USAF

October 1966

627A

AFWL-TR-66-105

An Aerodynamic Heating and Ablation Computer Program (HEATAB) is presented to establish a means by which heat transfer problems may be solved with minimum effort. This program computes the boundary layer conditions, time-temperature distribution in a body, the ablation recession rate, and weight loss. The program was written in Fortran IV for the CDC 6600 computer.
### UNCLASSIFIED

**Security Classification**

<table>
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<tr>
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