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EQUATIONS AND FORTRAN PROGRAM FOR APPROXIMATE AERODYNAMIC HEAT TRANSFER AND TRANSIENT TEMPERATURE DISTRIBUTIONS FOR LEADING EDGES AND FLAT PLATE SURFACES

by
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and
Alma S. Marks

October 1965
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ABSTRACT

The equations and a Fortran program to calculate supersonic and hypersonic aerodynamic heat transfer rates and transient temperature distributions for spherical leading edges and flat plate surfaces are presented in this report. The missile skin is composed of one to three different slab materials and/or thin wall combinations for flight trajectories or wind tunnel conditions. The Fortran program is written for the IBM 1620 40K digital computer.
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<tbody>
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</tr>
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1. Introduction

A general purpose Transient Temperature Aerodynamic Heat Transfer IBM 1620 Digital Computer Program for supersonic and hypersonic flight speeds is described herein. This computer program considers spherically blunted leading edges and/or flat plate surfaces. One dimensional temperature distributions through a missile skin composed of one to three different slab materials or a thin wall material followed or preceded by one or two different slab materials is available. The required flight environment is either a trajectory input based on the ARDC 1959 atmosphere or constant altitude and local flow properties (wind tunnel conditions).

2. Analysis

a. Stagnation Regions

Aerodynamic heat transfer coefficients for spherically blunted leading edge surfaces are separated into two regions. For non-dissociated gas properties, corresponding to flight speeds up to 6000 ft/sec, the external aerodynamic heat transfer coefficients for laminar and turbulent boundary layers are developed in this report. For dissociated gas properties, an approximation to the exact stagnation point heat transfer rate solution of Fay and Riddel and Detra and Hidalgo is used.

(1) Nondissociated Aerodynamic Heat Transfer Coefficient.

The important variables affecting the aerodynamic heat transfer coefficient for a spherically blunted leading edge surface are shown in Figure 1.

![Figure 1. Important Variables Affecting the Aerodynamic Heat Transfer Coefficient for a Spherically Blunted Leading Edge Surface](image-url)
(a) Laminar Boundary Layer. A modified Reynolds analogy for flow with constant thermal and transport properties through the boundary layer for spherical and cylindrical surfaces is used.

\[
St_s = \frac{Nu_{inc}}{Re_s Pr_s} = \frac{C_f}{2} \left( \frac{Pr_s}{Re_s} \right)^{-0.4} \tag{1}
\]

\[
\frac{H_{inc} Y}{k_s} = \frac{C_f}{2} \left( \frac{Pr_s}{Re_s} \right)^{0.4} \tag{2}
\]

Measurements of local skin friction coefficients on spherical and cylindrical surfaces indicate the normal laminar flow correlation for zero pressure gradient flow may be applied provided the constant of proportionality, using local Reynolds number, is considered to vary with location along the surface:

\[
C_f = \frac{f_1}{\sqrt{Re_s}} \tag{3}
\]

The factor \( f_1 \) of Equation (3) varies from 1.526 at the stagnation point to approximately 0.664 at a position 90 degrees from the stagnation point for the sphere and from 1.14 to 0.664 for the cylinder. Equation (2) can be expanded to

\[
\frac{H_{inc} Y}{k_s} = \frac{f_1}{2} k_s \left[ \frac{Pr_s V_s Y}{\mu_s} \right]^{0.5} \left( \frac{Pr_s}{Re_s} \right)^{0.4} \tag{4}
\]

Since the stagnation point value of \( Y \) and \( V_s \) are zero and large errors of heat transfer coefficient result from Equation (4) in the areas close to the stagnation point, it becomes convenient and more accurate to define a term \( \beta \) as given by Equation (5):

\[
V_s = \beta Y \tag{5}
\]

The value of \( \beta \) varies along the surface, with the sphere diameter, and with the free stream Mach number and temperature. At the stagnation point, application of elementary calculus yields the nondimensional velocity gradient \( \frac{dV}{dY} \). This nondimensional velocity gradient is a function of free stream Mach number only. A ratio of \( \beta/\beta_s \) was found to depend only on the location on the spherical surface.
Substituting $\beta Y$ for $V_s$ and $\frac{P_s}{R_g T_s}$ for $\rho_s$ in Equation (4) yields

$$H_{inc} \cdot Y = \frac{f_1}{2} k \left[ \frac{P_s \beta Y^2}{R_g T_s} \right]^{0.5} P_{T_s}^{0.4}$$

(6)

By dividing Equation (6) by $Y$, multiplying by $\sqrt{D}$, then multiplying the right hand side by $\sqrt{\beta_0/\beta_0}$ and $\sqrt{V_\infty/V_\infty}$, the equation may be written:

$$H_{inc} \cdot \sqrt{D} = 0.5 \left[ \frac{V_\infty P_s}{R_g} \right]^{0.5} Z_1 Z_2 Z_{T_s}$$

(7)

where

$$Z_1 = \sqrt{\frac{\beta_0 D}{V_\infty}} = \left\{ 1.4 + \frac{7}{M_{\infty}^2} \right\} \left[ 0.139 \left( 7 - \frac{1}{M_{\infty}^2} \right) \right]^{2.5}$$

(8)

$$Z_2 = f_1 \sqrt{\beta_0/\beta_0} = f(\theta)$$

(9)

and

$$Z_3 = k P_{T_s}^{0.4} / \sqrt{T_{T_s}}$$

(10)

Equation (7) has been developed for constant thermal and transport properties with $Z_3$ evaluated at local conditions. For an appreciable variation of temperature within the boundary layer, a reference temperature $T^*$ (T*) has proven to give excellent aerodynamic heat transfer coefficients:

$$T^* = T_s \left[ 0.50 + 0.039 M_s^2 \right] + 0.50 T_w$$

(11)
The properties of $Z_3$ in Equation (10) required to be evaluated at $T^*$, are indicated by the asterisk superscript (*), and are defined by the following equations:

When $T^* < 1000^\circ R$

$$k^* = \frac{0.23791763 \times 10^{-6} T^*^{1.52}}{T^* + 198.6}$$  \hspace{1cm} (12a)$$

When $T^* \geq 1000^\circ R$

$$k^* = 11.997 \mu^*,$$  \hspace{1cm} (12b)$$

Where

$$\mu^* = \frac{0.249 \times 10^{-6} T^*^{0.63}}{\mu_a}$$  \hspace{1cm} (13)$$

$$P_r^* = \mu^* c_p^* \frac{\mu_a}{k^*}$$  \hspace{1cm} (14)$$

and $C_p^* = f(T^*)$, as defined by Equation (56).

Then

$$N\sqrt{D} = 0.5 \left[ \frac{V_{in}P_b^*}{R_g} \right]^{0.5} Z_1 Z_2 Z_3^*.$$  \hspace{1cm} (15)$$

Figures 2 and 3 present $Z_1$ and $Z_2$.

At the stagnation point, the temperature becomes

$$T_{0*} = 0.5 \left[ T_{TOT} + T_w \right] \text{ for } M_{10} \rightarrow 0.0,$$  \hspace{1cm} (16)$$

where the total temperature, $T_{TOT}$, at the stagnation point is the total temperature of the free stream.

(b) Turbulent Boundary Layer. It is possible to have turbulent boundary layer flow over some portion of the leading edge and a method for the aerodynamic heat transfer coefficient is presented. The basic development is similar to the laminar boundary layer heat transfer development.

$$St_b = \frac{C_f}{2} P_r e^{-1/3}$$  \hspace{1cm} (17)$$
Figure 3. Laminar Leading Edge Skin Friction Proportionality and Velocity Gradient
The skin friction coefficient for turbulent boundary layers on the leading edge can be expressed as

\[ C_f = \frac{f_2}{R_{\infty}^{0.2}} \quad (18) \]

The leading edge geometry has only a minor effect on the value of the proportionality constant \( f_2 \) as compared to the laminar boundary layer. The final equation for turbulent leading edge aerodynamic heat transfer coefficient is

\[ H D^{0.2} = 0.5 \left[ \frac{V_{\infty} P_{\infty}}{R_{\infty}} \right]^{0.8} \left( \frac{Y}{D} \right)^{0.6} Z_1 Z_2 Z_3^* \quad (19) \]

where

\[ Z_1 = \left[ \frac{\beta D}{V_{\infty}} \right]^{0.8} \quad (20) \]

\[ Z_2 = f_2 \left( \frac{\beta}{k_{\infty}} \right)^{0.8} \quad (21) \]

and

\[ Z_3 = \left( \frac{k_{\infty} P_{\infty}^*}{(T_{\infty} P_{\infty}^*)^{0.8}} \right)^{1/3} \quad (22) \]

The exponents of Equation (14) reflect the basic changes in the skin friction correlation. Figures 2 and 4 show variations of \( Z_1 \) and \( Z_2 \). The term \( (Y/D)^{0.6} \) will cause a maximum aerodynamic heat transfer coefficient away from the stagnation point on a given surface and theoretically a value of zero at the stagnation point. In reality, the stagnation point flow is laminar and thus the aerodynamic heat transfer coefficient will not become zero. This turbulent analysis is not included in the Fortran program.

(c) Approximate Pressure Distribution. The reference temperature, \( T^* \), requires the local Mach number and local temperature. The basic aerodynamic heat transfer equations, Equation (7) for laminar boundary layer and Equation (19) for turbulent boundary
Figure 4. Turbulent Leading Edge Skin Friction Proportionality and Velocity Gradient

\[ \left( \frac{\theta}{\theta_0} \right)^{0.8} \]

POSITION ANGLE $\theta$ (deg)
layers, require local pressure value. A modified Newtonian-Prandtl-Meyer pressure ratio, $P_s$, as a function of angular position, $\theta$ is used.

$$P_s = P_\infty \frac{P_s}{P_{\text{TOT}}} \frac{P_{\text{TOT}}}{P_\infty}$$ \hspace{1cm} (23)

where

$$\frac{P_s}{P_{\text{TOT}}} = 1 - 0.957 \sin^2 \theta.$$ \hspace{1cm} (24)

The local Mach number is determined from the following equations:

$$M_s = \left(\frac{2}{\gamma - 1}\right) \left[\left(\frac{P_s}{P_{\text{TOT}}}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]$$ \hspace{1cm} (25)

and

$$\frac{P_{\text{TOT}}}{P_\infty} = \left[\left(\frac{\gamma + 1}{2}\right) \frac{\gamma + 1}{2\gamma M_\infty^2 - (\gamma - 1)}\right]^{\frac{1}{\gamma - 1}}.$$ \hspace{1cm} (26)

The local temperature $T_s$ is obtained from:

$$\frac{T_s}{T_\infty} = \left[\frac{2 + (\gamma - 1) M_\infty^2}{2 + (\gamma - 1) M_s^2}\right]$$ \hspace{1cm} (27)

for surface positions away from the stagnation point. At the stagnation point, the reference temperature, $T^*$, of Equation (11) does not require local temperature.

(2) Dissociated Air Aerodynamic Heat Transfer Rates. An approximate equation for the exact stagnation point aerodynamic heat transfer rate for flight velocities greater than 6000 ft/sec is presented.²

$$Q_w\sqrt{R_n} = 665 \left(\frac{V_\infty}{10^7}\right)^{1.15} \sqrt{\frac{\rho_\infty}{\rho_{\text{sea level}}}} \left[\frac{h_0 - h_w}{h_0 - h_{w,0}}\right]$$ \hspace{1cm} (28)
where

\[ h_0 = \text{stagnation enthalpy} = 6006 \ T_\infty + 0.5 \ V_\infty^2 \]  \hspace{1cm} (28a)

\[ h_w = \text{enthalpy at } T_w, \ "R = 778 \ g_a \ c_p \ T_w \]  \hspace{1cm} (28b)

and

\[ h_{w,100} = \text{enthalpy at } 300, \ "k = 3244100. \]  \hspace{1cm} (28c)

For variation of laminar heat transfer rates around the spherical blunted leading edge, the Lee's ratio of heat transfer rate to stagnation point heat transfer rate\(^3\) QR is presented in Figure 5.

Turbulent leading-edge boundary layer heat-transfer rate analyses are not included for the hypersonic flight speeds.

b. Flat Plate Regions

The aerodynamic heat-transfer coefficients for laminar and turbulent boundary layers over a flat plate and/or cone surface were developed in detail.\(^4\) Aerodynamic heat transfer variables are illustrated in Figure 6.

\[ M_\infty, P_\infty, T_\infty, q_{in}, q_{radiated}, q_{stored}, q_{conducted} \]

Figure 6. Aerodynamic Heat Transfer Variables for Flat Plates or Cones
Figure 5. Laminar Heat Transfer Distribution
The following equations express the flat plate aerodynamic heat-transfer coefficients:

\[ H_{FP} = C \cdot \varepsilon \left( \sqrt{\frac{T_s Y_s}{R}} \right)^n \left( \frac{\mu^*}{Y} \right)^{1-n} \frac{C_p \rho_s}{P \cdot \text{Pr}^* \gamma^3}. \] (29)

For laminar boundary layers

\[ C = 0.332 \] (30)
\[ n = 0.50, \] (31)

and for cone surfaces

\[ H_{cone} = H_{FP} \cdot \sqrt{3}. \] (32)

For turbulent boundary layers

\[ C = 0.01396 \] (33)
\[ n = 0.85, \] (34)

and for cone surfaces

\[ H_{cone} = H_{FP} \cdot \frac{2}{\sqrt{3}}. \] (35)

Also, the Reynolds number may be defined

\[ Re = 1063446 \cdot \rho_s \cdot M_s \cdot Y \sqrt{Y_s} \left( T_s + 198.6 \right) / T_s^2, \] (36)

where \( Y_s \) is defined by Equation (57).

c. **Time Increment and Material Properties**

The time increment, \( \Delta t \), is critical to the finite difference solution for the temperatures. The following properties are given for each material: density, \( \rho \); specific heat, \( C_p \); thermal conductivity, \( k \); total thickness, \( \tau_{tot} \); and number of layers, \( NLAY \).
\[ \tau = \frac{\tau_{tot}}{N_{LAY}} \]  
\[ \Delta t = \frac{0.5\rho C_p \tau^2}{k + \nu_c \nu} \]  

where \( \nu_c = 10 \) for first material, estimate for maximum value, and \( \nu_c = 0 \) for following materials. The time increment should be approximately the same for all the materials used.

Equation (38) is solved for each material and the smallest value is used.

Other required material functions are:

\[ F_1 = \frac{\Delta t}{(\rho C_p \tau)_1} \]  
\[ F_{k,1} = \left( \frac{k}{\tau} \right)_m \cdot \left( \frac{T}{K_{m-1}} \right) \]  

and

\[ B_m = \Delta t \left( \frac{k}{\rho C_p \tau} \right)_m \]  

where \( m \) is the number of the material.

d. One Dimensional Temperature Distribution

The basic heat balance for a multi-material skin is developed below.

- \( NL \) = Total number of layers for all materials plus end point (limited to 15 in program).
- \( L \) = Number of local point, from 1 to \( NL \).
- \( NMAT \) = Total number of materials (limited to 3 in program).
- \( M \) = Number of material, from 1 to \( NMAT \).
- \( T \) = Temperature for each point at the present time step.
- \( T' \) = Temperature for the point at the previous time step.
The temperature increment, $\Delta T$, for any point is the temperature difference between the present and previous time steps.

$$\Delta T = T - T'$$  \hspace{1cm} (42)

Then temperature increments between local layer and other layers at previous time step are defined.

$$D_1 = T'_L+1 - T'_L$$  \hspace{1cm} (43)

$$D_2 = T'_L-1 - T'_L$$  \hspace{1cm} (44)

$$D_3 = T'_1 - T'_1$$  \hspace{1cm} (45)

For all cases, heat in = heat out + heat stored, or

$$q_{in} = q_{out} + q_{stored}$$  \hspace{1cm} (1)

(1) **Multi-Slab Materials.** The multi-slab materials are shown in Figure 7.

![Multi-Slab Materials](image)

**Figure 7. Multi-Slab Materials**

(2) **Heat Balance at the Air Flow Side of Slab.** Heat in = $q_{in} = H(T_{rec} - T_1) = \text{Aerodynamic heat transfer rate}$. Heat out is the heat transfer to surrounding atmosphere plus the heat transfer to the next thickness.

$$q_{out} = \varepsilon \sigma (T_1 - T_\infty)^4 + k (T_1 - T_2) / \tau$$
Heat stored is the heat remaining in the first thickness:

\[ q_{\text{stored}} = 0.5 \Delta T_1 / F_1 \]

\[ T_{\text{rec}} = T_s \left[ 1 + 0.5 (\gamma_s - 1) R M_s^2 \right]. \quad (46) \]

For a Sphere: \( \gamma_s = 1.4 \).

For a F, P, or Cone: \( \gamma_s \) is defined by Equation (57).

Equation (28) defined \( Q_w \) for a sphere when the local velocity is greater than 6000 ft/sec, but for other cases,

\[ Q_w = H (T_{\text{rec}} - T_1) \quad (47) \]

\[ \dot{Q} = Q_w - \epsilon \sigma (T_1 / 100)^4. \quad (48) \]

With the heat balance \( q_{\text{in}} = q_{\text{out}} = q_{\text{stored}} \), the outside skin transient temperature for a slab is

\[ T_1 = T_1' + 2 \left[ F_1 \dot{Q} + B_1 D_1 \right]. \quad (49) \]

(3) **Heat Balance Around Interior Points.**

\[ q_{\text{in}} = k (T_{m-1} - T_m) / \tau_m \]

\[ q_{\text{out}} = k (T_m - T_{m-1}) / \tau_m \]

\[ q_{\text{stored}} = \frac{\rho C_p \Delta T}{\tau} (T - T_1). \]

The temperature at each small layer within the material is

\[ T_L = T_L' + B_m \left[ D_1 + D_2 \right] \quad (50) \]

where \( L = 2, 3 \ldots (NL-1) \).
(4) Heat Balance at Interface.

\[ T_L = T_L' + \frac{D_1 + F_m D_1}{\frac{1}{B_{m-1}} + \frac{F_m}{B_m}} \]

(51)

where L is the point between materials m and m-1.

(5) Heat Balance at Innermost Point.

\[ T_{NL} = T_{NL}' + 2 B_m D_1 \]

(52)

(6) Thin-Wall Followed by Multi-Slab Materials. The thin-wall followed by multi-slab materials is shown in Figure 8.

\[ q_{in} = H (T_{rec} - T_{1}) \]

where \( T_{rec} \) is defined by Equation (46)

\[ q_{out} = q_{radiative} + D_3 \]

and

\[ q_{stored} = \left[ \frac{(\rho c \rho T)}{2 A t} + \frac{1}{F_1} \right] (T_1 - T_f) \]

Then

\[ T_1 = T_1' + \frac{r_1 \tilde{Q} + k_1 D_1}{0.5 k_2/B_1 + r_2/F_1} \]

(53)
For a thin wall, the temperature is assumed to be constant through the entire thickness, thus

\[ T_2 = T_1 \]  

(54)

(7) Multi-Slab Materials Followed by a Thin Wall. The multi-slab materials followed by a thin wall are shown in Figure 9.

![Diagram of multi-slab materials followed by a thin wall](image)

Figure 9. Multi-Slab Materials Followed by a Thin Wall

For a thin inner wall, when \( N_{LAY_{NMAT}} = 1 \):

\[ T_{NL-1} = \frac{2D_2}{B_{m-1}} + \frac{2F_m}{B_m} \]  

(55)

where \( m \) = innermost material = \( NMAT \),

then

\[ T_{NL} = T_{NL-1} \ , \]

since the temperature is assumed constant through the thin material.
e. Specific Heat Ratios for Air

A correlation for specific heat ratio for air is

\[ C_p = f(T) \quad (56) \]

Where

<table>
<thead>
<tr>
<th>T</th>
<th>C_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>800</td>
<td>0.24</td>
</tr>
<tr>
<td>1700</td>
<td>0.27</td>
</tr>
<tr>
<td>3000</td>
<td>0.29</td>
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<tr>
<td>5000</td>
<td>0.31</td>
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<tr>
<td>9000</td>
<td>0.32</td>
</tr>
<tr>
<td>11,700</td>
<td>0.40</td>
</tr>
<tr>
<td>14,400</td>
<td>0.46</td>
</tr>
</tbody>
</table>

\[ \gamma_{local} = \frac{C_p}{[C_p - \frac{R_g}{J}]} \quad (57) \]

where

\[ J = 778 \frac{ft \cdot lb}{Btu} \times g_a \]

f. Flight Environment

The IBM 1620 digital computer program has the ARDC 1959 atmosphere subroutine as an integral part of the transient aerodynamic heat transfer calculation. Appendix B describes this subroutine. In addition, a constant altitude and/or constant local flow properties flight environment, such as wind tunnel testing, is included in the computer routine for flat plate or cone. The symbol, NCFIT, determines whether trajectory data or a constant value for altitude is used. If NCFIT is given 0, constant altitude, local Mach number, pressure, and temperature are given.

3. Conclusions

The aerodynamic heat transfer and transient temperature distribution computer program described in this report provides an economical preliminary design capability for heat transfer analysis. Comparison of transient temperatures with PERSHING Ballistic Missile flight test data\(^5\) and with more sophisticated aerodynamic heat transfer digital computer programs indicates very good agreement.
LITERATURE CITED


Appendix A

FORTRAN PROGRAM AND ITS USAGE

I. Fortran Program Statements

TEMPERATURE VS TIME FOR LAYERS OF SPHERE, FLAT PLATE, OR CONE

SW 1 ON -- FOR CARD OUTPUT AT ALL TIME STEPS

SW 2 ON -- FOR CARD INPUT OF -------- DTIME, DTOUT, TLO, THI

SW 2 OFF -- FOR TYPEWRITER INPUT OF -------- DTIME, DTOUT, TLO, THI

SW 3 ON -- TO END RUN, OUTPUT LAST STEP, BRANCH TO NEXT CASE

TODY = TYPF OF BODY

= 1.0 FOR SPHERE -- NCFIT = 2

= 2.0 FOR FLAT PLATE -- NCFIT = 5 OR 0

= 3.0 FOR CONE -- NCFIT = 5 OR 0

NCFIT = NO. OF CURVES FITTED --

= 6 FOR F.P. OR CONE -- GIVEN CONSTANT LOCAL M, P = T, ALT

= 2 OR 5 -- CURVES FITTED ARP --------

TI = ALTITUDE VS TIME

= 2. VELOCITY VS TIME

= 3. LOCAL M VS FREE STREAM MACH NUMBER

= 4. PS/PF VERSUS FREE STREAM MACH NUMBER

= 5. TS/TF VERSUS FREE STREAM MACH NUMBER;

SPHERE --------

TH=POSITION ANG, SNOR=NGSE RADIUS, QRET= Q RATIO

F.P. OR CONE -- TH=IDENTIFYING ANG, RNOR=SURFACE L, QRET=RET

NMAT = NUMBER OF MATERIALS -- 1, 2, OR 3

NL = TOTAL NUMBER OF SKIN LAYERS -- END POINT -- MAXIMUM = 15

SUBSCRIPTS -- FOR LOCAL -- FOR FREE STREAM

1000 FORMAT (1H )

1001 FORMAT (1H 42H TEMPERATURE VS TIME FOR LAYERS OF SPHERE)

1002 FORMAT (1H 46H TEMPERATURE VS TIME FOR LAYERS OF FLAT PLATE)

1003 FORMAT (1H 40H TEMPERATURE VS TIME FOR LAYERS OF CONE)

1004 FORMAT (1H 20H DTIME FOR EACH MAT)

1005 FORMAT (4E15.5, 115)

1024 FORMAT (1H 48H SWI D0ES ALL STEPS---SW2 CARD INPUTS 4 TIME VALS)

1025 FORMAT (1H 18H ---- SW 3 ENDS RUN)

1034 FORMAT (1H 45H INPUT--DTIME,DTOUT,TLO,THI----ON 4 LINES BY TI)

1094 FORMAT (1H 22H APP 1620 MIN REQUIRED)

1000 FORMAT (115)

1007 FORMAT (1E15.5, 115)

1008 PRINT (1H 49H DTIME= DTOUT= TLO= THI=)

1009 PRINT (1H 37H THETA= Y= RET=1)

1010 PRINT (1H 36H THETA= RN= OR=)

1011 PRINT (1H 44H TMELT= OEFF=)

1012 PRINT (1H 46H MATERIAL -- DTIME, M, K, RHO, CP, TAUTH, NLAY)

1013 PRINT (1H 35H ---- FOR EACH OUTPUT TIME STEP ----)

1014 PRINT (1H 39H TIME ALT=KFT VEL=FT/SEC RE)

1015 PRINT (1H 40H ODD TAUAN ---- HEAT COEFFS)

1016 PRINT (1H 27H MACH NO. PRESSURE TEMPERATURE -- LOCAL)

1017 PRINT (1H 48H MACH NO. PRESSURE TEMPERATURE -- FREE STREAM)

1018 PRINT (1H 43H TEMPERATURE AND COUNT FOR EACH SKIN LAYER)

1019 PRINT (1H 43H TIME, ALT. VEL ---- AT WALL MELTING POINT)

DIMENSION AP(15), TEMP(15), TEMP1(15), CONI(4,15), NUM(5)

READ ATMOSPHERIC PROPERTIES FROM AP TABLE OF APPENDIX B

NO 1 <= 11

READ 1005, ALT, TF, PF

AP(K1) = ALT # 3.2808E-33

AP(K2) = TF # 1.8

AP(K3) = PF # 0.70385

PRINT 1074

PRINT 1075
C    INPUT FOR EACH CASE -- BEGINS AT STATEMENT 2
7    PUNCH 1000
     PUNCH 1000
     READ 1007, TRODY, NCFIT
     READ 1005, TH, RNORY, ORRET
     READ 1005, TML, QE, E
     Y = RNORY
     RET = ORRET
     PRINT 1000
     PRINT 1000
     IF (TRODY - 2.0) 301, 302, 303
301   PUNCH 1001
     PRINT 1001
     PUNCH 1000
     PUNCH 1010
     OR = ORRET
     SORD = (2.0*RNORY)**.5
     Z2 = 1.522036 + TH*(1.5369)3F-03 + TH*(-3.702082E-04 + TH*2.668E-06)
     PSVPT = 1.0 - .957*SIN(TH/57.29578)**2
     GO TO 304
302   PUNCH 1002
     PRINT 1002
     PUNCH 1000
     PUNCH 1009
     NX = 1.0
     GO TO 304
303   PUNCH 1003
     PRINT 1003
     PUNCH 1000
     PUNCH 1009
     NX = 1.0**.5
     (32)
305   PUNCH 1005, TH, RNORY, ORRET
     PUNCH 1000
     PUNCH 1011
     PUNCH 1005, TML, QE, E
     PUNCH 1000
     PUNCH 1012
     PRINT 1000
     PRINT 1004
     READ 1006, NMAT
     NL = 1
     C MATERIALS LOOP -- COMPUTE MINIMUM DTIME FOR EACH MATERIAL
     V2 = 1.0
     M = 1
     NMAT
     READ 1005, C(M), RHO(M), CP(M), TAU,M, NUM(M)
     V1 = NUM(M)
     TAU(M) = TAU/M
     NL = NL + NUM(M)
     NUM(M+1) = 0.0
     F(M) = RHO(M)*CP(M)*TAU(M)
     TEMP(M) = C(M)/TAU(M)
     DTIMC = .5*F(M)/(F(M)+V?)
     V2 = 0.0
     PRINT 1007, DTIME, M
     PUNCH 1007, DTIMF, M
     PUNCH 1005, C(M), RHO(M), CP(M), TAU,M, NUM(M)
     IF (ISNF < KITCH) 400, 401
400   READ 1005, DTIMF, DTIMT, TLO, THI
     GO TO 407

22
401 PRINT 1034
ACCFPT 1005, DTIME
ACCEPT 1005, DTOUT
ACCFPT 1005, TLO
ACCFPT 1005, THI

402 NT = (THI - TLO) / DTIME + 1.
T1620 = NT / 10 * NL / 4
PRINT 1054
PRINT 1005, T1620
PUNCH 1000
PUNCH 1008
PUNCH 1005, DTIME, DTOUT, TLO, THI
DO 5 M=1, NUMMAT
   F(M) = DTIME / F(M)
   RIM = F(M) * TEMPL(M)
   IF (M=1) 5 6 5
   F(M) = TEMPL(M) / TEMPL(M-1)
5 CONTINUE
NL1=NUM(1)
NL2=NUM(2)
C READ INITIAL TEMPERATURES AND COUNT
DO 7 L=1, NL
7 READ 1007, TEMPL(L), L1
   G = 1.4
   GM1 = G-1.
   GP1 = G+1.
   G1 = 1./GM1
   G2 = 2./GM1
   RG = 1716.
   GA = 32*174
   GAB = 7.0
   TAUB = 0.0
   ABOUT = 0.0
   PUNCH 1000
   IF (NCFIT) 9, 8, 9
C CONSTANT LOCAL VALUES GIVEN
8 READ 1005, ALT, VFL
   READ 1005, SM, PC, TS
   PUNCH 1016
   PUNCH 1005, SM, PC, TS
9 PUNCH 1000
PUNCH 1013
PUNCH 1014
PUNCH 1015
IF (NCFIT) 10, 11, 12
10 PUNCH 1016
PUNCH 1017
11 PUNCH 1018
PUNCH 1000
TIMF = TLO
N = 0
C TIME STEP LOOP -- N=COUNTFR
110 N = N + 1
   TW = TEMPL(1)
   L1 = 1.
   Y = TIMF
   IF (NCFIT) 12, 60, 12
C CURVE FITS DATA LOOP
12 DO 95 1 = 1, NCFIT
IF (N=1) 15, 13, 15
READ 1006*, NUM(1)
L2 = NUM(1)+L1-1
DO 14 L=L1,L2
READ 1005*, CON(I,L1), CON(2*L1)
14 L2 = NUM(1)+L1-1
DO 20 L=L1,L2
IF(X-CON(2*L2)) 22, 27, 20
20 CONTINUE
L = L-1
22 L1 = L2 + 1
FX = IX-CON(1+L1)/CON(2*L1)-CON(1,L1)
V11 = CON(4,L1)+FX*(CON(1*L1)+FX*CON(1,L1))
TF (1-2) 35, 23, 35
23 ALT = V(1)
VEL = V(2)
ALT = 20850000.*ALT/(208500.*ALT)
DO 25 K=2,11
IF(ALTF-AP(K)) 26, 25
25 CONTINUE
K = K-1
DALT = ALT-AP(K)
TS = AP(K)+ALT*TS
TF = AP(K)+ALT*TS
PF = AP(K)+ALT*TS
IF(TS) 27, 28, 27
27 PF = AP(K)*ALT**TS
28 DF = .01879*PF/TF
FMSQ = VEL*VEL/
RG(QS*TF)
X = FM
IF (TFTY>1.) 35, 30, 35
C SPHERF -- LOCAL M, P, T
SMSO = G2*(PSVPT**(-GM1/G1-1.0))
SM = SMSO**.5
PS = PF*PSVPT**(*GP1**FMSQ)***(G/GM1)**(GP1/(2.*G*FMSQ-GM1))**G1
TV = TW
GO TO 41
35 CONTINUE
C FLAT PLATE OR CONE -- LOCAL M, P, T
SM = V(1)
PS = V(4)*PF
TS = V(5)*TF
TV = TS
A~0
SMSO = SMSO**.5
C TRFF AND COP -- FOR ALL CASES
C RE*, CPS*, CPRFF, AND NEW GAMMA -- FOR CONE OR FLAT PLATE
41 TRFF = .5*(IWS-WS**1.0*N0.578**SMSO))
URFF = .249F-06 * TRFF**.69 / GA
CREF = 1.997 * URFF
IF (TRFF<.1) 411, 411, 41
410 CREF = .237917633E-06 * TRFF**.52 (TRFF=.015)
COP = .26
IF(TTV-60) 66, 66, 66
V(T) = .719766
V(r) = .7197660
42
L = 2  
GO TO 89  

83  
$O_2 = TFMP(L-1) - TEMPL(L)$  
C  
END POINT TEMPERATURE INCREFMENT  
$DTMP = 2*BM*O_2$  
IF(L-1) 84, 89, 86  

84  
$D_1 = TEMPL(L+1) - TEMPL(L)$  
C  
INTERIOR TEMPERATURE INCREFMENT  
$DTMP = R(M) * (D1+D2)$  
IF (NL+1-L) 86, 85, 89  

85  
M = 2  
GO TO 88  

86  
IF (NL1+NL2+1-L) 89, 87, 89  

87  
M = 3  
C  
INTERFACE TEMPERATURE INCREFMENT  
$DTMP = 2*([D*:BM]+D2) / ([L*B(M-1)+F(M)]/B(M))$  
IF (NL-1-L) 89, 880, 89  

C  
INTERFACE AND END POINT TEMP INCREFMENT FOR THIN INNER MATERIAL  

88  
$DTMP = 2*[D2/(L*B(M-1)+2*F(M)/B(M))]$  
TEMP(L) = TFMP(L) + DTEMP  
L = NL  
C  
LOCAL TEMPERATURE  
$TEMP(L) = TEMPL(L) + DTMP$  
IF(TMP(L)-TMEL) 92, 900, 900  

900  
$TFMP(L) = TFMLT$  
IF (L-1) 92, 90, 92  
C  
MELTING POINT FOR WALL  
$QAN = QAP+DOT*DTIMF$  
$TAUAR = 12.2*QAR/((DFRH/(l)))$  
IF (AROUT) 92, 91, 92  

91  
PUNCH 1019  
PUNCH 1006, N  
PUNCH 1005: TIME, ALT, VEL  
AROUT = 1.X0  
92  
CONTINUE  

93  
DO 920 I=1+NL  

920  
$TEMPL(L) = TEMPL(L)$  
IF (SFNSF SWITCH 3) 95, 97  
921  
IF (SENSE SWITCH 1) 95, 93  
93  
IF (TOPTN-FTOT) 99, 94, 99  

94  
TPRNT=0.X0  
95  
PUNCH 1006, N  
PUNCH 1005: TIME, ALT, VEL, RF  
PUNCH 1005, OW, QDOT, H, TAIMAR  
96  
IF (FINCFIT) 97, 97, 96  
97  
PUNCH 1005: SM, PS, TS  
PUNCH 1005, FM, PF, TF  
98  
DO 98 L=1+NL  
99  
PUNCH 1007: TEMPL(L), L  
99  
TIME = TIME + TIMF  
TPRNT = TPRNT + DTIMF  
IF (SFNSF SWITCH 2) 7, 100  
100  
IF (TIME = TH1) 110, 110, 2  
END
2. **Input Format**

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Each Curve

When

NCFIT = 0 Each Segment

When

NCFIT = 0

Each Segment

When

NCFIT = 0 Each Layer + End Point

Each Material

Each Case

NSEC

Each Layer + End Point

Each Material

Each Case

NCFIT

Read 11 AP Cards Only Once
3. Input Comments

1) Eleven Atmospheric Properties Data Cards, as described in Appendix B

2) \[ \begin{align*}
\text{TBODY} &= \quad \text{NCFIT} = \\
\text{Sphere} &\quad 1. \quad 2 \\
\text{Flat Plate} &\quad 2. \quad 5 \ or \ 0 \\
\text{Cone} &\quad 3. \quad 5 \ or \ 0 \\
\end{align*} \]

When \( \text{NCFIT} \neq 0 \), the curves needed are

- Curve I: \( \text{ALT}, \text{ft vs Time, sec} \) 
- Curve II: \( \text{VEL}, \text{ft/sec vs Time, sec} \) 
- Curve III: \( M_s \text{ vs } M_\infty \) 
- Curve IV: \( P_s/P_\infty \text{ vs } M_\infty \) 
- Curve V: \( T_s/T_\infty \text{ vs } M_\infty \)

3) \( \text{Sphere:} \quad 0 \quad \text{RN} \quad \text{QR} \)
   \( \text{FP or Cone:} \quad 0 \quad \text{Y} \quad \text{RET} \)

(\( \theta \) is used for identification only for flat plate or cone)

4) Melting temperature effective heat of ablation and emissivity of wall material.

5) Number of materials = 1, 2, or 3.

6) Material properties, where \( m = 1 \) to \( \text{NMAT} \).

Sum of layers cannot exceed 14. \( \text{NLAY} \) cannot = 2.

7) Time inputs: By card - SW 2 ON. By typewriter on 4 lines - SW 2 OFF

\[ \text{NT} = \text{Total number of time steps} \]

\[ \text{NT} = (T^{\text{HI}} - T^{\text{LO}})/DTIME + 1. \]  \( \text{(A-1)} \)

8) Initial temperatures for each layer and end point. \( L_1 \) is input as convenience to use output TEMP cards to restart - does not necessarily equal \( L \).

9) Number of segments of the curve. Total number of segments for all curves cannot exceed 15.

10) Limits of segment:

- \( X = \text{Time, for Curves 1 and 2} \)  \( \text{(A-2)} \)
- \( X = M_\infty, \text{ for Curves 3, 4, and 5} \)  \( \text{(A-3)} \)
11) Coefficients of the normalized cubic equation:

\[ V_1 = A_0 + A_1 (F_X) + A_2 (F_X)^2 + A_3 (F_X)^3 \]  (A-4)

where

\[ F_X = \frac{(X - XLO)}{(XHI - XLO)} \]  (A-5)

and

\[ V_1 = ALT \]  (A-6)
\[ V_2 = VEL \]  (A-7)
\[ V_3 = M_s \]  (A-8)
\[ V_4 = \frac{P_g}{P_\infty} \]  (A-9)
\[ V_5 = \frac{T_s}{T_\infty} \]  (A-10)

12) Constant local conditions, given for flat plate or cone when NCFIT = 0. ALT and VEL are used for identification only.

4. IBM 1620 Operating Instructions

a. Compiling and Starting

1) Compile Fortran program on IBM 1620 40K digital computer starting at 08200 memory core.
2) Load object deck. Check console switches.

b. Console Switches

1) SW1 ON For output at all time steps
2) OFF For output only at time steps determined by DTOUT
3) SW2 ON Card input of time values -- DTIME, DTOUT, T1, T0, TH1
4) OFF Typewriter input of these values
5) SW3 ON Ends run, prints last time step, branches to next case
6) SW4 OFF During typewriter input
7) ON To make corrections in typewriter input
c. Typewriter Output and Input

The time increment, \( \Delta t \) or DTIME, is calculated for each material and printed. Operator determines \( \Delta t \) from smaller value, then inputs four time values by typewriter—unless SW2 is ON. The computed values for DTIME should be approximately the same for all materials used. DTOUT must be an exact multiple of DTIME.

A rough estimate of the machine time which will be required is printed. This enables the operator to leave the machine and plan for additional machine time, if necessary.

\[ T1620 = NT \times NL/40 \]  
(A-11)

Typewriter input and output for a sphere (Example 1) follows:

SW1 OUTS ALL STEPS--SW2 CARD INPUTS 4 TIME VALS  
SW3 ENDS RUN

TEMPERATURE VS TIME FOR LAYERS OF SPHERE

DTIME FOR EACH MAT
274.09802E-04   1
300.54519E-04   2
317.39871E-04   3

INPUT--DTIME, DTOUT, TLO, THI--ON 4 LINES BY TY
 .025RS
 .5RS
 16. RS
 18. RS

APP 1620 MIN REQUIRED
 .13000000E+02

D. After Ablation

When the wall temperature reaches the given melting temperature, TMELT, ablation begins. After this point the computed values for the temperatures of each layer may be doubtful since only a simple procedure is included for this ablation.

\[ Q_{AB} = \sum (Q \Delta t), \text{ while } T_w \leq TMELT \]  
(A-12)

\[ T_{AB} = \frac{12 Q_{AB}}{(Q_{eff} \rho_i)} \]  
(A-13)
e. Terminating and Restarting

The problem may be terminated before reaching the upper
time limit, TH1, and started again later as follows:

1) To terminate: Turn SW1 ON to putput values at all time
steps--to determine suitable TIME to restart. (SW3 on outputs last time
values only then branches to next case) Save the cards for temperatures
at each layer.

2) To begin again: The original input values are used
except TLO = TIME and initial temperatures for each layer and end point
are from last time step computed. The time values: DTIME, DTOUT,
TLO, and TH1 may be input on one card, instead of by typewriter, if
SW2 is ON.

5. Example Runs for Sphere, Flat Plate, and Cone

Case 1 is a sphere consisting of three materials: beryllium
(4 layers), molybdenum (3 layers) and a thin inner wall of aluminum.
The nose radius is one foot and the position angle is zero degrees. An
initial time of 16 seconds is given to utilize all heat coefficient
equations--those for velocities less and greater than 6000 ft/sec. Type-
writer input is used for DTIME, DTOUT, TLO and TH1 for Case 1 only.

Case 2 is a 4° flat plate, with Y = 2 feet, and composed of a thin
wall of beryllium and a slab of molybdenum. Altitude and velocity data
are the same as for Case 1. With initial time of 16 seconds and transi-
tion Reynolds number of 22500000 both laminar and turbulent boundary
layer equations are used.

Case 3 is a 4° cone with all input data the same as for Case 2,
except no curve fit data are used. Constant altitude, velocity and local
properties are given.

6. Input Data for Examples
   (Switch 1 on for first steps)
   (Switch 2 on for Cases 2 and 3)

   0. 288.16  101325.  AP59 1
   11000. 216.66  22632.  AP59 2
   25000. 216.66  2488.6   AP59 3
   47000. 282.66  120.444  AP59 4
   53000. 282.66  58.3215   AP59 5
   79000. 165.66  1.00946  AP59 6
   90000. 165.66  1.04438  AP59 7
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7. Output Data for Examples

a. Temperature versus Time for Layers of Sphere

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MATERIAL -- DTIME, H, K, RHO, CP, TAUT, NLAY

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**= FOR EACH OUTPUT TIME STEP ---

TIME ALT*KFT VEL*FT/SEC RF

OWN QDOT H TAUAR --- HFAT COEFF'S

MACH NO, PRESSURE TEMPERATURE -- LOCAL

MACH NO, PRESSURE TEMPERATURE -- FREE STREAM

TEMPERATURE AND COUNT FOR EACH SKIN LAYER

<p>| 1 | 16000000F+02 | 45981030F+02 | 62311290E+04 | 00000000F-99 |
| 2 | 83836200F+02 | 83882098F+02 | 00000000F-99 | 00000000F-99 |
| 3 | 00000000F-99 | 15872714E+05 | 36721364F+04 | 540.00000F-00 |
| 4 | 64375182F+01 | 29491558E+03 | 38998800E+03 | 540.00000F-00 |
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| 6 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 |
| 7 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 |
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| 10 | 83333656F+02 | 83330385F+02 | 00000000F-99 | 00000000F-99 |
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| 3 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 |
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| 5 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 | 540.00000F-00 |
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35
### Temperature versus Time for Layers of Flat Plate

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**MATERIAL**
- DTIME, M, K, RHO, CP, TAUT, NLAY
- THERMAL PROPERTIES

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<th>RHO</th>
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**DTIME**
- TOUT = TLO = THI =

**FOR EACH OUTPUT TIME STEP**

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<th>QNT</th>
<th>H</th>
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*63.9002F400*
c. Temperature versus Time for Layers of Cone

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**MATERIAL** -- DTIME, M, K, RHO, CP, TAU, NLAY

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**## FOR EACH OUTPUT TIME STEP ##**

* TIME, ALT, KFT, VEL, FT/SEC, RE

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**# FOR EACH SKIN LAYER**

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Appendix B

1959 ATMOSPHERIC PROPERTIES

Table I presents 1959 atmospheric properties used as input to the Fortran program.

Table I. ARDC 1959 Atmospheric Properties

<table>
<thead>
<tr>
<th>ALT, Meters</th>
<th>T, °K</th>
<th>P, Newtons/m²</th>
<th>Card #</th>
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<tbody>
<tr>
<td>0.0</td>
<td>288.16</td>
<td>101325.</td>
<td>1</td>
</tr>
<tr>
<td>11000.</td>
<td>216.66</td>
<td>22632.</td>
<td>2</td>
</tr>
<tr>
<td>25000.</td>
<td>216.66</td>
<td>2488.6</td>
<td>3</td>
</tr>
<tr>
<td>47000.</td>
<td>282.66</td>
<td>120.444</td>
<td>4</td>
</tr>
<tr>
<td>53000.</td>
<td>282.66</td>
<td>58.3215</td>
<td>5</td>
</tr>
<tr>
<td>79000.</td>
<td>165.66</td>
<td>1.00946</td>
<td>6</td>
</tr>
<tr>
<td>90000.</td>
<td>165.66</td>
<td>1.04438</td>
<td>7</td>
</tr>
<tr>
<td>105000.</td>
<td>225.66</td>
<td>0.00745265</td>
<td>8</td>
</tr>
<tr>
<td>160000.</td>
<td>1325.66</td>
<td>0.362003 E-03</td>
<td>9</td>
</tr>
<tr>
<td>170000.</td>
<td>1425.66</td>
<td>0.282362 E-03</td>
<td>10</td>
</tr>
<tr>
<td>700000.</td>
<td>3325.66</td>
<td>0.0</td>
<td>11</td>
</tr>
</tbody>
</table>

The following changes in dimensions are made, and the properties are stored into memory as:

\[ \text{AP (K, 1)} = \text{ALT}_{ft} = \text{ALT}_{meters} \times 3.2808333 \quad (B-1) \]

\[ \text{AP (K, 2)} = \frac{\text{T, °K}}{1.8} \quad (B-2) \]

\[ \text{AP (K, 3)} = \frac{\text{P, lbs/ft}^2}{\text{P, Newtons/m}^2} \times 0.0208854 \quad (B-3) \]

where K = 1 to 11
The local velocity, \( V_\infty \), is given in ft/sec and the local altitude, \( \text{ALT} \), is given in kilo-feet (geometric measure) and is converted to feet (geopotential measure).

\[
\text{ALTF} = 20856000 \cdot \frac{(\text{ALT})}{(20856 + \text{ALT})} \quad \text{(B-4)}
\]

\[
\Delta \text{ALT} = \Delta \text{ALT} = \text{ALTF} - \text{AP}_K \quad \text{(B-5)}
\]

\[
T_\infty = \text{AP}_K, \frac{2}{\text{ALT}} + \text{ALT} (TS) \quad \text{(B-6)}
\]

where \( TS \) is the temperature slope for the atmosphere layer.

\[
TS = \frac{\Delta \text{AP Temperature}}{\Delta \text{Altitude}} \quad \text{(B-7)}
\]

When \( TS = 0.0 \)

\[
P_\infty = \text{AP}_K, \frac{3}{e^j} \quad \text{(B-8)}
\]

where

\[
e = 2.718281828 \quad \text{(B-9)}
\]

and

\[
j = 0.01879 \frac{\Delta \text{ALT}}{\text{AP}_K} \quad \text{(B-10)}
\]

When \( TS \neq 0.0 \)

\[
P_\infty = \text{AP}_K, \frac{3}{T_\infty^j} \quad \text{(B-11)}
\]

where

\[
j = 0.01879/TS \quad \text{(B-12)}
\]

Then

\[
\rho_\infty = 0.01879 P_\infty / T_\infty \quad \text{(B-13)}
\]

and

\[
M_\infty = V_\infty \sqrt{\frac{R_g}{T_\infty}} \quad \text{(B-14)}
\]
## SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBODY</td>
<td>Type of configuration - 1. Sphere 2. Flat plate 3. Cone</td>
</tr>
<tr>
<td>NCFIT</td>
<td>Number of curves fitted for input data</td>
</tr>
<tr>
<td>TH</td>
<td>$\theta$ Angle, deg: Sphere; position angle Flat plate or cone; used for identification</td>
</tr>
<tr>
<td>D</td>
<td>Nose diameter of sphere, ft</td>
</tr>
<tr>
<td>RN</td>
<td>$R_n$ Nose radius of sphere, ft</td>
</tr>
<tr>
<td>Y</td>
<td>$Y$ Length along surface, ft</td>
</tr>
<tr>
<td>RNORY</td>
<td>Input symbol (RN or Y)</td>
</tr>
<tr>
<td>QR</td>
<td>$c/q$ Ratio of laminar heat transfer to stagnation rate heat transfer, from Figure 5</td>
</tr>
<tr>
<td>RET</td>
<td>$Re_t$ Transition Reynolds number, given for FP or cone</td>
</tr>
<tr>
<td>RE</td>
<td>$Re$ Local Reynolds number, defined by Equation (36) for FP or cone</td>
</tr>
<tr>
<td>QRRET</td>
<td>Input symbol (QR or RET)</td>
</tr>
<tr>
<td>TMELT</td>
<td>Melting temperature for wall, °R</td>
</tr>
<tr>
<td>QE</td>
<td>$q_{eff}$ Effective heat of ablation, Btu/lb</td>
</tr>
<tr>
<td>E</td>
<td>$\epsilon$ Emissivity of wall material</td>
</tr>
<tr>
<td>NMAT</td>
<td>Total number of materials; 1, 2 or 3</td>
</tr>
<tr>
<td>G(M)</td>
<td>$k_m$ Material thermal conductivity, Btu/ft·sec·°R</td>
</tr>
<tr>
<td>RHO(M)</td>
<td>$\rho_m$ Material density, lbs/ft³</td>
</tr>
<tr>
<td>CP(M)</td>
<td>$C_{pm}$ Specific heat for the material, Btu/lb·°R</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>( T_{\text{AUT}} )</td>
<td>Total thickness of the material, ft</td>
</tr>
<tr>
<td>( \tau_{\text{tot}} )</td>
<td>Thickness of each layer of the material, ft</td>
</tr>
<tr>
<td>( T_{\text{AU(M)}} )</td>
<td>Number of layers of each material (Total cannot exceed 14)</td>
</tr>
<tr>
<td>( N_{\text{LAY_m}} )</td>
<td>Functions of material properties, defined by Equations (39) to (41)</td>
</tr>
<tr>
<td>( T_{\text{ME}} )</td>
<td>Local time, sec</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>Time increment, sec, used for calculations, Equation (38)</td>
</tr>
<tr>
<td>( D_{\text{ME}} )</td>
<td>Time increment, sec, used for output; Multiple of ( \Delta t )</td>
</tr>
<tr>
<td>( \beta_{\text{10}} )</td>
<td>Initial time, sec, ( T_{\text{LO}} \geq 0.0 )</td>
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<tr>
<td>( \beta_{\text{hi}} )</td>
<td>Upper time limit, sec</td>
</tr>
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<td>( N_{\text{T}} )</td>
<td>Total number of time steps, Equation (A-1)</td>
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<tr>
<td>( T_{\text{1620}} )</td>
<td>Estimate of 1620 machine time required, Equation (A-11)</td>
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<td>( D_{\text{PRNT}} )</td>
<td>Count for time print-out</td>
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<tr>
<td>( A_{\text{BOUT}} )</td>
<td>Test for output of TIME, ALT, and VEL at first ablation</td>
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<tr>
<td>( \text{NUM}_{1} )</td>
<td>Number of segments to each of 2 or 5 curves given (Total number of segments cannot exceed 15)</td>
</tr>
<tr>
<td>( X_{10}, X_{\text{hi}} )</td>
<td>Limits of curve segment, input data</td>
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<tr>
<td>( A_{0}, A_{1}, A_{2}, A_{3} )</td>
<td>Normalized cubic curve fit constants, used in Equation (A-4)</td>
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<tr>
<td>( T_{\text{EMP}} )</td>
<td>Temperature for each skin layer at each time step, ( ^{\circ} \text{R} ); given for initial time step, then defined by Equations (49) to (55)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
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<tr>
<td>TEMPL</td>
<td>Temperature for each layer at previous time steps</td>
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<tr>
<td>DTEMP</td>
<td>Temperature increment for the local layer, Equation (42)</td>
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<td>TW</td>
<td>Wall temperature, °R, defined by Equations (49) and (53)</td>
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<tr>
<td>TEMP(NL)</td>
<td>Temperature for innermost point, defined by Equations (52) and (55)</td>
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<td>D1-2</td>
<td>Incremental temperature distribution, defined by Equations (43) to (45)</td>
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<tr>
<td>FM</td>
<td>Free stream Mach number, Equation (B-14)</td>
</tr>
<tr>
<td>SM</td>
<td>Local Mach number Sphere: from Equation (25) FP or Cone: given constant or $f(M_{\infty})$, Equation (A-8)</td>
</tr>
<tr>
<td>PF</td>
<td>Free stream pressure, lbs/ft², Equations (B-8) and (B-11)</td>
</tr>
<tr>
<td>PS</td>
<td>Local pressure, lbs/ft² Sphere: from Equation (23) FP or Cone: given constant or $f(M_{\infty})$, Equation (A-9)</td>
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<tr>
<td>PSVPT</td>
<td>Ratio of local pressure to stagnation pressure, Equation (24)</td>
</tr>
<tr>
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<td>Free stream temperature, °R, Equation (B-6)</td>
</tr>
<tr>
<td>TS</td>
<td>Local temperature, °R Sphere: from Equation (27) FP or Cone: given constant or $f(M_{\infty})$, Equation (A-10)</td>
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<td>AP</td>
<td>Atmospheric Properties of Table 1 in Appendix B</td>
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<tr>
<td>AP&lt;sub&gt;K, l&lt;/sub&gt;</td>
<td>Altitude, ft, geopotential measure, Equation (B-1)</td>
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<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
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<td>--------</td>
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<tr>
<td>$AP_{K,2}$</td>
<td>Atmospheric temperature, °R, Equation (B-2)</td>
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<tr>
<td>$AP_{K,3}$</td>
<td>Atmospheric pressure, lbs/ft$^2$, Equation (B-3)</td>
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<tr>
<td>ALT</td>
<td>Local altitude, kilo-feet, geometric measure, Equation (A-6)</td>
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<td>ALT</td>
<td>Local altitude, ft, geopotential measure, Equation (B-4)</td>
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<tr>
<td>$\Delta ALT$</td>
<td>Difference between local and layer base altitude, ft, geopotential measure, Equation (B-5)</td>
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<tr>
<td>$V_{\infty}$</td>
<td>Local free stream velocity, ft/sec, Equation (A-7)</td>
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<tr>
<td>$DF$</td>
<td>Free stream density, lbs/ft$^3$, Equation (B-13)</td>
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<tr>
<td>$\rho_{\infty}$</td>
<td>Sea level density, 0.092378 slugs/ft$^3$</td>
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<tr>
<td>$Q_{AB}$</td>
<td>Heating rate during ablation, Equation (A-12)</td>
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<td>$\tau_{ab}$</td>
<td>Preliminary estimate of total ablation thickness, in., Equation (A-13)</td>
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<td>$Q_{W}$</td>
<td>Aerodynamic heating rate, Btu/ft$^2$ - sec, Equations (28) and (47)</td>
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<tr>
<td>$Q_{DOT}$</td>
<td>Defined by Equation (48)</td>
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<tr>
<td>$T_{REC}$</td>
<td>Recovery temperature, °R, Equation (46)</td>
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<tr>
<td>$H$</td>
<td>Aerodynamic heat coefficient, Btu/ft$^2$-sec - °R, defined by Equations (15), (19), (29), (32), and (35)</td>
</tr>
<tr>
<td>$Z_{1,2,3}$</td>
<td>Factors of Equations (7), (15) and (19). Defined by Equations (8) to (10) and (20) to (22)</td>
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<tr>
<td>$H X$</td>
<td>Flat plate to cone heat transfer factor, as used in Equations (32) and (35)</td>
</tr>
<tr>
<td>$h$</td>
<td>Enthalpy, ft$^2$/sec$^2$, used in Equation (28)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
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<td>CREF</td>
<td>Reference thermal conductivity, Btu/ft-sec-°R Equations (12a) and (12b)</td>
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<td>UREF</td>
<td>Reference viscosity, lbs-sec/ft², Equation (13)</td>
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<td>Reference Prandtl number, Equation (14)</td>
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<tr>
<td>TREF</td>
<td>Reference temperature, °R, Equation (11)</td>
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<tr>
<td>COP</td>
<td>Specific heat for air, Equation (56)</td>
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<td>G</td>
<td>Ratio of specific heats; for air, γ = 1.4</td>
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<tr>
<td>GL</td>
<td>Computed γ as a function of temperature, Equation (57)</td>
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<tr>
<td>R</td>
<td>Recovery factor: laminar, R = 0.85, turbulent, R = 0.892</td>
</tr>
<tr>
<td>GA</td>
<td>Acceleration for gravity; 32.174 ft/sec²</td>
</tr>
<tr>
<td>RG</td>
<td>Gas constant, for air, Rg = 1716 ft²/sec²-°R</td>
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<tr>
<td>σ</td>
<td>Stefan-Boltzmann constant, 0.48096 X 10⁻⁵</td>
</tr>
<tr>
<td>St</td>
<td>Stanton number, Equations (1) and (17)</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
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<tr>
<td>Cf</td>
<td>Skin friction coefficient, Equations (3) and (18)</td>
</tr>
<tr>
<td>f₁, f₂</td>
<td>Leading edge Cf proportionality factor for laminar and turbulent boundaries</td>
</tr>
<tr>
<td>θ</td>
<td>Velocity gradient parameter</td>
</tr>
</tbody>
</table>
SUBSCRIPTS

AB  Ablation properties
∞  Free stream properties
S  Local properties
M  Material properties, counts materials from 1 to NMAT
NL  Total number of skin layers plus end point, NL ≤ 15
L  Number of the layer, from 1 to NL
N  Counts time steps
I  Counts curves fitted for input data, from 1 to NCFIT
inc  Incompressible conditions
_o  Stagnation conditions
TOT  Total conditions
K  Number of base of altitude layer
FP  Flat plate
W  Wall

SUPERSCRIPTS

*  Reference properties
_i  Temperatures at previous time step
EQUATIONS AND FORTRAN PROGRAM FOR APPROXIMATE AERODYNAMIC HEAT TRANSFER AND TRANSIENT TEMPERATURE DISTRIBUTIONS FOR LEADING EDGES AND FLAT PLATE SURFACES

**Abstract**

The equations and a Fortran program to calculate supersonic and hypersonic aerodynamic heat transfer rates and transient temperature distributions for spherical leading edges and flat plate surfaces are presented in this report. The missile skin is composed of one to three different slab materials and/or thin wall combinations for flight trajectories or wind tunnel conditions. The Fortran program is written for the IBM 1620 40K digital computer.
Stagnation regions
Flat plate regions
One dimensional temperature distribution
Specific heat ratios
Flight environment

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3. REPORT TITLE: Enter the complete report title in capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all-caps in parenthesis immediately following the title.

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