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A SIMPLIFIED STREAMLINE SWALLOWING PROCEDURE FOR THE WINDWARD MERIDIAN OF AXISYMMETRIC BLUNT BODIES

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THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY

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ABSTRACT

A relatively simple procedure has been developed to include variable boundary layer edge entropy in an inviscid flow solution on the windward ray of axisymmetric blunt bodies. Variable boundary layer edge entropy is significant downstream of the nose region on blunt bodies due to entropy gradients along the curved bow shock. Laminar and turbulent boundary layer growth models are used in a mass balancing technique to account for the effects of entropy gradients produced at the bow shock. The solution is driven by the inviscid surface pressure distribution, mass flow within the boundary layer, and bow shock shape. The code takes about 10 min/case to run on an IBM AT personal computer. Heat transfer comparisons to experimental data and other heating rate codes are favorable. The method is accurate from $M_\infty = 2.8$ to 15 for cones with flow incidence angles up to 25°.

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1.0 INTRODUCTION

Predicting aerothermal heating along the windward meridian of axisymmetric blunt bodies in supersonic and hypersonic flight is a common engineering problem. A simple, fast, and inexpensive way to calculate heating is to correlate boundary layer (BL) edge conditions to a heat transfer coefficient. Inherent to the method is determining the flow properties at the BL edge through the solution of greatly simplified forms of the Navier-Stokes equations. Ever present is the drive toward simpler methods that sacrifice as little accuracy as possible when compared to complete Navier-Stokes solutions to the body surface.

The classical (and simplest) approach for calculating BL edge conditions is to neglect coupling between the inviscid flow region and the BL, thereby treating the BL edge as an isentropic surface. The properties along the BL edge are found by following the stagnation streamline as it passes through the normal bow shock and then by assuming an isentropic expansion from the stagnation point around the body surface. The method requires only the pressure distribution and normal shock entropy for a complete thermodynamic definition of the BL edge. Currently, a computer code named ABBOHT (Axisymmetric Blunt Body Heat Transfer) is used to calculate cold (isothermal) wall heat transfer to the windward ray of blunted bodies in just such a manner.

In 1953 Ferri and Libby[1,2] found that entropy gradients induced by bow shock curvature around a blunted body produce a coupling effect between the inviscid region and the BL that can invalidate the classical solution. First, the entropy along the BL edge will continuously vary aft of the nose region; second, the velocity gradient at the predicted BL edge ($\partial u/\partial y$) will not be zero (producing nonsimilar BL growth) as previously assumed. The latter effect is significant when the external stream vorticity is of the same order of magnitude as the average BL vorticity (i.e., low Reynolds no. combined with high Mach no. flow). External flow vorticity effects are small at high Reynolds no. flow and on slender blunted cones (half angles less than 25°). Since that is the flow regime commonly used in ABBOHT, it was desired to upgrade the code to include variable entropy effects while accepting the BL similarity limitations.

Modifications to the classical, first-order approach to include shock curvature effects were investigated from 1960 to 1968 by Zakkay and Krause, Wilson, Rotta and Zakkay, and Murzinov.[3-6] All found the need to account for variable BL entropy through "entropy layer swallowing" or "streamline swallowing." That event occurs as follows: BL growth along a body is caused by mass entrainment of the inviscid external flow with streamlines that have passed through an increasingly oblique portion of the bow shock. Mass entrainment eventually swallows the high-entropy BL from the nose region. Consequently, the BL downstream of the nose region consists of lower entropy streamlines resulting in higher BL velocities and higher heat transfer rates than for the classical method. Low BL velocities and heat transfer at aft body stations in the old version of ABBOHT are documented in Ref. 7.

[1]A. Ferri and P. A. Libby, "Note on the Interaction Between the Boundary Layer and the Inviscid Flow," *J. Aeronaut. Sci.* **21**, 130 (1954)

[2]A. Ferri, "Some Heat Transfer Problems in Hypersonic Flow," in *Aeronautics and Astronautics*, Pergamon Press, New York, pp. 344-377 (1960)

[3]V. Zakkay and E. Krause, "Boundary Conditions at the Outer Edge of the Boundary Layer on Blunted Conical Bodies," *AIAA J.* **1**, 1671-1672 (1963).

[4]R. E. Wilson, "Laminar Boundary Layer Growth at Hypersonic Speeds," *J. Spacecr. Rockets* **2**, 490-496 (1965).

[5]N. R. Rotta and V. Zakkay, "Effects of Nose Bluntness on the Boundary Layer Characteristics of Conical Bodies at Hypersonic Speeds," *Astronaut. Acta* **13**, 507-516 (1968).

[6]I. N. Murzinov, "Laminar Boundary Layer on Blunt Bodies, Allowing for Vorticity of the External Stream," NASA TT F-11007 (Jun 1966).

[7]J. B. Kouroupis, "Comparison of Aerodynamic Heating Between Sharp and Blunt Bodies," JHU/APL BBE/EM-5292 (12 Mar 1986)

2.0 STREAMLINE SWALLOWING METHODS

2.1 MASS BALANCING

Two simplified (first-order) approaches have been developed to account for entropy layer swallowing in an inviscid code. The first is called mass balancing, whereby the mass flow in the BL at the station of interest is matched with the mass flow in a free-stream cylinder of appropriate radius (y_{sh}) as shown in Fig. 1, which is based on a figure in Ref. 8. The value of y_{sh} is defined as

$$y_{sh} = \frac{\dot{m}}{\sqrt{\pi \rho_\infty u_\infty}} .$$

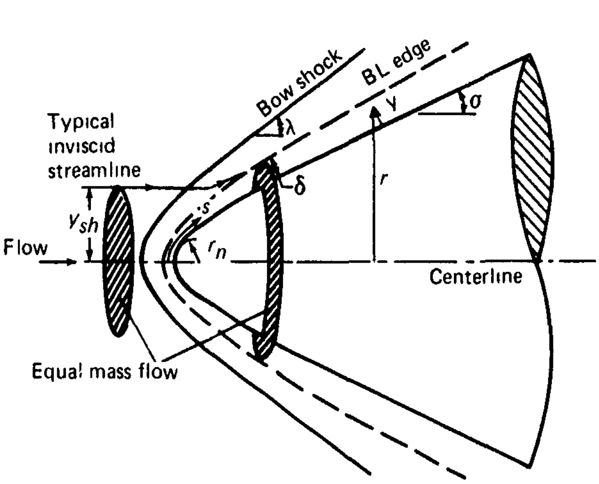

Figure 1 Streamline swallowing on a blunted body.

The bow shock angle at y_{sh} is then used to calculate the entropy behind the shock, which is used with the inviscid surface pressure to determine BL edge conditions. Thus, the bow shock shape, inviscid pressure distribution, and BL mass flow are required for the solution of the above equation.

In 1970-71 Mayne, Adams, and Dyer[8,9] built on the work done by Patankar and Spalding[10] to develop heat transfer codes that use mass balancing to account for streamline swallowing for both laminar and turbulent BL flow. Here, BL equations are expressed in a normalized Von Mises coordinate system and are solved using an implicit, finite-difference marching technique. BL mass flow is readily derived from that solution. A Method of Characteristics solution is used for the inviscid region to calculate bow shock shape and surface pressure. Mayne's laminar method accounts for nonsimilar BL growth, but the turbulent method does not.

In 1972 Price and Harris[11] used a technique similar to Mayne's but solved the *nonsimilar* BL equations for laminar, transitional, and turbulent flow. Thus, all three BL flow regimes can account for the effects of vorticity interaction. As with Mayne's method, an inviscid flow solution from the bow shock to the body surface was added to define the surface pressure distribution and bow shock shape, thereby allowing the inclusion of mass balancing. The program was revised in 1982[12] to increase its accuracy and computational efficiency.

In 1974 DeJarnette and Hamilton[13] devised a different approach for using mass balancing to account for streamline swallowing. First, a modified Newtonian surface pressure distribution is calculated over the body. Inviscid surface streamlines are then defined using Euler's equation along with two stream functions. This is an inverse method, where the bow shock shape can be found from stream function values. Those values also define the BL mass flow rate, which is matched to free-stream flow rates. The method is iterative, does not account for nonsimilar BL growth, and is generally less accurate than Mayne's method; it is, however, simpler and can be extended easily to three-dimensional geometries. Modifications to make the basic technique noniterative were made by Fivel.[14] Additional changes to make it simpler (albeit less accurate) for the rapid

[8]A. W. Mayne, Jr. and J. C. Adams, Jr., "Streamline Swallowing by Laminar Boundary Layers in Hypersonic Flow," AEDC-TR-71-32, Arnold Engineering Development Center, Tullahoma, Tenn. (Mar 1971).

[9]A. W. Mayne, Jr. and D. F. Dyer, "Comparisons of Theory and Experiment for Turbulent Boundary Layers on Simple Shapes at Hypersonic Conditions," *Proc. 1970 Heat Transfer and Fluid Mechanics Institute*, Stanford University Press, 168-188 (1970).

[10]S. V. Patankar and D. B. Spalding, "A Finite-Difference Procedure for Solving the Equations of the Two-Dimensional Boundary Layer," *Int J. Heat Mass Transfer* **10**, 1389-1411 (1967).

[11]S. M. Price and J. E. Harris, "Computer Program for Solving Compressible Nonsimilar Boundary-Layer Equations for Laminar, Transitional, or Turbulent Flows of a Perfect Gas," NASA TM X-2458 (1972).

[12]J. E. Harris and D. K. Blanchard, "Computer Program for Solving Laminar, Transitional, or Turbulent Compressible Boundary-Layer Equations for Two-Dimensional and Axisymmetric Flow," NASA TM-83207 (Feb 1982).

[13]F. R. DeJarnette and H. H. Hamilton, "Aerodynamic Heating on 3-D Bodies Including the Effects of Entropy Layer Swallowing," *J. Spacecr. Rockets* **12**, 5-12 (Jan 1975).

[14]H. J. Fivel, "Numerical Flow Field Program for Aerodynamic Heating Analysis," AFFDL-TR-79-3128, Vol. I, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio (1979).

and economical computation of heating rates and surface temperatures throughout an entire trajectory were made by DeJarnette et al.[15]

2.2 INVISCID APPROACH

The second simplified approach used to calculate variable BL edge entropy was born of the need to account for entropy layer swallowing over three-dimensional shapes (i.e., space shuttles), where mass balancing techniques become very complicated, and at high-incident angles, where mass balancing using similar BL development overpredicts heat transfer. This approach accounts for entropy layer swallowing by assuming BL edge conditions to be equal to inviscid properties at the hypothetical BL thickness. The BL thickness is found through its relation to the momentum thickness, which is derived from the momentum integral equation using an expression relating Reynolds no. and skin friction. A complete inviscid flow solution is required for this method.

The inviscid technique was originally developed by Zoby, Moss, and Sutton[16] in 1980. BL edge conditions found in this manner, when combined with the approximate heating relations given in Ref. 16, yield favorable heat transfer comparisons over blunted bodies for a variety of wind tunnel and flight conditions, although the technique has been used primarily for high-incident-angle and three-dimensional problems.

2.3 NEW ABBOHT METHOD

The method chosen for incorporation into ABBOHT is a simplified mass balancing version. It retains the advantage of requiring only the inviscid pressure distribution (as with DeJarnette's method) instead of the entire inviscid flow field (as with the Mayne, Price and Zoby methods). Moreover, it is simpler than either of the mass balancing methods discussed above because it neither solves the complex BL equations (as with the Mayne and Price methods) nor requires the use of multiple stream functions (as with DeJarnette's method). This new method uses a unique "tangent-blunted-cone" pressure technique (already contained in the old version of ABBOHT) conceived at APL by L. B. Weckesser and developed by L. L. Perini.[17] This approach does not include nonsimilar BL growth, so its ability to do large half-angle cones is limited. For computational efficiency, only simple relations are used for BL growth models and heating rate correlations.

Presented below is a description of the new method to calculate streamline swallowing effects as incorporated into ABBOHT. The new method also is compared to the old ABBOHT version; experimental data; the prediction methods of Mayne, DeJarnette, and Zoby; and viscous shock layer (VSL) predictions.

3.0 DISCUSSION

The first step in calculating BL edge conditions in ABBOHT is to determine the inviscid surface pressure distribution as described in Ref. 17. To use the mass balancing technique to account for streamline swallowing, the inviscid pressure distribution is coupled with a BL (mass flow rate). To incorporate the required procedure into ABBOHT, two geometrical additions must first be made: laminar and turbulent BL growth models for compressible flow (ABBOHT does not include transition region heating); and the bow shock shape. A dis-

[15] F. R. DeJarnette, L. A. Kania, and A. Chitty, "Aerodynamic Heating and Surface Temperatures on Vehicles for Computer-Aided Design Studies," AIAA Paper 83-0411 (Jan 1983).

[16] E. V. Zoby, J. N. Moss, and K. Sutton, "Approximate Convective Heating Equations for Hypersonic Flows," *J. Spacecr. Rockets* **18**, 64–70 (Jan 1981).

[17] L. L. Perini and J. B. Kouroupis, "A Simplified Procedure for Calculating Pressure Distributions Over Axisymmetric Blunt Nosed Bodies," JHU/APL BBE/EM-5230 (14 May 1985).

cussion of how the additional ABBOHT constituents are calculated is presented first, followed by an overview of the complete procedure for calculating heat transfer rates and, finally, a comparison of results. The ABBOHT code is written in Fortran 77 and was run on an IBM AT desktop computer for all results.

3.1 BOUNDARY LAYER GROWTH

3.1.1 Laminar Boundary Layer

The governing equation used for mass flow rate in a BL over a conical body is

$$\dot{m} = 2\pi r \rho_e u_e (\delta - \delta^*) \ .$$

Therefore, δ and δ^* must be modeled. Since it is desired to know the momentum thickness Reynolds no. as a criterion for BL transition, θ also must be calculated. All BL growth calculations start at the nose/body tangency point. Ness[18] modeled the three BL parameters for compressible, laminar flow over a sharp cone by solving the energy and X-momentum equations assuming $Pr = 1$, P_e, T_e, M_e, u_e, T_w, ν_w, γ = constant and $\beta = 0$. While these are crude assumptions for a blunted cone (especially in the expansion-compression region at the nose/body tangency point), they have been demonstrated herein to be adequate for use in this model. The resulting equations for δ, δ^*, and θ are

$$\delta = \frac{S\ T_e}{\sqrt{3}\ \sqrt{u_e S/\nu_w}\ \ T_w} \left\{3.00\ \frac{T_w}{T_e} + 2.01 \left[1 + \frac{\gamma - 1}{2}\ M_e^2 - \frac{T_w}{T_e}\right] - 1.62\ \frac{\gamma - 1}{2}\ M_e^2\right\} ,$$

$$\delta^* = \frac{S\ T_e}{\sqrt{3}\ \sqrt{u_e S/\nu_w}\ \ T_w} \left\{0.993\ \frac{T_w}{T_e} + 0.383\ \frac{\gamma - 1}{2}\ M_e^2\right\} ,$$

$$\theta = \frac{0.383\ S\ T_e}{\sqrt{3}\ \sqrt{u_e S/\nu_w}\ \ T_w} \ .$$

[18] N. Ness, "Dynamics of Viscous Fluids," Course Notes, Dept. of Aerospace Engineering, West Virginia University (Sep 1965)

The resulting equation for mass flow rate is

$$m = \frac{2\pi r u_e \rho_e S T_e}{\sqrt{3}\ \sqrt{u_e S/\nu_w}\ \ T_w} \left\{2.007\ \frac{T_w}{T_e} + 2.01 \left[1 + \frac{\gamma - 1}{2}\ M_e^2 - \frac{T_w}{T_e}\right] - 2.003\ \frac{\gamma - 1}{2}\ M_e^2\right\} .$$

To account for the initial BL thickness caused by the blunted nose, the stagnation BL thickness is first calculated from Ref. 19 using

$$\delta_s = 6(0.763) \left(\frac{\rho_e \mu_e}{\rho_w \mu_w}\right)^{0.4} \left(\frac{\nu_w}{\beta_s}\right)^{0.5} ,$$

where

$$\beta_s = \frac{u_\infty}{2R_n} \left(1 + \frac{1.56}{(1 + M_\infty^2)^{0.79}}\right) .$$

The equation (obtained from Ref. 20) for the stagnation point velocity gradient is empirical and valid for all free-stream Mach numbers.

The value of δ_s is then added to the sharp cone BL thickness at the nose/body tangency point, yielding the initial BL thickness at the start of the calculations.

3.1.2 Turbulent Boundary Layer

Whereas the laminar BL equations lend themselves to a closed-form solution for BL growth, the turbulent equations do not. Many semi-empirical and correlation methods to predict turbulent BL development are available. The method chosen for use in ABBOHT (the new version) is a flat plate formulation originally proposed for incompressible, turbulent flow by Head[21] in 1958 and then extended for compressible flow by Green[22] in 1967. This method was chosen for its proven accuracy in the flow regime of interest and because it solves directly for the quantity ($\delta - \delta^*$), which is used for modeling the BL mass flow rate.

[19] R. W. Truitt, *Fundamentals of Aerodynamic Heating*, The Ronald Press Co., New York (1960).

[20] L. L. Perini, "Compilation of Experimental Stagnation Point Velocity Gradients and Heat Transfer Data in Subsonic and Supersonic Flow," JHU/APL AEO-75-29 (14 Aug 1975).

[21] M. R. Head, "Entrainment in the Turbulent Boundary Layer," Aeronautical Research Council Reports and Memoranda, R & M No. 3152 (Sep 1958).

[22] J. E. Green, "The Prediction of Turbulent Boundary Layer Development in Compressible Flow," *J. Fluid Mech.* **31**, 753–778 (1968).

The underlying assumption for Head's method is that the BL entrainment rate is proportional to the velocity defect in the outer portion of the BL. The velocity defect can be approximated as the function of a modified form parameter (H_1) multiplied by the external stream velocity, or

$$\text{entrainment rate} = \frac{d(u_e\Delta)}{dx} = u_e F(H_1) ,$$

where

$$H_1 = \frac{\Delta}{\theta}$$

and

$$\Delta = \delta - \delta^* .$$

It was empirically determined that

$$F = 0.0306\ (H_1 - 3.0)^{-0.653}$$

for incompressible flow.

Using Head's assertion that density variation in the outer part of the BL had little effect on the entrainment mechanism, Green inferred that the incompressible relationship between F and H_1 also is valid for compressible flow. However, Head's relationship between H (which is used in the momentum integral equation below) and H_1 was inaccurate for compressible flow; therefore, Green provided empirical transformation functions between the compressible and incompressible versions of the form parameters.

Since F is assumed to be unaffected by density variation, Green accounted for compressibility effects simply by inserting density into the entrainment rate equation, yielding

$$\frac{d}{dx}\ (\rho_e u_e \Delta) = \rho_e u_e F .$$

By expanding the derivative and substituting

$$-\frac{M_e^2}{u_e}\ \frac{du_e}{dx} \text{ for } \frac{1}{\rho_e}\frac{d\rho_e}{dx} ,$$

Green obtained the following compressible entrainment rate equation:

$$\frac{d\Delta}{dx} = F + (M_e^2 - 1)\ \frac{\Delta}{u_e}\ \frac{du_e}{dx} .$$

The momentum integral equation for compressible flow over a flat plate is

$$\frac{d\theta}{dx} = \frac{c_f}{2} - (H + 2 - M_e^2)\ \frac{\theta}{u_e}\ \frac{du_e}{dx} .$$

The conventional form parameter, H (for compressible flow), in the above equation is found through an empirical transformation function together with an assumed quadratic BL temperature distribution, which is good for isothermal walls and small pressure gradients. The compressible skin friction (c_f) is determined using Eckert's reference temperature transformation between incompressible and compressible flow. Since this growth model was derived for flat plates, the BL growth rate was reduced by a factor of $2.25^{0.2}$ to compensate for axisymmetric effects. The correction factor for turbulent flow was derived using the Mangler transformation (see Appendix C of Ref. 23). Three-dimensional effects on BL growth are not accounted for, effectively yielding a sharp cone BL growth model. As with the laminar BL model, the sharp cone turbulent growth model has been demonstrated herein to be adequate for use in this heat transfer method. It is not the intent of the work reported here to accurately model the structure of the BL, but only to estimate its mass flow rate.

By marching the entrainment and momentum integral equations using an explicit, first-order-accurate technique, the development of the necessary parameters (θ and Δ) for mass flow rate predictions and the momentum thickness Reynolds no. is readily accomplished. Turbulent BL mass flow rate is simply

$$\dot{m} = 2\pi r \rho_e u_e \Delta .$$

3.2 BOW SHOCK SHAPE

The bow shock shape equation, empirically derived by Billig,[24] is used for this model. Billig assumes a hyperbolic shock, asymptotic to the sharp cone-attached shock angle. Since only the bow shock *angle* is required for streamline swallowing, the equation for coordinates of the shock given by Billig was differentiated to yield the slope as

$$\tan\lambda = \frac{R_c}{y_{sh}} \left(1 + \frac{y_{sh}^2\ \tan^2\eta}{R_c^2}\right)^{0.5} ,$$

where

$$R_c = 1.143\ R_n \exp\left(\frac{0.54}{(M_\infty - 1)^{1.2}}\right)$$

and η is the sharp cone-attached shock angle obtained from Simon and Walter[25] as

[23]C. Gazley, Jr., "Theoretical Evaluation of the Turbulent Skin-Friction and Heat Transfer on Cone in Supersonic Flight," R49A0524, General Electric Co. (Nov 1949).

[24]F. S. Billig, "Shock-Wave Shapes around Spherical- and Cylindrical-Nosed Bodies," *J. Spacecr. Rockets* **4**, 822–823 (1967).

[25]W. E. Simon and L. A. Walter, "Approximations for Supersonic Flow Over Cones," *AIAA J.* **1**, 1696–1697 (1963).

$$\sin \eta = \left(\frac{1}{M_\infty^2} + \frac{\gamma+1}{2} \sin^2\sigma \right)^{0.5} .$$

Thus, for a given y_{sh}, R_n, and σ, the slope of the bow shock can be easily found.

4.0 PROCEDURE

4.1 LAMINAR AND TURBULENT FLOW

Streamline swallowing calculations begin at the nose/body tangency point. For laminar BL flow, the procedure progresses as follows:

1. Step surface distance.
2. Calculate new surface pressure (constant downstream of nose region).
3. Use current value of BL edge entropy with new pressure to estimate new BL edge properties.
4. Calculate new mass flow rate.
5. Calculate new radius of free-stream cylinder to match mass flow rate.
6. Calculate new bow shock angle at given y_{sh}.
7. Calculate new entropy on downstream side of shock.
8. Compare entropy from step 7 with previous value.
9. If not converged, use entropy from step 7 and repeat procedure beginning with step 3 until converged. All BL edge properties are now thermodynamically consistent and the process repeats again at step 1 until the transition Reynolds no. is reached.

The quantities δ and δ^* are continually calculated for laminar flow and their last two values are saved so that the turbulent equations may be properly initialized. After calculating initial values for the turbulent entrainment and momentum equations, the turbulent streamline swallowing procedure continues as follows:

1. Step surface distance.
2. Calculate new surface pressure.
3. Step entrainment and momentum equations using backward differencing to find new values for Δ and θ.
4. Use new values for Δ and θ with BL edge conditions to calculate new form parameter and mass flow rate.
5. Calculate new radius of free-stream cylinder to match mass flow rate.
6. Calculate new bow shock angle at given y_{sh}.
7. Calculate new entropy on downstream side of shock.
8. Use new entropy with new surface pressure from step 2 to calculate new BL edge conditions.
9. Compare entropy from step 7 with previous value.
10. If not converged, use entropy from step 7 and repeat procedure beginning with step 4 until converged.
11. Repeat beginning with step 1 until end of body is reached.

There are three parameters driving the streamline swallowing solutions; i.e., the bow shock angle, the body radius, and the surface distance. Consequently, as the bow shock angle approaches that for a sharp cone well downstream of the nose, the BL edge properties also will approach those for a sharp cone. This phenomenon is illustrated in Section 5.0.

4.2 HEAT TRANSFER

Many methods are available to calculate heat transfer rates given BL edge properties and wall temperature. Therefore, to understand better the heat transfer comparisons, a brief review of the heating methods used by ABBOHT is presented below.

4.2.1 Stagnation Point Heating

Stagnation point heating is accomplished with Lees's equation,[26] modified to include wall temperature effects by using Eckert's reference temperature to evaluate density and viscosity. The resulting equation (assuming $Pr = 0.72$) is

$$q_s = 0.88 \left((\rho_* \mu_*)_s \beta_s \right)^{0.5} (h_r - h_w)_s .$$

4.2.2 Laminar Heating

Laminar heating also is accomplished with Lees's method, which requires the stagnation point heating rate as an input. The cold wall heating rate is defined as

$$\dot{q}_w = \frac{q_s \rho_* \mu_* u_e r}{2 \sqrt{(\rho_* \mu_*)_s \beta_s s_x}} .$$

4.2.3 Turbulent Heating

The solution of the momentum integral equation with an assumed 1/7-power velocity profile is used for turbulent heating relations. Eckert's reference enthalpy method[27] is used to account for compressibility effects and the Reynold's analogy factor of Colburn is used to convert skin friction into a heat transfer coefficient. To convert the flat plate relation into one for an axisymmetric body, a correction factor of $2.25^{0.2}$ was used, effectively treating three-dimensional heating effects as constant. The resulting heating rate is

$$\dot{q}_w = \frac{0.0348 \rho_* u_e}{Re_*^{0.2} Pr^{0.67}} (h_r - h_w) .$$

5.0 COMPARISON OF RESULTS

To illustrate the effects of streamline swallowing on BL edge conditions, results from the old and new versions of ABBOHT will be compared. Figure 2 shows the entropy distribution along the edge of laminar and turbulent BLs up to an S/R_n of 300, with the new model compared to the constant entropy value used in the old model. Also shown for comparison is the sharp cone BL edge entropy. The BL edge entropy with streamline swallowing is seen to decrease rapidly toward the sharp cone asymptote for turbulent BL flow, and more gradually for laminar BL flow. The sharp cone value is 16% below the normal shock value.

Figure 3 compares the edge Mach nos. for the same BL shown in Fig. 2. In this case the edge Mach nos. are heading toward the sharp cone value, rapidly for turbulent flow and gradually for laminar flow. The increase in edge velocity from the classical solution will have a direct effect on heat transfer rates as shown by the heating equations in Section 4.2. Although the effect of increased velocity significantly increases the heat transfer coefficient, the increased heating rate is moderated by an accompanying decrease in the recovery enthalpy.

ABBOHT can be run using either ideal or equilibrium air properties. Except when noted otherwise, all cases presented herein were run with the latter.

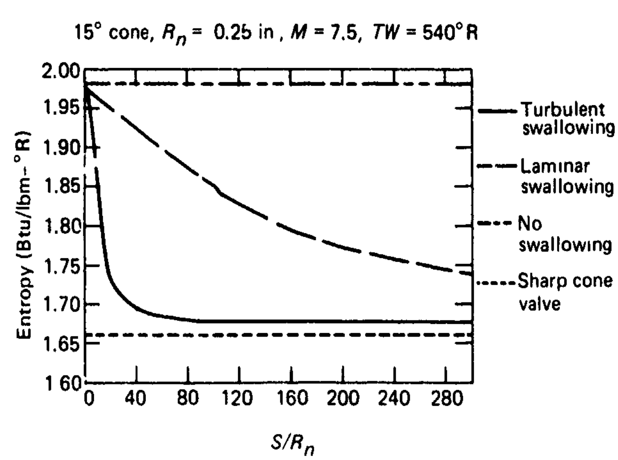

Figure 2 Entropy along a boundary layer edge.

[26]L. Lees, "Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Flight Speeds," *Jet Propul.* **26**, 259-269 (1956).

[27]E. R. G. Eckert, "Engineering Relations for Friction and Heat Transfer to Surfaces in High Velocity Flow," *J. Aeronaut. Sci.* **12**, 585-587 (1955).

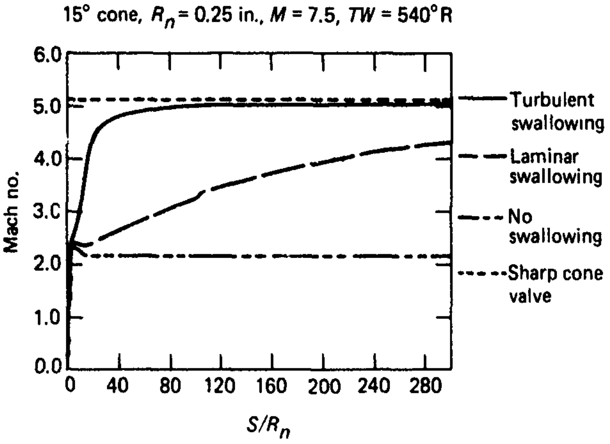

Figure 3 Mach no. along a boundary layer edge.

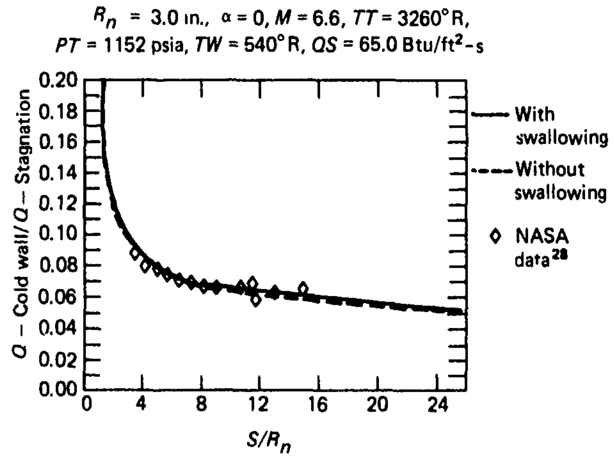

Figure 4 Heat transfer on a 12.5° blunted cone.

The laminar heating distributions for the old and new versions of ABBOHT are compared to experimental data from Ref. 28 in Fig. 4. Included with the test conditions is Lees's stagnation point heating rate (none of the experimental data presented included a measurement of stagnation point heating). Both codes accurately predict laminar heating rates for the given conditions. Streamline swallowing has very little effect on heating rates in the nose region of this body.

Figure 5 shows the laminar heating distribution for a less severe heating condition.[29] Here again, the two theories fit the data equally well. Laminar heating predictions are within 10% of the experimental data in Figs. 4 and 5.

The locations most affected by streamline swallowing are downstream of the nose region in the turbulent BL flow regime. This point is best illustrated in Fig. 6, which shows heat transfer to a slightly blunted 5° cone at Mach 10. The difference between the old and new versions of ABBOHT is approximately 20% in the turbulent flow regime. Results from both versions are compared to Mayne's method as well as experimental data obtained by Mayne.[30] The turbulent heating distribution predicted by ABBOHT is not as high as

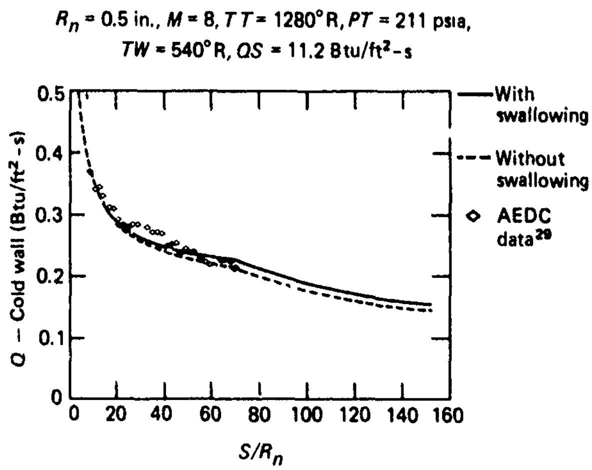

Figure 5 Heat transfer on a 7° blunted cone.

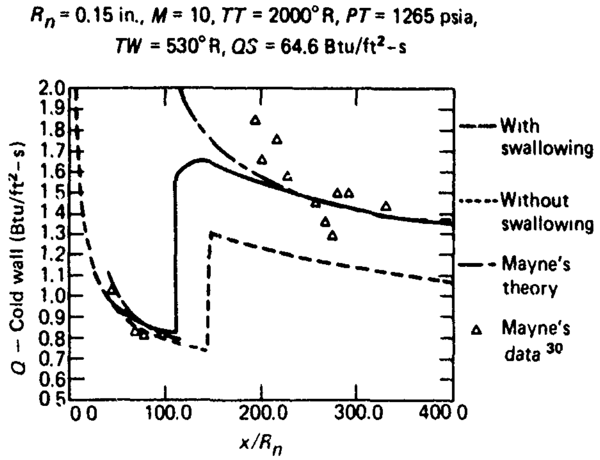

Figure 6 Heat transfer on a 5° blunted cone.

[28] R. J. Nowak, C. W. Albertson, and L. R. Hunt, "Aerothermal Tests of a 12.5° Cone at Mach 6.7 for Various Reynolds Numbers, Angles of Attack, and Nose Shapes," NASA TP-2345 (Jan 1985).

[29] D. B. Carver, "Heat Transfer, Surface Pressure and Flow-Field Surveys on Conic and Biconic Models with Boundary Layer Trips at Mach Number 8—Phases IV and VI," AEDC-TSR-80-V14, Arnold Engineering Development Center, Tullahoma, Tenn. (Mar 1980).

[30] A. W. Mayne, Jr., "Calculation of the Boundary-Layer Flow the Windward Symmetry Plane of a Spherically Blunted Axisymmetric Body at Angle of Attack, Including Streamline-Swallowing Effects," AEDC-TR-73-166, Arnold Engineering Development Center, Tullahoma, Tenn. (Oct 1973).

Mayne's theory at $x/R_n < 250$ but converges with it at the sharp cone value farther downstream. The turbulent experimental data have considerable scatter and range from 19% higher to 10% lower than the new ABBOHT predictions. This is a marked improvement from the solution without swallowing, which ranges from 13 to 48% lower than the experimental data in the turbulent flow regime. Laminar flow calculations show a slightly better correlation to experimental data for ABBOHT results rather than for Mayne's theory.

Figures 7 and 8 show additional comparisons to experimental turbulent data. In general, the curves with swallowing overpredict heat transfer in the fully turbulent flow regime by 5 to 15%, while those without swallowing underpredict heating from 10 to 25%. In Fig. 8, a BL trip was used at an S/R_n of 4. It is believed that low Reynolds no. turbulent flow (low BL vorticity) induced significant vorticity interaction in the nose region of this body, accounting for the high estimate of heat transfer at $S/R_n < 30$. In addition to improving heating rate predicitons by 5 to 10%, the method with swallowing also produces heating rate distributions more representative of the trends in the data.

To assess ABBOHT's performance with streamline swallowing at a higher Mach no., two cases were run with ideal air properties for comparison with the results of the DeJarnette and Zoby methods, obtained from Ref. 31. Additionally, a VSL solution, which accurately models variable entropy as well as vorticity interaction effects (also obtained from Ref. 31), is given. Figures 9 and 10 show turbulent heating results for a 5° cone at Mach 15 and angles of attack of 0 and 20°, respec-

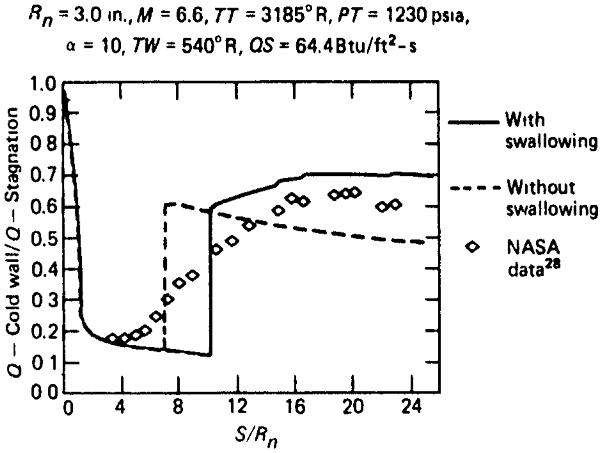

Figure 7 Heat transfer on a 12.5° blunted cone.

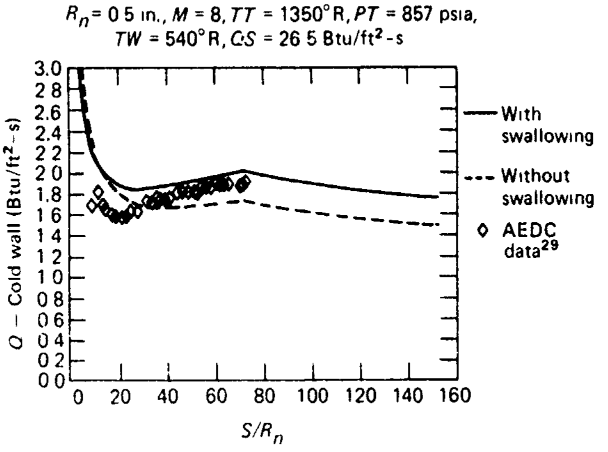

Figure 8 Heat transfer on a 7° blunted cone.

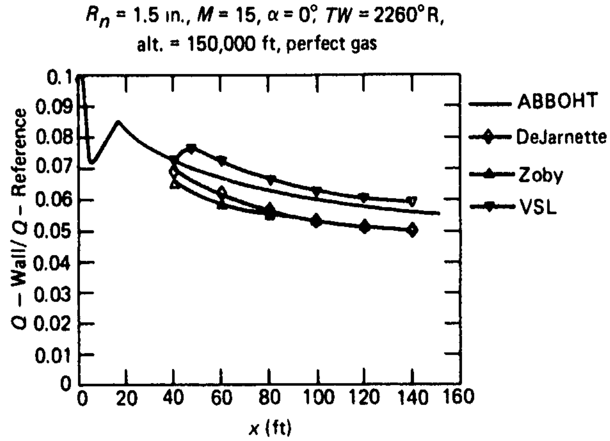

Figure 9 Turbulent heating on a 5° cone.

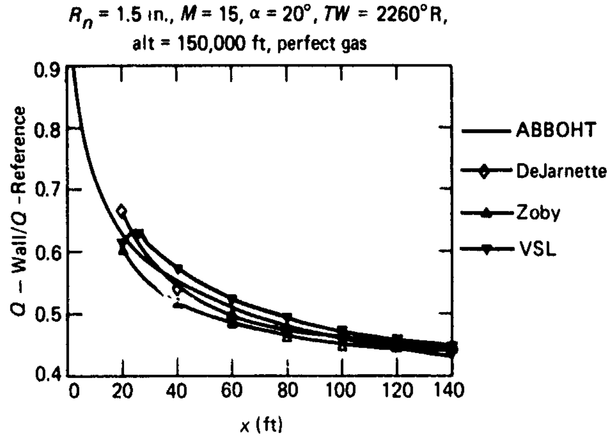

Figure 10 Turbulent heating on a 5° cone.

[31]E. V. Thompson, E. V. Zoby, K. E. Wurster, and P. A. Gnoffo, "An Aerothermodynamic Study of Slender Conical Vehicles," AIAA Paper No. 87-1475, presented at AIAA 22nd Thermophysics Conf. (Jun 8-10, 1987).

tively. In both cases, ABBOHT is generally higher than the DeJarnette and Zoby solutions and below the VSL solution. The total spread in all four solutions is approximately 18%. Usually, a VSL solution is considered the most accurate since it most closely models the physics of fluid heat and momentum transfer. However, without experimental data, it is impossible to support this presumption. Nevertheless, the close proximity of the ABBOHT solution to the VSL solution is a positive result. It also is encouraging that ABBOHT accurately modeled turbulent heat transfer on a blunted cone with a moderately high flow incidence angle (25°) at high Mach no. and altitude conditions, where vorticity interaction is moderate.

To appreciate the limits of the new ABBOHT version, a case was run that included high vorticity interaction. The body was a 40° sphere cone with a 1-ft nose radius. The flow conditions were obtained from Ref. 32. For turbulent flow, transition was assumed to be instantaneous at the nose/body tangency point. The resulting laminar and turbulent heating distributions are compared to Mayne's method and a VSL solution from Ref. 32 in Fig. 11.

Both ABBOHT and Mayne's turbulent streamline swallowing technique (neither of which account for vorticity interaction) overpredict the turbulent VSL solution by as much as 60 and 40%, respectively. A check of the pressure distribution and entropy swallowing distance in ABBOHT revealed them to be approximately the same as the VSL solution. Sources of error in the ABBOHT solution include the absence of a well-defined BL edge caused by vorticity interaction and loss of accuracy in the turbulent heating relation at high incidence angles. Because of the limited range of the approximations employed, ABBOHT should be used only to predict turbulent heating to axisymmetric bodies with incidence angles of less than 25°.

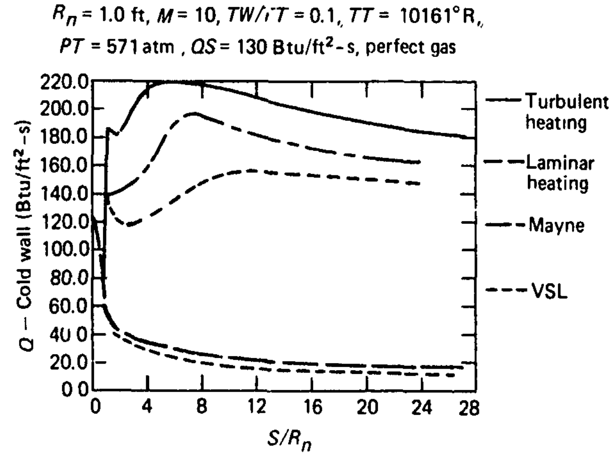

Figure 11 Heat transfer on a 40° blunted cone.

Laminar heating predictions were within 3% of the VSL solution for Mayne's method (not shown) and within 10% for ABBOHT. The favorable comparison for laminar flow suggests that ABBOHT can be used at high incidence angles to predict laminar heating under these conditions. The equivalent cone method (summing the cone angle and angle of attack) does not work well for laminar flow[33] and should therefore be avoided.

6.0 SUMMARY AND CONCLUSIONS

A simplified technique has been developed to add streamline swallowing to an inviscid axisymmetric heat transfer code named ABBOHT. Streamline swallowing effects are significant downstream of the nose region on axisymmetric blunt bodies where BL edge entropy is significantly lower than in the nose region. To account for variable BL entropy, a mass balancing technique was used to couple the inviscid pressure distribution with mass flow rates from newly added BL devel-

[32] E. C. Anderson and D. C. Wilcox, "Vorticity Interaction Effects on Blunt Bodies," NASA CR-2778 (Jan 1977).

[33] E. V. Zoby and A. L. Simmonds, "Engineering Flowfield Method with Angle-of-Attack Applications," *J. Spacecr. Rockets* **22**, 398 (1985).

opment models. In addition to the BL growth models, only an empirical bow shock definition was required to complete the geometry for the new procedure. The new ABBOHT code is simpler than previous mass balancing techniques because it does not solve the complete BL equations, it does not include the use of stream functions, and it does not require a definition of the entire inviscid flow field.

Compressible laminar BL growth was calculated directly with Ness's equations[18] for the BL and displacement thicknesses (see subsection 3.1.1). Compressible turbulent BL development was accomplished using Green's method,[22] which marches the first-order BL momentum integral equation together with the mass entrainment equation. Both procedures require iteration for BL edge conditions.

Comparisons to the old version of ABBOHT indicate a significant increase in turbulent heat transfer (from 10 to 30%) aft of the nose region. New ABBOHT heating results matched experimental data almost as well as Mayne's method for a 5° blunted cone in Mach 10 flow. In general, experimental data ranged from 19% higher to 10% lower than ABBOHT predictions; virtually all of the scatter was associated with turbulent flow cases. Turbulent heating comparisons to DeJarnette, Zoby, and VSL solutions at Mach 15 were very good up to a flow incidence angle of 25°. However, at a larger incidence angle (with high vorticity interaction), ABBOHT significantly overpredicted heat transfer rates. Laminar heating was only slightly higher with streamline swallowing and within 10% of the experimental results.

Until further validation runs and improvements to the code are made, the Mach 15 case with an incidence angle of 25° should be considered the upper bound of the applicability range for the new ABBOHT code. Above 25°, turbulent heat transfer calculations will be high. A listing of the ABBOHT source code with all subroutines (except the air property curve fitting algorithm) is contained in Appendix A and the variable definitions are presented in Appendix B.

ACKNOWLEDGMENTS

The author gratefully acknowledges F. T. Buckley and L. L. Perini for their help and guidance throughout the development stages of the ABBOHT code. This work was conducted under the supervision of L. B. Weckesser, Supervisor of the Bumblebee Engineering Group at APL.

REFERENCES

[1]A. Ferri and P. A. Libby, "Note on the Interaction Between the Boundary Layer and the Inviscid Flow," *J. Aeronaut. Sci.* **21,** 130 (1954).

[2]A. Ferri, "Some Heat Transfer Problems in Hypersonic Flow," in *Aeronautics and Astronautics,* Pergamon Press, New York, pp. 344-377 (1960).

[3]V. Zakkay and E. Krause, "Boundary Conditions at the Outer Edge of the Boundary Layer on Blunted Conical Bodies," *AIAA J.* **1,** 1671-1672 (1963).

[4]R. E. Wilson, "Laminar Boundary Layer Growth at Hypersonic Speeds," *J. Spacecr. Rockets* **2,** 490-496 (1965).

[5]N. R. Rotta and V. Zakkay, "Effects of Nose Bluntness on the Boundary Layer Characteristics of Conical Bodies at Hypersonic Speeds," *Astronaut. Acta* **13,** 507-516 (1968).

[6]I. N. Murzinov, "Laminar Boundary Layer on Blunt Bodies, Allowing for Vorticity of the External Stream," NASA TT F-11007 (Jun 1966).

[7]J. B. Kouroupis, "Comparison of Aerodynamic Heating Between Sharp and Blunt Bodies," JHU/APL BBE/EM-5292 (12 Mar 1986).

[8]A. W. Mayne, Jr. and J. C. Adams, Jr., "Streamline Swallowing by Laminar Boundary Layers in Hypersonic Flow," AEDC-TR-71-32, Arnold Engineering Development Center, Tullahoma, Tenn. (Mar 1971).

[9]A. W. Mayne, Jr. and D. F. Dyer, "Comparisons of Theory and Experiment for Turbulent Boundary Layers on Simple Shapes at Hypersonic Conditions," *Proc. 1970 Heat Transfer and Fluid Mechanics Institute,* Stanford University Press, 168-188 (1970).

[10]S. V. Patankar and D. B. Spalding, "A Finite-Difference Procedure for Solving the Equations of the Two-Dimensional Boundary Layer," *Int. J. Heat Mass Transfer* **10,** 1389-1411 (1967).

[11]S. M. Price and J. E. Harris, "Computer Program for Solving Compressible Nonsimilar Boundary-Layer Equations for Laminar, Transitional, or Turbulent Flows of a Perfect Gas," NASA TM X-2458 (1972).

[12]J. E. Harris and D. K. Blanchard, "Computer Program for Solving Laminar, Transitional, or Turbulent Compressible Boundary-Layer Equations for Two-Dimensional and Axisymmetric Flow," NASA TM-83207 (Feb 1982).

[13]F. R. DeJarnette and H. H. Hamilton, "Aerodynamic Heating on 3-D Bodies Including the Effects of Entropy Layer Swallowing," *J. Spacecr. Rockets* **12,** 5-12 (Jan 1975).

[14]H. J. Fivel, "Numerical Flow Field Program for Aerodynamic Heating Analysis," AFFDL-TR-79-3128, Vol. I, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio (1979).

[15]F. R. DeJarnette, L. A. Kania, and A. Chitty, "Aerodynamic Heating and Surface Temperatures on Vehicles for Computer-Aided Design Studies," AIAA Paper 83-0411 (Jan 1983).

[16]E. V. Zoby, J. N. Moss, and K. Sutton, "Approximate Convective Heating Equations for Hypersonic Flows," *J. Spacecr. Rockets* **18,** 64-70 (Jan 1981).

[17]L. L. Perini and J. B. Kouroupis, "A Simplified Procedure for Calculating Pressure Distributions Over Axisymmetric Blunt Nosed Bodies," JHU/APL BBE/EM-5230 (14 May 1985).

[18]N. Ness, "Dynamics of Viscous Fluids," Course Notes, Dept. of Aerospace Engineering, West Virginia University (Sep 1965).

[19]R. W. Truitt, *Fundamentals of Aerodynamic Heating,* The Ronald Press Co., New York (1960).

[20]L. L. Perini, "Compilation of Experimental Stagnation Point Velocity Gradients and Heat Transfer Data in Subsonic and Supersonic Flow," JHU/APL AEO-75-29 (14 Aug 1975).

[21]M. R. Head, "Entrainment in the Turbulent Boundary Layer," Aeronautical Research Council Reports and Memoranda, R & M No. 3152 (Sep 1958).

[22]J. E. Green, "The Prediction of Turbulent Boundary Layer Development in Compressible Flow," *J. Fluid Mech.* **31,** 753-778 (1968).

[23]C. Gazley, Jr., "Theoretical Evaluation of the Turbulent Skin-Friction and Heat Transfer on Cone in Supersonic Flight," R49A0524, General Electric Co. (Nov 1949).

[24]F. S. Billig, "Shock-Wave Shapes around Spherical- and Cylindrical-Nosed Bodies," *J. Spacecr. Rockets* **4,** 822-823 (1967).

[25]W. E. Simon and L. A. Walter, "Approximations for Supersonic Flow Over Cones," *AIAA J.* **1,** 1696-1697 (1963).

[26]L. Lees, "Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Flight Speeds," *Jet Propul.* **26,** 259-269 (1956).

[27]E. R. G. Eckert, "Engineering Relations for Friction and Heat Transfer to Surfaces in High Velocity Flow," *J. Aeronaut. Sci.* **12,** 585-587 (1955).

[28]R. J. Nowak, C. W. Albertson, and L. R. Hunt, "Aerothermal Tests of a 12.5° Cone at Mach 6.7 for

Various Reynolds Numbers, Angles of Attack, and Nose Shapes," NASA TP-2345 (Jan 1985).

[29]D. B. Carver, "Heat Transfer, Surface Pressure and Flow-Field Surveys on Conic and Biconic Models with Boundary Layer Trips at Mach Number 8—Phases IV and VI," AEDC-TSR-80-V14, Arnold Engineering Development Center, Tullahoma, Tenn. (Mar 1980).

[30]A. W. Mayne, Jr., "Calculation of the Boundary-Layer Flow in the Windward Symmetry Plane of a Spherically Blunted Axisymmetric Body at Angle of Attack, Including Streamline-Swallowing Effects," AEDC-TR-73-166, Arnold Engineering Development Center, Tullahoma, Tenn. (Oct 1973).

[31]E. V. Thompson, E. V. Zoby, K. E. Wurster, and P. A. Gnoffo, "An Aerothermodynamic Study of Slender Conical Vehicles," AIAA Paper No. 87-1475, presented at AIAA 22nd Thermophysics Conf. (Jun 8-10, 1987).

[32]E. C. Anderson and D. C. Wilcox, "Vorticity Interaction Effects on Blunt Bodies," NASA CR-2778 (Jan 1977).

[33]E. V. Zoby and A. L. Simmonds, "Engineering Flowfield Method with Angle-of-Attack Applications," *J. Spacecr. Rockets* **22**, 398 (1985).

APPENDIX A

PROGRAM TO COMPUTE HEAT TRANSFER ON BLUNT BODIES
VERSION 2.0, JULY 1987
ENTHALPY BASE OF OUTPUT IS O°R, ENTHALPY BASE OF AIRTBL USED IN CODE IS O°R

```
C-----------------------------------------------------------------

C                    MAIN PROGRAM

      COMMON  NOUT,NP,XTAB(100),YTAB(100),DSO,TO,PO,PTO,TTO,ALF,TIME,
     1 HRT(50),RUC(50),STA(50),XLEN(50),NPTS,ZO,VO,STRAN,RN,DELC,
     2 RR,RG,LT,ISTEP,IX,SDIST(10),FREEM(20,10),EDGEMR(20,10),
     3 EDGEPR(20,10),NFIL,NUM,JSTEP,ITY,IAIR
      COMMON/ALPHAN/TITLE,HEAT,CONV,BUG,TYPE,QS,TRAN,TURB,GEO,LAM
      COMMON/LOGICAL/NURL
      CHARACTER*1 QS,NURL
      CHARACTER*3 CONV,BUG,HEAT,LAM
      CHARACTER*4 TYPE,TRAN,TURB,GEO
      CHARACTER*7 NFORMAT(10)
      CHARACTER*60 TITLE
      CHARACTER*80 FILE5,FILE6,FILE7,FILE8,FILE9,FILE10,FILE11,FILE12,
     1FILE13,FILE14,FILE15,FILE16,FILE17,FILE18
      REAL*4  MACH,MO,LT
      DATA NFORMAT/'FIRST','SECOND','THIRD','FOURTH','FIFTH','SIXTH',
     1'SEVENTH','EIGHTH','NINTH','TENTH'/

C --------------- NAME INPUT AND OUTPUT FILES --------------------

  924 FORMAT(A80)
  925 FORMAT(30H INPUT DATA FILE =?             )
      WRITE(0,925)
      READ(0,924)FILE5
      OPEN(5,FILE=FILE5)
  926 FORMAT(30H OUTPUT DATA FILE =?            )
      WRITE(0,926)
      READ(0,924)FILE6
      OPEN(6,FILE=FILE6)
  928 FORMAT(30H PLOT OUTPUT FILE =?            )
      WRITE(0,928)
      READ(0,924)FILE8
      OPEN(8,FILE=FILE8)
      IX=-1

C ---------------------- READ INPUT ---------------------------

      READ(5,910,ERR=998) TITLE
      READ(5,914) IAIR,ITY,IQS,ITR,IGE,NPTS,NOUT,NP
      READ(5,915) DELC,RN,RR,RG,ALF,LT,DSO,STRAN
      IF(ITY.EQ.1)TYPE='FLT '
      IF(ITY.EQ.2.OR.ITY.EQ 3)TYPE='TEST'
      IF(IQS.EQ.1)QS='L'
      IF(IQS.EQ.2)QS='D'
      IF(ITR.EQ.1)TRAN='REYS'
      IF(ITR.EQ.2)TRAN='REYT'
      IF(ITR.EQ.3)TRAN='PANT'
      IF(IGE.EQ.1)GEO='CONE'
      IF(IGE.EQ.3)GEO='FLAT'
      IF(IGE.EQ.4)GEO='DISK'
      IF(IGE EQ 5)GEO='SPHE'
      IF(IGE EQ.6)GEO='CYLI'
```

```
C --------------- READ NUMBER OF URLIM FLOW TABLES TO CREATE ----------------

      WRITE(0,1003)
 1003 FORMAT(1X,'CREATE URLIM LOCAL FLOW TABLES? (Y/N)'    )
      READ(0,1004)NURL
 1004 FORMAT(A1)
      IF(NURL.EQ.'Y'.OR.NURL.EQ.'y')THEN
      WRITE(0,929)

C --------------- READ FLOW DISTANCE TO EACH STATION (FT) -----------------

  929 FORMAT(1X,45H NUMBER OF FLOW STATIONS (UP TO 10) - ?            )
      READ(0,930)NUM
  930 FORMAT(I5)
      WRITE(0,960)
  960 FORMAT(5X,'LIST SURFACE DISTANCE TO EACH STATION (FT) USING FREE
     1FORMAT ')
      READ(0,*)(SDIST(I),I-1,NUM)
      NEWNUM-8 + NUM
      DO 12 I-9,NEWNUM
      WRITE(0,939)NFORMAT(I-8)
  939 FORMAT(1X,' FILE NAME FOR ',A7,' STATION - ?')
      IF(I.EQ.9)THEN
      READ(0,924)FILE9
      OPEN(I,FILE-FILE9)
      ELSEIF(I.EQ.10)THEN
      READ(0,924)FILE10
      OPEN(I,FILE-FILE10)
      ELSEIF(I.EQ.11)THEN
      READ(0,924)FILE11
      OPEN(I,FILE-FILE11)
      ELSEIF(I.EQ.12)THEN
      READ(0,924)FILE12
      OPEN(I,FILE-FILE12)
      ELSEIF(I.EQ.13)THEN
      READ(0,924)FILE13
      OPEN(I,FILE-FILE13)
      ELSEIF(I.EQ.14)THEN
      READ(0,924)FILE14
      OPEN(I,FILE-FILE14)
      ELSEIF(I.EQ.15)THEN
      READ(0,924)FILE15
      OPEN(I,FILE-FILE15)
      ELSEIF(I.EQ.16)THEN
      READ(0,924)FILE16
      OPEN(I,FILE-FILE16)
      ELSEIF(I.EQ.17)THEN
      READ(0,924)FILE17
      OPEN(I,FILE-FILE17)
      ELSEIF(I.EQ.18)THEN
      READ(0,924)FILE18
      OPEN(I,FILE-FILE18)
      ENDIF
   12 CONTINUE
      ENDIF

C ------------ READ WALL TEMPS  AT NPTS STATIONS ----------------

      IF (NPTS.EQ 0) GO TO 1000
      READ(5,915) (XLEN(I),I-1,NPTS)
      READ(5,915) (STA(I),I-1,NPTS)
```

```
C -------------- READ INPUT FLOW PARAMETERS ----------------------

      IF(ITY.EQ.1.OR.ITY.EQ.2) GO TO 549
      READ(5,915,END=999)TIME,ZO,VO,PTO,TTO
      GO TO 551
  549 READ(5,915,END=999)TIME,ZO,VO,PO,TO
  551 JSTEP=JSTEP+1
  910 FORMAT(A60)
  914 FORMAT(10I5)
  915 FORMAT(7F10.0)

C ------------ CALL AEROTHERMAL HEATING (AND PRESSURE DIST) SUBROUTINE

      CALL QDIST
      GO TO 1000

C ------------------ CONSTRUCT URLIM TABLES IN SEPARATE FILES --------

  999 IF(NURL.EQ.'Y'.OR.NURL.EQ.'y')THEN
      NFIL=9
      DO 11 J=1,NUM
      WRITE(NFIL,901)SDIST(J)
      WRITE(NFIL,902)

C ----------------- WRITE VALUES IN URLIM TABLES FOR M=0,1 ----- -----

      WRITE(NFIL,903)0.,1.,1.
      WRITE(NFIL,903)1.,1.,1.
  901 FORMAT(1X,'LOCAL FLOW TABLE FOR STATION AT S=',F10.2,1X,'FT')
  902 FORMAT(10X,'MO',13X,'M/MO',11X,'P/PO')

C -------------- WRITE URLIM FLOW TABLES FOR M > 1 -----------------

      WRITE(NFIL,903)(FREEM(I,J),EDGEMR(I,J),EDGEPR(I,J),I=1,JSTEP)
  903 FORMAT(1X,F12.4,2F14.4)
      NFIL=NFIL+1
   11 CONTINUE
      ENDIF
C     IF(IX.EQ.1) GO TO 900
      IF(IX.EQ.1) GO TO 998
      IX=IX-1
 998  END

C --------------- -- END MAIN PROGRAM ------------------------

C ---------- AEROTHERMAL HEATING (AND PRESS. DIST.) SUBROUTINE ----

      SUBROUTINE QDIST
C /*----------------------------------------------------------
C     THIS SUBROUTINE (QDIST) USES,
C      ATM    THE 1962 STANDARD ATMOSPHERE
C      AIRTBL MAIN DRIVER FOR AIR PROPERTIES
C      WRKHAT THE CURVE-FIT AIR PROPERTIES
C      PIF1   LINEAR INTERPOLATION
C ---------------------------------------------------------*/
      COMMON  NOUT,NP,XTAB(100),YTAB(100),DSO,TO,PO,PTO,TTO,ALF,TIME,
     1 HRT(50),RUC(50),STA(50),XLEN(50),NPTS,ZO,VO,STRAN,RN,DELC,
     2 RR,RG,LT,ISTEP,IX,SDIST(10),FREEM(20,10),EDGEMR(20,10),
     3 EDGEPR(20,10),NFIL,NUM,JSTEP,ITY,IAIR
      COMMON/ALPHAN/TITLE,HEAT,CONV,BUG,TYPE,QS,TRAN,TURB,GEO,LAM
      COMMON/LOGICAL/NURL
      CHARACTER*1 QS,NURL
```

```
      REAL*4 NUW,NUE,MDOT,ME2,MO2,MNORM,JUNK,JUNK1,JUNK2,JUNK4
      DIMENSION STAB(100)

C ---------------- INIATIALIZE VARIABLES AND CONSTANTS --------------

      HREF=8465.0
      PREF=2116.224
      TGJ=50062.744
      TDUM=1.
      GAM=1.40
      CPO=0.24
      RAD=57.2957795
      DTR=1.0/RAD
      SO=1.0E-5
      RHOO=1.0
      AO=1.0
      WO=1.0
      PW=1.0
      TSW=1.0
      HS=1.0
      SST=1.0
      RHOST=1.0
      AST=1.0
      WST=1.0
      MMARKER=0
      MARKER=0
      IFLAG=0
      DBL1=0.
      DBL2=0.
      DDD=0.
      DD1=0.
      DD2=0.
      VE1=0.
      VE2=0.
      TTS=1.0
      TE=1.0
      HW=1.0
      PR=0.72
      IFLAG1=0
      RHOS=1.0
      HE=1.0
      SW=1.0
      SS=1.0
      RHOE=1.0
      RHOW=1.0
      MUREF=1.15312E-5
      RHREF=0.0803707
      DIM=1.0
      I1=1
      I2=2
      I4=4
      I5=5
      PI=3.14159
      KK=0
      CONV = 'YES'
      LAM='YES'
      SMAX = 1.1*XLEN(NPTS)
      NN=0
      IX = 1
      DIM = 1.0
      RET=0.0
      DS = DSO
```

```
      FSXL=0.0
      SX=0.0
      FSTL=0.0
      ST=0.0
      RES=0.0
      SR=0.0
      SL=0.0
      KKK=0
      IF (TYPE.NE.'TEST') GO TO 260
C ------------- INPUT TOTAL FREE STREAM TEST CONDITIONS -----------
      SSO=0.
      IF(ITY.EQ.2)GO TO 261
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PTO,TTO,HTO,SSO,DU1,DU2,I4)
      ELSE
      CALL AIRTBL(PTO/144.,TTO,HTO,SSO,DU1,DU2,DU3,I4,N)
      ENDIF
      HO = HTO - VO**2/TGJ
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PO,TO,HO,SSO,RHOO,AO,I5)
      PO=PO/144.
      ELSE
      CALL AIRTBL(PO,TO,HO,SSO,RHOO,AO,DU3,I5,N)
      ENDIF
      AO=49.014*SQRT(TO)
      MO=VO/AO
      PO=PO*144.
      GO TO 262
C-------INPUT STATIC FREE STREAM TEST CONDITIONS-------------------------
  261 AO=49.014*SQRT(TO)
      GO TO 280
C-- - ---INPUT FLIGHT CONDITIONS---------------
  260 CALL ATM(ZO,PO,TO,DU1,AO,RHOO)
  280 MO=VO/AO
C ------- CALCULATE TOTAL ENTHALPY --------------
      HTO =  VO**2/TGJ + CPO*TO
C ---CALCULATE OTHER FREE STREAM STATIC AND TOTAL CONDITIONS-------------
      SSO=0.
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PO,TO,HO,SSO,RHOO,AO,I4)
      CALL PAIR(PTO,TTO,HTO,SSO,DU1,DU2,I5)
      ELSE
      CALL AIRTBL(PO/144.0,TO, HO, SSO,RHOO,AO,WO,I4 ,N)
      CALL AIRTBL(PTO,TTO,HTO,SSO,DU1,DU2,DU3,I5 ,N)
      PTO=PTO*144.0
      ENDIF
C ----------- CONDITIONS BEHIND SHOCK ----------------
  262 IF(IAIR.EQ.1)THEN
      CALL PGNS(MO,SSO,SS2,R2R1)
      ELSE
```

```
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PTS,TTS,HTO,SS2,RHOS,AS,I5)
      ELSE
      CALL AIRTBL(PTS,TTS,HTO,SS2,RHOS,AS,WS,I5,N)
      PTS = PTS*144.0
      ENDIF
      MO2 = MO*MO
C -------- STAG. PT. VELOCITY GRADIENT FOR SPHERE -----------------------
        BETA = (VO/2./RN)*(1.+1.56/(1.+MO2)**.79)
C ------------- COHEN CORRELATIONS AT STAG. PT.----------
        RHOMUE = (0.225*(PTS/PREF)**0.992)/
     &           (1.0-1.0213*(1.0-(HTO/HREF)**0.3329))
        TW=TTS
        SSW=0.
        IF(IAIR.EQ.1)THEN
        CALL PAIR(PTS,TW HW,SSW,RHOW,AW,I4)
        ELSE
        CALL AIRTBL(PTS/144.,TW,HW,SSW,RHOW,AW,WW,I4,N)
        ENDIF
        RHOMUW = (0.225*(PTS/PREF)**0.992)/
     &           (1.0-1.0213*(1.0-(HW/HREF)**0.3329))
        RHOMUE=RHOMUE*MUREF*RHREF
        RHOMUW=RHOMUW*MUREF*RHREF
        NUE=RHOMUE/RHOS**2.
        NUW=RHOMUW/RHOW**2.
C -------- STAG. PT. BOUNDARY LAYER THICKNESS -------------------
      DDELTAS = 6.* 0.763* (RHOMUE/RHOMUW)**0.4
     &          *(NUW/BETA)**0.5
C ------------- VON KARMAN GEOMETRY (WITH 35 DEG NOSE TIP)----
      IF(GEO.NE.'VK') GO TO 14
      DEL=DELC+ALF
      XT = RN*(1.0-SIN(DEL*DTR))
      XTC= RN*(1.0-SIN(DELC*DTR))
      YT = RN*(COS(DEL*DTR))
      YTC= RN*(COS(DELC*DTR))
      STN = RN*(90.0-DEL)/RAD
      SRTP=YT
      CALL SCONE(GAM,PC,MO,DEL,PO)
C ------------ BLOG GEOMETRY -------------------------*/
   14 IF (GEO.NE.'BLOG') GO TO 300
      DELTA=ACOS((RG-RR)/(RG-RN))
      DELTA=DELTA*RAD
      DEL=DELTA + ALF
      RRR=(RN-RG)*COS(DEL*DTR) + RG
      YT=RG*(RG-RRR)/(RG-RN)+RRR-RG
      YTC=RG*(RG-RR)/(RG-RN)+RR-RG
      XT=RN-SQRT(RN**2.-YT**2.)
      STN = 2.0*RN*ASIN(SQRT(XT**2.+YT**2.)/2./RN)
      TH1 = 90.0-(180.0*STN/RN/PI)
  300 IF(GEO.NE.'CONE') GO TO 320
```

```
C -------- BLUNTED CONE GEOMETRY ----------------------------------

      XT =RN*(1.0 - SIN(DEL*DTR))
      YT = RN * COS(DEL*DTR)
      YTC = RN * COS(DELC*DTR)
      XTC=RN*(1.0-SIN(DELC*DTR))
      STN=RN*(90.0-DEL)/RAD
      SRTP=YT

C------ STAGNATION POINT VELOCITY GRADIENTS FROM PERINI --------------

  320 SS=SS2
      IF(GEO.EQ.'SPHE'.OR.GEO.EQ.'CONE'.OR.GEO.EQ.'ENNK'.OR.
     1 GEO.EQ.'BLOG'.OR.GEO.EQ.'VK')
     2DUEDS=(VO/2./RN)*(1.1+1.56/(1.+MO2)**.79)

C ------------ CHECK FOR CONVERGENCE IN AIRTBL ---------------

      IF(N.LE.1) GO TO 330
      WRITE(6,920)
  920 FORMAT(22H NO CONV, GO TO NEXT      )
      CONV = 'NAY'
      RETURN

C ------------------ BEGIN MARCHING -----------------------------

 330  S= SO-DS
 100  SL = S
      S = S + DS
      IF(GEO.EQ.'VK'.AND.S.GE.(STN+0.04134))GO TO 1505
 1504 SEFF=SEFF + DS
      XF=0.0
      GO TO 1502

C ------------ GEOMETRY FOR VON KARMAN --------------------------

 1505 PHI1=ACOS(1.-(2.*X/LT))
      Y1=RR*SQRT((PHI1-(SIN(2.*PHI1))/2.)/PI)
      PHI2=ACOS(1.-(2.*(X+DX)/LT))
      Y2=RR*SQRT((PHI2-(SIN(2.*PHI2))/2.)/PI)
      DY=Y2-Y1

C--------- COORDINATE TRANSFORMATION FOR VK ANGLE OF ATTACK ----------

      XXX1=X-Y1*TAN(ALF*DTR)
      XXX2=(X+DX)-Y2*TAN(ALF*DTR)
      YYY1=(Y1/COS(ALF*DTR)) + XXX1*TAN(ALF*DTR)
      YYY2=(Y2/COS(ALF*DTR)) + XXX2*TAN(ALF*DTR)
      DYYY=YYY2-YYY1
      DXXX=XXX2-XXX1

C ------------- INCIDENCE ANGLE FOR VK AT ANGLE OF ATTACK -----------

      THL=TH
      TH=ATAN(DYYY/DXXX)*RAD
      S=S-DS
      DS=SQRT(DX**2+DY**2)
      RADIUS=Y1+DY
      S=S+DS
      X=X+DX
      Y=Y1+DY
```

```
 1502 IF(TST.GT.1080..AND.IAIR.NE.1) GAM=1.4493-4.535E-5*TST
      IF(TST.GT.3600..AND.IARI.NE.1) GAM=1.29

C ------------ CALCULATE LOCAL REYNOLDS NUMBERS ----------------------

      IF(KKK.EQ.0)GO TO 416
      RHOMUE = (0.225 * (PE/PREF)**0.992)/
     &          (1.C - 1.0213 * (1.0-(HE/HREF)**0.3329))
      RHOMUE=RHOMUE*MUREF*RHREF
      NUE=RHOMUE/RHOE**2.
      IF(KKK.EQ.0)NUE=NUW
  416 RES=VE*S/NUE
      RET=VE*DM/NUE
      IF(TRAN.EQ.'REYS'.AND.RES.LT.STRAN)GO TO 15
      IF(TRAN.EQ.'REYT'.AND.RET.LT.STRAN)GO TO 15
      LAM='NO'
      IF(MARKER.LE.2.OR.S.LE.STN.OR.KKK.EQ.0)LAM='YES'
      GO TO 19
   15 LAM='YES'

C ---------------------EMPERICAL PRESSURE DISTRIBUTIONS---------*/

C --------------- SPHERICAL PORTION OF VK NOSE ---------------

   19 IF(GEO.NE.'VK')GO TO 16
      IF(S.GE.STN)GO TO 341
      TH=(S/RN)*RAD
      X = RN*(1.-COS(TH*DTR))
      PE=PTS-(PTS-PO)*(SIN(TH*DTR)**2)
      Y = RN*SIN(TH*DTR)
      SR=Y
      TH=90.-TH
      GO TO 101

C --------------- CONE PORTION OF VK NOSE -------------

  341 IF(S.GE.(STN+.04134))GO TO 342
      X = XT +(S-STN)*COS(DEL*DTR)
      Y = YT +(S-STN)*SIN(DEL*DTR)
      SR = Y
      RADIUS = YTC + (S-STN)*SIN(DELC*DTR)
      TH = DEL
      CALL BCONE(PE,PC,DEL,RN,X,S,MO)
      GO TO 101

C -------------- VK PORTION OF VK CONTOUR -------------

  342 IF(TH.GE.0.3) GO TO 20
      WRITE(6,1501)
 1501 FORMAT( ' BODY SLOPE < 0.3 DEG - STOP CALCULATIONS')
      RETURN
   16 IF(GEO.NE.'CONE') GO TO 400

C ---BLUNTED CONE PRESSURES,(BLICK & FRANCIS,AIAA JR., V.4,#3)  */

      IF(S.GT.STN) GO TO 340
      TH =(S/RN)*RAD
      X  = RN*(1.0-COS(TH*DTR))
      PE   = PTS -(PTS-PO)*(SIN(TH*DTR)**2)
      Y = RN*SIN(TH*DTR)
      SR=Y
```

```
      RADIUS=YTC+(X-XTC)*TAN(DELC*DTR)
      SR=Y
      TH=DEL
      CALL BCONE(PE,PC,DEL,RN,X,S,MO)
      GO TO 101

C  ------------END OF CONE ------------------------------------
C------------BLOG SPHERICAL NOSE---------------------------

  400 IF(KK.EQ.1) GO TO 1013
      IF(S.GT.STN) GO TO 410
      TH=90.0-(180.0*S/RN/PI)
      X=RN*(1.0-SIN(TH*DTR))
      Y=RN*COS(TH*DTR)
      SR=Y
      PE=PTS-(PTS-PO)*SIN((90.0-TH)*DTR)**2
      CALL XMACH(GAM,ME,PE/PTS)
      THL = TH
      GO TO 101

C ---- NEED CONDITIONS EXACTLY AT TANGENCY POINT, SO IF WE ALREADY
C ----- STEPPED PAST IT WE RETURN TO TANG PT EXACTLY -------

  410 KK=1
      TH=90.0-(180.0*STN/RN/PI)
      X=RN*(1.0-SIN(TH*DTR))
      Y=RN*COS(TH*DTR)
      RADIUS=RN*COS(TH*DTR)
      SR=Y
      PE=PTS-(PTS-PO)*SIN((90.0-TH)*DTR)**2
      CALL XMACH(GAM,ME,PE/PTS)
      THL = TH
      GO TO 101

C------------OGIVE SURFACE-----------------------------

 1013 DELT=DS*180.0/PI/RG
      TH = THL-DELT
      IF(TH.GE.0.3) GO TO 420
      WRITE(6,919)
  919 FORMAT( '  BODY SLOPE < 0.3 DEG STOP CALCULATIONS')
      RETURN
  420 X = XT+2.0*RG*SIN((TH1-TH)*DTR/2.0)*COS((TH1+TH)*DTR/2.0)
      Y=YT+2.0*RG*SIN((TH1-TH)*DTR/2.0)*SIN((TH1+TH)*DTR/2.0)
      SR=Y
      THC=TH-ALF
      TH1C=TH1-ALF
      RADIUS=YTC+2.0*RG*SIN((TH1C-THC)*DTR/2.0)*SIN((TH1C+THC)*DTR/2.0)
   20 IF(TH.LE.3.0) GO TO 430

C --------- SHARP CONE PRESSURE ---------------------------

      CALL SCONE(GAM,PC,MO,TH,PO)
      XF=RN*(1.0-SIN(TH*DTR))+(Y-RN*COS(TH*DTR))/TAN(TH*DTR)
      IF(GEO.EQ.'VK')
     1XF=RN*(1.0-SIN(TH*DTR))+(YYY2-RN*COS(TH*DTR))/TAN(TH*DTR)

C --------- BLUNTED CONE PRESSURE FROM SHARP CONE PRESSURE ------

      CALL BCONE(PE,PC,TH,RN,XF,S,MO)
  430 CALL PRMY(GAM,PE,DELT,ME,PE)
  440 CALL XMACH(GAM,ME,PE/PTS)
```

```
 101  N=1

C ------------------------ WALL CONDITIONS --------------

      CALL PIF1(TW,S,XLEN,NPTS,STA)
      PW  = PE
      SSW=0.
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PW,TW,HW,SW,RHOW,AW,I4)
      ELSE
      CALL AIRTBL(PW/144.0,TW,HW,SSW,RHOW,AW,WW,I4  ,N)
      ENDIF

C -------------- CHECK FOR TURBULENCE ------------------------

      IF(LAM.EQ.'NO')GO TO 63

C   ---------------- B.L. EDGE CONDITIONS ------------

   60 IF(KKK.EQ.0) PE=PTS
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PE,TE,HE,SS,RHOE,AE,I1)
      ELSE
      CALL AIRTBL(PE/144.0,TE,HE,SS,RHOE,AE,WE,I1,N)
      ENDIF
      IF(KKK.EQ.0) HE=HTO
      VE=MAX(1.0,TGJ*(HTO-HE))
      VE=SQRT(VE)
      AE=49.014*SQRT(TE)
      ME=VE/AE
      IF(IFLAG.GE.1) GO TO 56
      ME2 = ME * ME
      IF(S.LT.STN) GO TO 99
      IF(MARKER.GE.1) GO TO 51

C  -- CALCULATE EFFECTIVE SHARP CONE FLOW DISTANCE AT TANGENCY PT ----
C  ----------- SHARP CONE DISTANCE TO TANGENCY PT ---------

        S1 = YT/SIN(TH*DTR)

C  ------- COHEN CORRELATION ----------------------------

        RHOMUW=(0.225*(PE/PREF)**0.992)/
     &           (1.0-1.0213*(1.0-(HW/HREF)**0.3329))
        RHOMUW=RHOMUW*MUREF*RHREF
        NUW=RHOMUW/RHOW**2.

C -------- PSEUDO REYNOLDS NO. ---------------------------

        SQRE = SQRT(VE*S1/NUW)

C ------ BL THICKNESS AT TANG. PT - SHARP CONE, LAMINAR - N. NESS----

        DDS = (TE*S1/1.732/SQRE/TW)*(3.0*TW/TE + 2.01*
     &          (1.+(GAM-1.)*ME2/2.-TW/TE) - 1.62*(GAM-1.)*ME2/2.)

C ------ ADJUST FLOW DISTANCE FOR BLUNTNESS EFFECT -------------

        FF= 1.
        DBL = DDELTAS + FF * DDS
        VENUW=SQRT(VE/NUW)
      SEFF = (1.732*VENUW*TW*DBL/TE)/(3.0*TW/TE + 2.01*
```

```
C ------- CALC BL MASS FLOW FOR LAMINAR CASE (LBM/S) --------

   51   MARKER = MARKER + 1
        RHOMUW=(0.225*(PE/PREF)**0.992)/
     $          (1.0-1.0213*(1.0-(HW/HREF)**0.3329))
        RHOMUW=RHOMUW*MUREF*RHREF
        NUW=RHOMUW/RHOW**2.
   56   ME2 = ME * ME

C ------------- B.L. MASS FLOW RATE ----------------------

        SQRE=SQRT(VE*SEFF/NUW)
      MDOT = 2.*PI*RADIUS*VE*RHOE*SEFF*TE/1.732/SQRE/
     &          TW * (2.007*TW/TE + 2.01*(1.+(GAM-1.)*ME2/2.-TW/TE)
     &          -2.003 * (GAM-1.)*ME2/2.)

C --------- RADIUS OF FREE STREAM TO MATCH MDOT -----------

   57 YS = SQRT(MDOT/PI/RHOO/VO)

C ---------- SHARP CONE ATTACHED SHOCK ANGLE --------------

      ETA = SQRT(1./MO**2.+(GAM+1.)*(SIN(TH*DTR))**2./2.)
      ETA = ASIN(ETA)*RAD

C ----------- BOW SHOCK ANGLE (GAMMA) - BILLIG -----------

      RM1 = 0.54/(MO-1.)**1.2
      RC = 1.143*RN*EXP(RM1)
      TANGAM = RC/YS * SQRT(1.+(YS*YS*(TAN(ETA*DTR)**2.)/RC**2.))
      GAMMA=RAD*ATAN(TANGAM)

C -----------PASS THRU BOW SHOCK -----------------------

      VNORM = VO*SIN(GAMMA*DTR)
      VTAN = VO*COS(GAMMA*DTR)
      MNORM=VNORM/AO
      IF(IAIR.EQ.1)THEN
      CALL PGNS(MNORM,SSO,SS2,R2R1)
      ELSE
      CALL SHOCK(MNORM,VNORM,VTAN,RHOO,PO/144.,HO,V2,SS2,R2R1,P2)
      ENDIF

C ------ CHECK FOR TURBULENCE  -------------

      IF(LAM.EQ.'YES') GO TO 64
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PE,TE,HE,SS2,RHOE,AE,I1)
      ELSE
      CALL AIRTBL(PE/144 ,TE,HE,SS2,RHOE,AE,WE,I1,N)
      ENDIF
      VE=SQRT(TGJ*(HTO-HE))
      DVE=VE-VE2
      AE=49.014*SQRT(TE)
      ME=VE/AE

C ---------- COMPARE ENTROPY DOWNSTREAM OF SHOCK W/PREVIOUS BL ENTROPY -----

   64 IF(ABS(SS-SS2).GT.0.001)THEN
      IFLAG=IFLAG+1
      IF(IFLAG.LE 10)GO TO 49
      IFLAG1=IFLAG1+1
```

```
      WRITE(6,600)S
      GO TO 150
  600 FORMAT(//,'STREAMLINE SWALLOWING FAILED',F5.4,'FT FROM
     & NOSE DUE TO AN ENTROPY DISCONTINUITY')

C ----------- SET ENTROPY PREVIOUS VALUE EQUAL TO CURRENT VALUE ----

   49 SS=SS2
      IF(LAM.EQ.'NO')GO TO 74
      GO TO 60
      ELSE
   48 SS=SS2
      VE1=VE2
      VE2=VE
      IFLAG=0
      IFLAG1=0
      IF(LAM.EQ.'NO')GO TO 99

C ------------ LAMINAR BL THICKNESS - N. NESS -----------

      DBL=(SEFF*TE/1.732/SQRE/TW)*(3.0*TW/TE + 2.01*(1.+(GAM-1.)
     &      *ME2/2.-TW/TE)-1.62*(GAM-1.)*ME2/2.)
      DBL1=DBL2
      DBL2=DBL
      DDD=(SEFF*TE/1.732/SQRE/TW)*(0.993*TW/TE+0.383*(GAM-1.)*ME2/2.)
      DD1=DD2
      DD2=DDD
      DM=0.383*SEFF*TE/1.732/SQRE/TW
      GO TO 99
      ENDIF

C ---------- TURBULENT STREAMLINE SWALLOWING ------------

   63 MARKER=MARKER+1
      IF(MMARKER.EQ.1) GO TO 61
      MMARKER=1

C --------------CALC INITIAL CONDITIONS -----------------
C ----------INITIAL MASS FLOW THICKNESS FROM LAMINAR MDOT --------------

         BIGD = MDOT/2./PI/RADIUS/RHOE/VE

C -------------- DISPLACEMENT THICKNESS -------------------------

         DD = DBL-BIGD

C ----------- MOM THICKNESS ----------------------------------------

         DM = RET*MUE/RHOE/VE

C -------------INITIAL ENTRAINMENT RATE ----------------------------

         F = ((DBL-DBL1)-(DDD-DD1))/DS

C --------------INITIAL VELOCITY CHANGE ----------------

         DVE = VE-VE1

C ----------------INITIAL SHAPE PARAMETER -----------------

         H = DD/DM
```

```
C --------------STEP ENTRAINMENT EQ ---------------------

   61 DBIGD = F*DS + (ME2-1.)*BIGD*DVE/VE

C --------------STEP MOMENTUM INTEGRAL EQ ----------------

      DDM = CF*DS/2. - (H+2.-ME2) * DM *DVE/VE

C -------------- NEW MASS FLOW THICKNESS -------------

      BIGD = BIGD + DBIGD/2.25**.2

C ---------------NEW MOMENTUM THICKNESS ---------------

      DM = DM + DDM/2.25**.2

C ---------------- MODIFIED COMPRESSIBLE SHAPE PARAMETER ------------

      H1 = BIGD/DM

C -------TRANSFORMED COMPRESSIBLE SHAPE PARAMETER ---------

      HBAR = 1. + (0.9/(H1-3.3))**0.75

C --------------- KINEMATIC (INCOMP) SHAPE PARAMETER --------

        TERM1 = (HBAR+1.)*(HBAR-1.)**2.
        TERM2 = TERM1/HBAR/(3.*HBAR-1.)/(2.*HBAR-1.)
        TERM3 = R*ME2*TERM2/5.
        TERM4 = HBAR*(HBAR+1.)
        TERM5 = TERM4/(3.*HBAR-1.)/(2.*HBAR-1.)
        TERM6 = 1.-TERM5
        TERM7 = R * ME2 * TERM6/5.
        TERM8 = 1. + TERM7
        TERM9 = TERM3/TERM8
      HK = HBAR * (1.+TERM9)

C -----------------KINEMATIC MODIFIED SHAPE PARAMETER ------

      H1K = 3.4 + 1.87/(HK-0.5)**3.8

C -----------------NEW ENTRAINMENT RATE -----------------

      F = 0.0306 * (H1K-3.0)**(-.653)

C -- -------------- NEW SHAPE PARAMETER ---------------

  74    HR = HE + R*VE**2/TGJ
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PW,TR,HR,JUNK,JUNK1,JUNK2,I2)
      ELSE
      CALL AIRTBL(PW/144.,TR,HR,JUNK,JUNK1,JUNK2,JUNK4,I2,N)
      ENDIF
      H=(TW/TE)*HBAR+TR/TE-1.

C ------------------ NEW DISP. THICKNESS --------------------

      DD=H*DM

C ------------------ NEW BL THICKNESS ------------------

      DBL=H1*DM+DD
```

```
C ------------------ INCOMPRESSIBLE TRANSFORMED REYNOLDS NO --------

      RETINC = (MUE/MST) * RET

C ------------------- NEW SKIN FRICTION FROM INCOMP CORRELATION -----

      CFINC = 0.246*EXP(-1.56*HBAR)*RETINC**(-0.268)
      CF = (TE/TST) * CFINC

C -------------------- MASS FLOW RATE -------------------

      MDOT = 2.*PI*RADIUS*VE*RHOE*BIGD
      GO TO 57

C----------------REC FACTOR----------------------------

   99 R = SQRT(PR)
      IF (LAM.NE.'YES') R=PR**(1.0/3.0)

C -------------- REC ENTH --------------------------------

      HR = HE + R*VE**2/TGJ

C---------ECKERT'S REFERENCE ENTHALPY-----------------------

      HS = HE + 0.5*(HW-HE) + 0.22*(HR-HE)

C----------------- REFERENCE CONDITIONS  ---------------------

      SST=0.
      IF(IAIR.EQ.1)THEN
      CALL PAIR(PW,TST,HS,SST,RHOST,AST,I2)
      ELSE
      CALL AIRTBL(PW/144.0,TST,HS,SST,RHOST,AST,WST,I2 ,N)
      ENDIF

C------------------ COHEN CORRELATIONS--------------------

      RMER =(0.225*(PE/PREF)**0.992)/
     1  (1.0 - 1.0213*(1.0 - ((HE+  0.0)/HREF)**0.3329))
      RMSR =(0.225*(PE/PREF)**0.992)/
     1  (1.0 - 1.0213*(1.0 - ((HS+  0.0)/HREF)**0.3329))
      RMS = RMSR*MUREF*RHREF
      RME = RMER*MUREF*RHREF
      MST = RMS/RHOST
      MUE = RME/RHOE
      IF(LAM.EQ.'NO')GO TO 12
      IF(KKK.NE.0) GO TO 520
      RMES = RME
      RMSS = RMS

C ------------- STAG. PT. VELOCITY GRADIENT -------------

      DUEDSS=(VO/2./RN)*(1.1+1.56/(1.+MO2)**.79)
      RMWR =(0.225*(PE/PREF)**0.992)/
     1  (1.0 - 1.0213*(1.0 - ((HW+  0.0)/HREF)**0.3329))
      RMWS = RMWR*MUREF*RHREF

C------------------LEES STAG PT COLD WALL (540 R) Q-----------------------------

      QSTAGL=0.88*SQRT(RMSS*DUEDSS)*(HTO-128.7)
```

```
       STAGD=17600.0*SQRT(RHOO/0.07647)*(VO/26000.0)**3.15/SQRT(RN)
     1        *((HTO-128.7)/HTO)
      QSTAGD=QSTAGD*(2.0**((DIM-1.0)/2.0)) *SQRT(DUEDS/DUEDSS)

C---------------- FAY,RIDDELL STAG PT COLD WALL Q -------------------- ---

      QSTAGF=0.94*(RMWS**0.1)*(RMES**0.4)*SQRT(DUEDSS)*(HTO-128.7)
      QSTAGF=QSTAGF*(2.0**((DIM-1.0)/2.0))*SQRT(DUEDS/DUEDSS)

C --------------- STAG. PT. HEAT TRANSFER COEFF. ---------------

      RUCH1 = QSTAGL/(HTO-128.7)
      RUCHL=RUCH1
      HRL= HR
      MRL=0.0
      PEL=PE
      GO TO 102
  520 RES = RHOE*VE*S/MUE
C     FSX1=RHOE*VE*(MUE**0.25)*(SR**(1.25*DIM))
C     SX1 = SX1+(FSX1+FSX1L)*DS/2.0
C     FSX1L=FSX1
      FSX = RMS*VE*(SR**(2.0*DIM))
      SX = SX+(FSX+FSXL)*DS/2.0
      FSXL=FSX
C     FST=FSX*RME/RMS
C     ST = ST+(FST+FSTL)*DS/2.0
C     FSTL=FST

C----------------------LAMINAR FLOW-----------------------
C-----------LEES EQUATION FOR HT. TRANSFER COEFF.-----------

      RUCH1=QSTAGL*RMS*VE*SR**DIM/SQRT(RMSS*DUEDS *2.0*SX)/
     1 (2.0**(DIM/2.0) )/(HTO-128.7)
      GO TO 102

C -----------------TURBULENT FLOW--------------------------
C------ SHARP CONE HT. XFER COEFF. NASA TECH PAPER 2345 JAN. 1985 --

   12 RUCH1 = 0.0296*2.25**.2*RHOST*VE/PR**0.667
     1 /(RHOST*VE*S/MST)**0.20

C ------ COLD (ISOTHERMAL) WALL AND PSEUDO-HOT WALL HT. XFER -------

  102 QHW=RUCH1*(HR-HW)
      QCW=RUCH1*(HR-128.7)

C-----------------PRINTOUTS----------------------------------

      IF(KKK.NE.0) GO TO 540
      WRITE(6,900)TITLE
      WRITE(0,900)TITLE
  900 FORMAT(1X,A62/)
      IF( GEO.EQ.'BLOG')WRITE(6,901)
  901 FORMAT(3X,'BLUNTED OGIVE,AXISY-FLOW'              )
      IF( GEO.EQ.'CONE')WRITE(6,904)
  904 FORMAT(3X,'AXISYMMETRIC FLOW(CONE)'               )
      IF( GEO.EQ.'VK')WRITE(6,1506)
 1506 FORMAT(3X,'VON KARMAN,AXISYM-FLOW'                )
      WRITE(6,909)
  909 FORMAT(3X,'LEES STAG POINT Q'                     )
      WRITE(6,912)
  912 FORMAT(3X,'TURB Q VIA MOM. INTEGRAL EQ. USING 1/7TH POWER FOR VEL.
```

```
C     HOX-HO-128.7

C ----------- WRITE TO OUTPUT FILE AND SCREEN ---------------- -

      WRITE(6,1014)
      WRITE(6,913)TIME,ALF,DELC,RN,RR,RG,XT,YT
      WRITE(0,913)TIME,ALF,DELC,RN,RR,RG,XT,YT
      IF(TYPE.EQ.'TEST')GO TO 817
      WRITE(6,1009)ZO,VO,MO,SSO,TTO,TO,PTO/2116.224,PO/2116.224,HTO,HO,
     &TW
      WRITE(0,1009)ZO,VO,MO,SSO,TTO,TO,PTO/2116.224,PO/2116.224,HTO,HO,
     &TW
      GO TO 818
  817 WRITE(6,1010)MO,VO,TTO,TO,PTO/2116.224,PO/2116.224,HTO,HO,TW,SSO
      WRITE(0,1010)MO,VO,TTO,TO,PTO/2116.224,PO/2116.224,HTO,HO,TW,SSO
  818 WRITE(6,1034)PTS/2116.224,SS2,TTS,R2R1,P2/2116.224
      WRITE(0,1034)PTS/2116.224,SS2,TTS,R2R1,P2/2116.224
 1014 FORMAT(1X,'ENTHALPY = 0 AT 0 DEG R'/
     1 1X,'COLD WALL Q BASED ON WALL TEMP OF 540 DEG R'/
     2 1X,'HOT WALL Q BASED ON SUPPLIED WALL TEMP'//)
  913 FORMAT(
     3 1X,'TIME (SEC)       ',F12.4/
     4 1X,'RADOME GEOMETRY:'/
     5 1X,'       ANGLE OF ATTACK = ',F10.3/
     6 1X,'       CONE ANGLE (DEG) = ',F10.3/
     7 1X,'       NOSE RADIUS (FT) = ',F12.4/
     8 1X,'       BASE RADIUS AT TANG. PT. (FT) = ',F12.4/
     9 1X,'       OGIVE RADIUS (FT) = ',F12.4/
     1 1X,'       COORDINATES OF NOSE/BODY TANG. PT. (FT) ARE X =',F5.5/
     2 1X,'                                                   Y =',F5.5/)
 1009 FORMAT(
     1 1X,'FREE STREAM FLIGHT CONDITIONS:'/
     2 4X,' ALTITUDE (FT)       ',F12.4,2X,'VELOCITY (FT/S)        ',F12.4/
     3 4X,' MACH NO.            ',F12.4,2X,'ENTROPY (BTU/LBM-R)    ',F12.5/
     4 4X,' TOT. TEMP (R)       ',F12.4,2X,'STATIC TEMP (R)        ',F12.4/
     5 4X,' TOT. PRESS (ATM)    ',F12.4,2X,'STATIC PRESS (ATM)     ',F12.4/
     6 4X,' TOT. ENTH (BTU/LBM)',F12.4,2X,'STATIC ENTH (BTU/LBM)',F12.4/
     7 4X,' WALL TEMP (R)       ',F12.4/)
 1010 FORMAT(
     1 1X,'FREE STREAM TUNNEL CONDITIONS:'/
     2 4X,' MACH NO.            ',F12.4,2X,'VELOCITY (FT/S)        ',F12.4/
     3 4X,' TOT. TEMP (R)       ',F12.4,2X,'STATIC TEMP (R)        ',F12.4/
     4 4X,' TOT. PRESS (ATM)    ',F12.4,2X,'STATIC PRESS (ATM)     ',F12.4/
     5 4X,' TOT. ENTH(BTU/LBM)  ',F12.4,2X,'STATIC ENTH (BTU/LBM)',F12.4/
     6 4X,' WALL TEMP (R)       ',F12.4,2X,'ENTROPY (BTU/LBM-R)    ',F12.5/
     7 )
 1034 FORMAT(
     1 1X,'STAGNATION POINT CONDITIONS:'/
     2 4X,' TOT. PRESS (ATM)    ',F12.4,2X,'ENTROPY (BTU/LBM-R)    ',F12.5/
     4 4X,' TOT. TEMP (R)       ',F12.4/
     4 4X,' DENSITY RATIO ACROSS NORMAL SHOCK (RHO2/RHO1)',8X,' ',F12.4/
     5 4X,' STATIC PRESS BEHIND NORMAL SHOCK (ATM)',8X,'        ',F12.4/
     6)
      WRITE(6,611)
      WRITE(0,611)
      WRITE(6,914)QSTAGL,QSTAGF,QSTAGD
      WRITE(0,914)QSTAGL,QSTAGF,QSTAGD
      WRITE(0,926)
  611 FORMAT(2X,'COLD WALL QSTAG FOR    LEES    FAY-RIDDELL     DETRA-'
     1,'KEMP-RIDDELL(BTU/FT2-S)')
  914 FORMAT(21X,F8.2,4X,F8.2,10X,F8.2/)
```

```
      FREEM(JSTEP,ISTEP) = MO
      EDGEMR(JSTEP,ISTEP) = ME/MO
      EDGEPR(JSTEP,ISTEP) = PE/PO
      ISTEP = ISTEP + 1
      ENDIF

C ---- PRINT COLUMN HEADING IN OUTPUT FILE EVERY 40TH WRITE STEP-

  724 IF(KKK.EQ.0.OR.MOD(KKK,NOUT*40).EQ.0)GO TO 560
      GO TO 570
  560 IF(KKK.NE.0 ) WRITE(6,918)
  918 FORMAT(1H1)
      WRITE(6,915)
  915 FORMAT( 54H  S/RN    X/RN  Y/RN  RAD/RN  TH   PE/PO    ME/MO   VE ,
     1        48H  SS     HE/HTO   RES    RET      DBL      RUCH ,
     2        31H   HR     QCW     QHW     LAM )
  926 FORMAT( 45H  S/RN          PE/PO   ME  TE/TTS    RUCH  HR  ,
     1        17H   QCW/QS  LAM  )

  ----------- WRITE TO OUTPUT FILE WHEN REMAINDER(NOUT/KKK) = 0 ------

  570 IF(MOD(KKK,NOUT).EQ.0.OR.KKK.EQ.0) GO TO 580
      GO TO 590
C 580 HEX=HE-128.7
C     HRX=HR-128.7
  580 CP=64.4*(PE-PO)/(RHOO*VO**2.)
      ST=QHW/RHOE/VE/(HR-HW)
      IF(GEO.EQ.'VK'.AND.S.GE.(STN+.04134))THEN
      WRITE(6,916)
     1S/RN,XXX2/RN,YYY2/RN,RADIUS/RN,TH,PE/PO,ME/MO,VE,SS,HE/HTO,
     2RES,RET,DBL,RUCH1,HR,QCW,QHW,ST,LAM
      ELSE
      WRITE(6,916)
     1S/RN,X/RN,Y/RN,RADIUS/RN,TH,PE/PO,ME/MO,VE,SS,HE/HTO,
     2RES,RET,DBL,RUCH1,HR,QCW,QHW,ST,LAM
      ENDIF
  916 FORMAT(1X,2F7.2,2F6.2,F6.1,2F7.3,F7.0,F7.4,F7.3,2(1PE9.2),E10.3,
     1      0PF8.5,F8.1,2F9.3,E12.4,2X,A3)

C ----TURBULENT DEBUG WRITE ------------------------------

C     WRITE(6,955)
C 955 FORMAT( 52H S/RN    PE/PO    VE      BIGD          HBAR         MDOT,
C    1        49H         DM          DBL          F              H     ,
C    2        12H         H1   )
C     WRITE(6,956)
C    1S/RN,PE/PO,VE,BIGD,HBAR,MDOT,DM,DBL,F,H,H1
C 956 FORMAT(1X,2F6.2,F7.0,8E12.3)

C----FOR PLOT FILE--------------------------------------

      IF(GEO.EQ.'VK'.AND.S.GE.(STN+.04134))THEN
      WRITE(8,916)
     1S/RN,XXX2/RN,YYY2/RN,RADIUS/RN,TH,PE/PO,ME/MO,VE,SS,HE/HTO,
     2RES,RET,DBL,RUCH1,HR,QCW,QHW,ST,LAM
      ELSE
      WRITE(8,916)
     1S/RN,X/RN,Y/RN,RADIUS/RN,TH,PE/PO,ME/MO,VE,SS,HE/HTO,
     2RES,RET,DBL,RUCH1,HR,QCW,QHW,ST,LAM
      ENDIF

C ------------- FOR PRINT TO SCREEN --------------------
```

```
C--------------------INTERPOLATION FOR RUCH & HR--------------

  550 IF(MOD(KKK,NOUT).EQ.0)GO TO 551
C     HEX=HE-128.7
C     HRX=HR-128.7
  551 C = (XLEN(IX)-SL)/(S-SL)
      PEX=PEL+C*(PE-PEL)
      RUC(IX) = RUCHL +C*(RUCH1-RUCHL)
      HRT(IX) = HRL + C*(HR-HRL)
      MRX=MRL+C*(ME-MRL)

C ----------- WRITE TO SCREEN ------------------------

      WRITE(0,930)
     1S/RN,PE/PO,ME,TE/TTS,RUCH1,HR,QCW/QSTAGL,LAM
  930 FORMAT(1X,F8.2,F9.2,F7.2,F6.2,F9.5,F7.1,F6.2,4X,A3)

C ----------- STEP STATION FOR WALL TEMP ------------------------

      IX = IX+1
 105  KKK = KKK+1
      RUCHL = RUCH1
      PEL=PE
      HRL = HR
      MRL=ME
      IF(S + DS.LT.SMAX)GO TO 100
      DS = SMAX-S
      IF(DS.GT.0.0) GO TO 100
      LAM = 'YES'
  150 RETURN
      END

      SUBROUTINE SCONE(GAM,PC,MI,DEL,PO)
      REAL*4 MI2,MI4,MI6,MI
      DTR=1.0/57.3
C     GAM = 1.4
      MI2 = MI*MI
C /* SHARP CONE PRESSURE (SIMON & WALTER , AIAA JR., V.1,#7 )  */
      SD2 =  SIN(DEL*DTR)**2
      MI4 = MI2*MI2
      MI6 = MI4*MI2
      GP7 = GAM+7.0
      F1  = GP7/4.0 - (GAM-1.0)**2/16.0 + 6.0/MI6 +
     1 (MI2-1.0)/MI4/SIN(DEL*DTR)
      CPC=F1*SD2
      PCO = 1.0 + GAM*MI2*CPC/2.0
      PC = PCO*PO
      RETURN
      END
      SUBROUTINE BCONE(PE,PC,DEL,RN,X,S,MO)
C /* BLUNTED CONE PRESSURES,(BLICK & FRANCIS,AIAA JR., V.4,#3)  */
      REAL*4 MO,NX
      PI=3.14
      SP   = X*(DEL*PI/180.0)**2/RN
      IF (SP.GT.0.106)GO TO 40
      NX= -0.303*( LOG(SP) + 2.24)
      PE   =(0.929*(MO/2.8)**NX)*PC
      GO TO 100
   40 CONTINUE
      IF(SP.LE.0.106) GO TO 90
      IF(SP.GE.1.06) GO TO 90
      NX=-0.116*SQRT(MO-2.8)*SIN( (LOG(SP)+2.24)/0.731)
      PE = PC*(SP**0.032)*EXP(NX)
      GO TO 100
  90  PE = PC
 100  RETURN
      END
```

```
      SUBRCUTINE PRMY(GAM,PE,DTX,M,P)
C  /* PRANDTL MEYER TURNING P-F(DTHETA),NACA1135,EQ(174)
C      FOR SMALL TURNING ANGLES    */
      REAL*4 M,M2,M4,M6,M2M1
C     GAM-1.4
      M2-M*M
      M4-M2*M2
      M6-M2*M4
      GP1-GAM+1.0
      M2M1-M2-1.0
      DT-DTX*3.14/180
      PR-1.0-GAM*M2*DT, SQRT(M2M1)
     1     +GAM*M2*(GP1*M4-4.0*M2M1)*DT*DT/(4.0*M2M1**2)
     2     -(GAM*M2*DT**3/2.0/M2M1**3.5)*
     3     (GP1*M4**2/6.0-(5.0+7.0*GAM-2.0*GAM**2)*M6/6.0
     4      +5.0*GP1*M4/3.0-2.0*M2+4.0/3.0)
      PE-PR*P
      RETURN
      END
      SUBROUTINE XMACH(GAM,M,PPT)
C   /*  MACH FUNCTION, M-F(P/PTOTAL) NACA1135, EQ(44)  */
      REAL*4 M
C     GAM-1.4
      GM1-GAM-1.0
      M-SQRT((PPT**(-GM1/GAM)-1.0)*2.0/GM1)
      RETURN

      DO 100,I - 2,N
      IF(X.LE.XLIST(I)) GO TO 200
  100 CONTINUE
      I - N
  200 F-FLIST(I-1)+(X-XLIST(I-1))*(FLIST(I)-FLIST(I-1))/
     1 (XLIST(I)-XLIST(I-1))
      RETURN
      END
      SUBROUTINE PGNS(M1,SS1,SS2,RHOR1)
C ---- PERFECT GAS - NORMAL SHOCK SUBROUTINE
      REAL*4 M1,M12
      M12-M1*M1
      P2OP1- 1. + 2.8/2.4 * (M12 - 1.)
      R2OR1 - 2.4 * M12 /(2.+.4*M12)
      T2OT1-P2OP1/R2OR1
      CP-.24
      R-.068554
      SS2-SS1+CP*ALOG(T2OT1)-R*ALOG(P2OP1)
      RETURN
      END
      SUBROUTINE PAIR(P,T,H,SS,RHO,A,I)
C ------- PERFECT GAS AIR RELATIONS -----------
      PREF-2116.224
      TREF-537.
      SREF-0.59945
      CP-.24
      R1-53.34
      R2-.068554
      GOTO(10,20,40,40,50)I
   10 T-TREF*EXP((SS-SREF+R2*ALOG(P/PREF))/CP)
      H-CP*T
      GO TO 60
   20 T-H/CP
      SS-CP*ALOG(T/TREF)-R2*ALOG(P/PREF)+SREF
      GO TO 60
   40 SS-SREF+CP*ALOG(T/TREF)-R2*ALOG(P/PREF)
      H-CP*T
      GO TO 60
   50 T-H/CP
      P-PREF*EXP((CP*ALOG(T/TREF)-SS+SREF)/R2)
```

```
 60 RHO=P/R1/T
    A=4C.014*SQRT(T)
    RETURN
    END


C ----- REAL GAS SUBROUTINE TO PASS THROUGH A NORMAL OR OBLIQUE
C ----- SHOCK GIVEN PROPERTIES ON UPSTREAM SIDE
    SUBROUTINE SHOCK(MNORM,VNORM,VTAN,RHO1,P1,H1,V2,SS2,R2R1,P2P)
    REAL MNORM,VNORM,VTAN,RHO1,P1,H1
    R2R1=6.*MNORM**2./(MNORM**2.+5.)
    R2=R2R1*RHO1
    ERR=100.
    DO 1C i=1,50
    P2=P1+RHO1*VNORM**2.*(1.-1./R2R1)*2.1584E-4
    H2=H1+VNORM**2./2.*(1.-1./R2R1**2.)/25051.6
    PP=P2
    HP=H2
    N=0
    SS2=0.
    I2=2
    CALL AIRTBL(PP,T2,HP,SS2,RHOP,A2,W2,I2,N)
    RHO2=RHOP
    ERR=ABS((RHO2-R2)/RHO2)
    IF(ERR.LT.1.0E-4) GO TO 11
    R2=RHO2
    R2R1=RHO2/RHO1
 10 CONTINUE
 11 CONTINUE
    V2N=VNORM/R2R1
    V2=SQRT(V2N**2.+VTAN**2.)
    P2P=P2*144.
    RETURN
    END


    SUBROUTINE SNUGS(PC,TR,I)
    DIMENSION PC(3),TR(3),A(2)
    PC(3)= PC(1) + (1.0-TR(1))*(PC(2)-PC(1))/(TR(2)-TR(1))
    A(1) = ABS(TR(1)-1.0)
    A(2) = ABS(TR(2)-1.0)
    TMAX = MAX  (A(1),A(2))
    DO 100 I = 1,2
    IF (TMAX.EQ.A(I))GO TO 9
100 CONTINUE
  9 PC(I) = PC(3)
    RETURN
    END
```

APPENDIX B

ABBOHT VARIABLE DEFINITIONS

AE	speed of sound at BL edge (ft/s)
ALF	angle of attack (deg)
ALT	altitude (ft)
AO	free-stream speed of sound (ft/s)
AS	speed of sound at stagnation point (ft/s)
AST	speed of sound at Eckert's reference enthalpy (ft/s)
AW	speed of sound at wall (ft/s)
BETA	velocity gradient (ft/s-ft)
BIGD	mass flow thickness (ft)
CF	compressible skin friction coefficient
CFINC	incompressible skin friction coefficient
CONV	convergence identifier
CP	pressure coefficient
CPO	specific heat of air at constant pressure (Btu/lbm-°F)
DBIGD	mass flow thickness change (ft)
DBL	BL thickness (ft)
DBL1,2	stored values of BL thickness (ft)
DD	displacement thickness (ft)
DD1,2	stored values of BL displacement thickness (ft)
DDD	BL displacement thickness (ft)
DDELTAS	stagnation point BL thickness (ft)
DDM	momentum thickness change (ft)
DDS	BL thickness at nose/body tangency point (ft)
DEL	incident angle at nose/body tangency point (deg)
DELC	cone half angle (deg)
DELT	change in incidence angle (deg)
DELTA	body angle at nose/body tangency point (deg)
DIM	geometry identifier
DM	momentum thickness (ft)
DS	surface distance step (ft)
DTR	degrees to radian factor (0.01745)
DU1	free-stream stagnation density (lbm/ft^3)
DU2	dummy variable
DU3	dummy variable
DUEDS	velocity gradient (ft/s-ft)
DUEDSS	velocity gradient at stagnation point (ft/s-ft)
DVE	velocity change (ft/s)
DXXX	change in *x* coordinate of body surface for von Karman radome shape at angle of attack (ft)
DYYY	change in *y* coordinate of body surface for von Karman radome shape at angle of attack (ft)
EDGEMR	BL edge Mach no./free-stream Mach no.
EDGEPR	BL edge pressure/free-stream pressure
ETA	sharp cone-attached shock angle (deg)
F	entrainment rate (ft/s-ft)
FF	scale factor (currently 1.0)
FREEM	free-stream Mach no.

FSX	RMS*VE*Y^2
GAM	ratio of specific heats
GAMMA	bow shock angle (deg)
GEO	geometry identifier
H	compressible conventional shape parameter (DD/DM)
H1	compressible modified shape parameter (BIGD/DM)
H1K	incompressible modified shape parameter
HBAR	transformed shape parameter
HE	BL edge enthalpy based on 0°R (Btu/lbm)
HEX	BL edge enthalpy based on 540°R (Btu/lbm)
HK	incompressible conventional shape parameter
HO	free-stream static enthalpy based on 0°R (Btu/lbm)
HR	recovery enthalpy based on 0°R (Btu/lbm)
HREF	reference enthalpy for Cohen correlation (8465 Btu/lbm)
HRL	last (previous) recovery enthalpy based on 0°R (Btu/lbm)
HRT	recovery enthalpy based on 0°R (Btu/lbm)
HRX	recovery enthalpy based on 540°R (Btu/lbm)
HS	Eckert's reference enthalpy based on 0°R (Btu/lbm)
HTO	total enthalpy based on 0°R (Btu/lbm)
HTX	total enthalpy based on 540°R (Btu/lbm)
HW	wall enthalpy based on 0°R (Btu/lbm)
I	dummy indexing variable
I1-I5	1-5
IAIR	switch between perfect and equilibrium air properties
IFLAG	no. of laminar streamline swallowing iterations to converge
IFLAG1	no. of times laminar streamline swallowing iterations have been hung up in loop at a discontinuity
IGE	geometry specification variable
IQS	currently not used
ISTEP	indexes for each flow station
ITR	transition criterion index
ITY	initial condition index
IX	index for each change in NPTS
J	dummy indexing variable
JSTEP	steps for each flow case
JUNK,1,2,4	dummy variables
KKK	equals zero for first iteration
LAM	laminar BL identifier
LT	length of radome to tangency point (ft)
MACH	Mach no.
MARKER	steps for each marching step
MDOT	mass flow rate (lbm/s)
ME	Mach no. at BL edge
ME2	Mach no. at BL edge squared
MMARKER	equals 1 to initialize turbulent swallowing equations
MNORM	free-stream Mach no. normal to bow shock
MO	free-stream Mach no.
MO2	free-stream Mach no. squared
MRL	last (previous) BL edge Mach no.
MRX	interpolated Mach no. at BL edge
MST	viscosity at Eckert's reference enthalpy (lbm/ft-s)
MUE	viscosity at BL edge (lbm/ft-s)
MUREF	reference viscosity for Cohen correlation (1.15312E-5 lbm/ft^2-s)

MUS	viscosity at stagnation point (lbm/ft-s)
NOUT	output to print and plot files every NOUT step
NPTS	number of stations wall temperature will be specified
NUE	kinematic viscosity at BL edge (ft^2/s)
NURL	switch for creating output files
NUW	kinematic viscosity at wall (ft^2/s)
P	pressure (lbf/ft^2)
PC	surface pressure (lbf/ft^2)
PE	pressure at BL edge (lbf/ft^2)
PEL	last (previous) BL edge pressure (lbf/ft^2)
PEX	interpolated pressure at BL edge (lbf/ft^2)
PI	3.14159
PO	free-stream static pressure (lbf/ft^2)
PR	Prandtl no.
PREF	conversion factor from atm to psf (2116.224 lbf/ft^2)
PTO	free-stream total pressure (lbf/ft^2)
PTS	pressure at stagnation point (lbf/ft^2)
PW	static pressure at wall (lbf/ft^2)
Q	heat transfer rate (Btu/ft^2-s)
QCW	cold wall heat transfer rate based on wall temperature of 540°R (Btu/ft^2-s)
QHW	hot wall heat transfer rate (Btu/ft^2-s)
QSTAGD	Detra, Kemp, Riddell stagnation point heat transfer rate (Btu/ft^2-s)
QSTAGF	Fay-Riddell stagnation point heat transfer rate (Btu/ft^2-s)
QSTAGL	Lees's stagnation point heat transfer rate (Btu/ft^2-s)
R	recovery factor
RAD	1 radian = 57.3
RADIUS	radius of body in body coordinate system (ft)
RC	term in equation for bow shock angle
RES	Reynolds no. based on surface distance
RET	Reynolds no. based on momentum thickness
RETING	incompressible Reynolds no.
RG	radius of ogive (ft)
RHOE	density at BL edge (lbm/ft^3)
RHOMUE	density × viscosity at BL edge (lbm^2/ft^4-s)
RHOMUW	density × viscosity at wall (lbm^2/ft^4-s)
RHOO	free-stream density (lbm/ft^3)
RHOS	stagnation point density (lbm/ft^3)
RHOST	density at Eckert's reference enthalpy (lbm/ft^3)
RHOW	density at wall (lbm/ft^3)
RHREF	reference density for Cohen correlation (0.0803707 lbm/ft^3)
RM1	term in equation for bow shock angle
RME	density × viscosity at BL edge (lbm^2/ft^4-s)
RMER	dummy variable
RMES	RME at stagnation point (lbm^2/ft^4-s)
RMS	density × viscosity at Eckert's reference enthalpy (lbm^2/ft^4-s)
RMSR	dummy variable
RMSS	RMS at stagnation point (lbm^2/ft^4-s)
RMWR	dummy variable
RMWS	density × viscosity at wall at stagnation point (lbm^2/ft^4-s)

RN	nose radius (ft)
RR	radius of radome base at tangency point (ft)
RRR	*y* coordinate of radome base including angle of attack (ft)
RUC	interpolated heat transfer coefficient (lbm/ft^2-s)
RUCH1	heat transfer coefficient (lbm/ft^2-s)
RUCHL	last (previous) heat transfer coefficient (lbm/ft^2-s)
S	surface distance (ft)
S1	sharp cone distance to tangency point (ft)
SEFF	effective sharp cone surface distance (ft)
SL	last (previous) surface distance (ft)
SMAX	maximum surface distance (ft)
SO	initial surface distance (ft)
SQRE	square root of VE × S1/NUW
SR	*y* coordinate of body in free-stream coordinate system (ft)
SRTP	*y* coordinate of nose/body tangency point in free-stream coordinate system (ft)
SS	entropy at BL edge (Btu/lbm-°R)
SSO	free-stream entropy (Btu/lbm-°R)
SS2	entropy at stagnation point (Btu/lbm-°R)
SST	entropy at Eckert's reference enthalpy (Btu/lbm-°R)
SSW	entropy at wall (Btu/lbm-°R)
STA	wall temperature (°R)
STN	surface distance to nose/body tangency point (ft)
STRAN	transition Reynolds no.
TANGAM	tangent of GAMMA
TDUM	dummy variable
TE	BL edge temperature (°R)
TERM1-9	terms in shape factor conversion equations
TGJ	50,063 (lbm-ft^2/Btu-s^2)
TH	body incidence angle to flow (deg)
TH1	body slope at nose/body tangency point with respect to free-stream (deg)
THL	last (previous) incidence angle (deg)
TI	time (s)
TIME	time (s)
TO	free-stream static temperature (°R)
TOO	total temperature (°R)
TR	recovery temperature (°R)
TRAN	specifies transition correlation
TST	temperature at Eckert's reference enthalpy (°R)
TTO	free-stream total temperature (°R)
TTS	stagnation point temperature (°R)
TURB	turbulent BL identifier
TYPE	specifies format of input conditions
V2	velocity immediately behind shock (ft/s)
VE	velocity at BL edge (ft/s)
VE1,2	saved BL edge velocities (ft/s)
VENUW	VE × NUW (ft^3/s^2)
VNORM	free-stream velocity normal to bow shock (ft/s)
VO	free-stream velocity (ft/s)
VTAN	free-stream velocity tangential to bow shock (ft/s)
WE	molecular weight at BL edge (lbm/lbm-mol)
WO	free-stream molecular weight (lbm/lbm-mol)

WS	molecular weight at stagnation point (lbm/lbm-mol)
WST	molecular weight at Eckert's reference enthalpy (lbm/lbm-mol)
WW	molecular weight of gas at wall (lbm/lbm-mol)
X	*x* coordinate of body in free-stream coordinate system (ft)
XLEN	surface distance (ft)
XT	*x* coordinate of nose/body tangency point at angle of attack in free-stream coordinate system (ft)
XTC	surface *x* coordinate in body coordinate system at nose/body tangency point (ft)
XXX1,2	*x* coordinate of body surface for von Karman radome shape at angle of attack (ft)
Y	*y* coordinate of body in free-stream coordinate system (ft)
YS	radius of free-stream stream tube required to match MDOT (ft)
YT	*y* coordinate of nose/body tangency point at angle of attack in free-stream coordinate system (ft)
YTC	surface radius in body coordinate system at nose/body tangency point (ft)
YYY1,2	*y* coordinate of body surface for von Karman radome shape at angle of attack (ft)
ZO	altitude (ft)

GLOSSARY

- c_f – skin friction
- F – entrainment parameter
- h – enthalpy
- H – conventional form parameter (δ^*/θ)
- H_1 – modified form parameter ($\delta - \delta^*/\theta$)
- m – boundary layer mass flow rate
- M – Mach no.
- P – pressure
- Pr – Prandtl no.
- PT – total pressure
- q – heat transfer rate
- QS – stagnation point heat transfer rate
- r – radius of body at S
- R – radius
- Re – Reynolds no.
- S – surface distance from stagnation point
- s_1 – function defined in Ref. 26
- T – temperature
- TT – total temperature
- TW – wall temperature
- u – velocity
- x – longitudinal coordinate
- y – radius from centerline
- α – angle of attack
- β – velocity gradient (du_e/ds)
- γ – ratio of specific heats (c_p/c_v)
- δ – boundary layer thickness
- δ^* – boundary layer displacement thickness
- Δ – mass flow thickness
- η – sharp cone-attached shock angle
- θ – boundary layer momentum thickness
- λ – bow shock angle
- μ – viscosity
- ν – kinematic viscosity
- ρ – density
- σ – cone incident angle to flow

Subscripts

- c – sharp cone
- e – boundary layer edge
- n – blunted nose
- r – recovery
- s – stagnation point
- sh – shock
- w – wall
- $*$ – Eckert's reference temperature
- ∞ – free stream

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