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Naval Ordnance Laboratory
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THE DRAG OF SLIGHTLY BLUNTED SLENDER CONES

Prepared by:
W. Carson Lyons, Jr. and H. S. Brown

ABSTRACT: A computer program is presented for calculating the various components comprising the total drag coefficient for slightly blunted slender cones. The program is applicable for either the case of a completely laminar boundary layer or where transition occurs on the cone. Weak viscous interaction effects are taken into account. Local flow properties which exist at the outer edge of the boundary layer along the cone are also computed.

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The computer program described in this report is used extensively in the analysis and correlation of various types of aerodynamic data and for the prediction of the behavior of test models, particularly those being flown at hypersonic speeds in the ballistics ranges.

E. F. SCHREITER
Captain, USN
Commander

A. E. Seigel
A. E. SEIGEL
By direction

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ILLUSTRATIONS

INTRODUCTION

A program has been formulated and coded for use on an IBM 7090 for calculating the drag coefficient of a slightly blunted cone. The program is applicable for cases where the boundary layer is either completely laminar, completely turbulent, or the flow is mixed, with transition occurring on the cone.

The equations that are used do not require that the flow along the outer edge of the boundary layer be isentropic. A variation in entropy along this surface due to the curved bow shock wave is allowed. This effect results in a decrease in the skin-friction drag from that for a sharp cone. For slender cones where the skin-friction drag is a significant portion of the total drag, this effect of blunting the cone plays an important role in the determination of the total drag.

Viscous interaction effects are considered, and the increase in skin-friction coefficients due to transverse curvature and induced pressure effects are taken into account. The increase in pressure drag due to induced pressure resulting from large boundary-layer displacement thicknesses is also taken into account. These effects can be significant for conditions of low Reynolds numbers and high Mach numbers.

As a result of the method used to calculate the skin-friction coefficients, local flow properties at the outer edge of the boundary layer are also determined. The integrated boundary-layer thickness parameters (momentum and displacement) are calculated.

No attempt was made to include real gas effects such as dissociation or ionization of the flow over the cone.

The program can be used to evaluate the effects of Mach number, Reynolds number, wall-to-recovery temperature ratio, nose bluntness, cone angle, and the location of boundary-layer transition on the total drag coefficient or on the various components. Some of these effects will be shown in comparisons of calculations with experimental data, and in discussions of the drag characteristics of slightly blunted slender cones.

Care has been taken in coding the program for the machine calculations to provide as simple an input as possible to afford ease in operation. Information concerning running of the program is provided in Appendix A, along with a complete listing of the program. Appendix B is a print-out of a sample test case which was run using this program.

DESCRIPTION OF EQUATIONS

The total drag coefficient is formed by summing the pressure drag coefficient, the skin-friction drag coefficient, and the base drag coefficient plus incremental increases to the pressure and skin-friction drag coefficients due to viscous interaction effects. The equations used to obtain each of these coefficients will be discussed separately. As will be seen, to perform some of these calculations it is necessary to have values of inviscid sharp-cone properties for the particular case of interest. The equations used for these computations will also be discussed.

Inviscid Cone Properties

The following method is used to calculate the flow properties which would exist on a hypothetical sharp cone having the same half angle as the blunted cone being considered, and for the same free-stream Mach number being considered. These properties are calculated using the simple relations given by Blick in reference (3). Relations are presented for calculating the temperature and the velocity of the inviscid flow along the cone referenced to the respective free-stream quantities. Using these two relations, the Mach number can be determined. The inviscid sharp-cone pressure can be calculated using the relation given by Linnell and Bailey (ref. (4)) and presented again in reference (3). These equations are used in the program for calculating the inviscid cone pressure, temperature, and Mach number.

Geometric Characteristics of a Spherically Blunted Cone

It was desired to be able to express geometric quantities for the spherically blunted cone in terms of the cone half angle, the nose-to-base radius ratio, and the radius of the base. Two quantities in particular are necessary: the distance from the stagnation point to the point of tangency between the spherical nose cap and the conical frustum, S_T, and the total wetted length from the stagnation point to the base of the cone, S_{MAX}. These two quantities are given by

$$S_T = r_B \frac{r_N}{r_B} \left(\frac{\pi}{2} - \theta_c\right)$$

and

$$S_{MAX} = r_B \left[\frac{r_N}{r_B} \; \frac{\pi}{2} - \theta_c + \frac{1 - r_N/r_B \; \mathrm{SIN}\left(\frac{\pi}{2} - \theta_c\right)}{\mathrm{SIN}\; \theta_c}\right]$$

Laminar Boundary-Layer Calculations

Calculations of the laminar boundary-layer characteristics are first made neglecting viscous interaction effects such as induced pressure and transverse curvature. The equations used for making these laminar calculations were derived by Wilson and reported in reference (5). This is a momentum-integral method which utilized available flat plate results. The flow characteristics are followed along streamlines through the bow shock wave, using oblique shock relations, and then expanded isentropically to the point where the streamline intersects the outer edge of the boundary layer. The boundary-layer thickness defining the outer edge is determined through a mass balance of the flow in the free stream and that in the boundary layer at this intersection point. Having defined the properties at the outer edge of the boundary layer, the boundary-layer characteristics are determined from a step-by-step technique using the momentum-integral equations and necessary thickness parameters and skin-friction coefficients taken from flat plate results. The viscosity ratios were evaluated using Southerland's equation in the form

$$\frac{\mu}{\mu_1} = 1 + \frac{198.6/T_1}{T/T_1 + 198.6/T_1}\left(\frac{T}{T_1}\right)^{3/2}$$

The momentum-thickness Reynolds number based on flow properties just outside the boundary layer is calculated using the relation

$$R_{\theta_1} = \frac{R_{\theta_c} M_1 (T_1 + 198.6)}{M_c (T_c + 198.6)}\left(\frac{T_c}{T_1}\right)^2$$

These laminar equations are applied to the region between the point of intersection of the spherical nose and the conical frustum and either the end of the cone, in the case of an all-laminar boundary layer, or the point of boundary-layer transition for the case of a mixed laminar-turbulent boundary layer.

Turbulent Boundary-Layer Calculations

For cases where transition from laminar to turbulent flow is specified to occur on the body, then at this point of transition the calculation procedure is changed to one applicable to the turbulent boundary layer. The procedure used is still a momentum-integral method, and was formulated and reported by Wilson in reference (6). Having values for R_{θ_c}, R_{x_c}, and C_f computed at the point of transition using the laminar boundary-layer equations just described, a value for R_{θ_c}, some distance, x, downstream from the transition point can be calculated using an integral form of the momentum-integral equation as described in reference (6). This then allows a step-by-step, simultaneous solution of the turbulent boundary-layer characteristics and the inviscid flow field properties at the outer edge of the boundary layer to be carried out. As indicated in reference (6), to obtain the thickness parameters it is necessary to assume a velocity profile. A power law profile is assumed with an exponent of 1/7, although it is a simple matter to perform the calculations using a different value for the exponent. Some errors were found in one of the equations in reference (6). This has been corrected in this program, and the correct form of the equation appears in the listing of equations in a following section of this report.

Viscous Interaction Effects

At high Mach numbers and low Reynolds numbers the thickness of a laminar boundary layer on a slender cone can be significant compared to the local radius of the cone. Under these conditions an interaction between the thick boundary layer and the inviscid flow field can exist. Two predominate viscous interaction effects are induced pressure and transverse curvature. These viscous interaction effects are characterized by a viscous interaction parameter, $\bar{\chi}$, defined as

$$\bar{\chi} = \frac{M^3 \sqrt{C}}{\sqrt{Re}}$$

where

$$C = \frac{T + 198.6 \sqrt{T_w/T}}{T_w + 198.6}$$

For small values of $\bar{\chi}$ (weak interaction), Probstein (ref. (4)) has presented equations for calculating the induced pressure on a cone. Also in reference (4), Probstein has presented equations for calculating the increase in the local skin-friction coefficient on a cone due to induced pressure and transverse curvature effects. The relations in reference (4) were developed for a sharp cone, assuming that the properties, including $\bar{\chi}_c$, were constant along the cone. Since for these present calculations the Mach number, and hence $\bar{\chi}$, vary significantly along the cone, the local value of $\bar{\chi}_e$ at points along the cone are used in the calculations for the induced pressure and the increase in the skin-friction coefficients, instead of $\bar{\chi}_c$ based on inviscid sharp-cone values as shown in reference (4). The equations used to calculate the induced pressure effects involve two functions, F_1 and F_2, both of which are functions only of K, the hypersonic similarity parameter. The functions F_1 and F_2 are presented in reference (4) in both equation form and graphically. Due to the complexity, however, of the equations, the curves were approximated for values of K between 1 and 2 with a simple linear expression for F_1 and a quadratic expression for F_2. These two expressions are

$$F_1(K) = 0.8992 - 0.1049K_c$$

and

$$F_2(K) = 0.6192 - 0.3822K_c + 0.0798K_c^{\,2}$$

where

$$K_c = M_\infty \theta_c$$

Drag Coefficient Components

In all cases, the calculated drag coefficients were based on free-stream dynamic pressure and the area of the base of the cone. A skin-friction drag coefficient is obtained by integrating the local shear stress over the surface of the cone and then dividing the results by the just-mentioned reference quantities. Since the local skin-friction coefficients calculated using the equations given in references (4), (5), and (6) are referenced to local dynamic pressure and the exposed, wetted area, then the shear stress is simply

$$\tau = C_f q_e A_{WETTED}$$

The skin-friction drag coefficient can then be written as

$$C_{D_F} = \frac{2}{r_B^2} \int_{S_T}^{S} \Gamma C_f ds$$

where

$$\Gamma = \frac{p_c}{p_\infty} \frac{M_e}{M_\infty}^2 \left[\frac{r_N}{r_B} r_B + (S - S_T) \text{SIN } \theta_c \right] \text{COS } \theta_c$$

The increase in the skin-friction drag coefficient due to induced pressure is given by

$$\Delta C_{D_{F_{IP}}} = \frac{2}{r_B^2} \int_{S_T}^{S} \Gamma (\Delta C_{f_{IP}}) \, ds$$

The increase in the skin-friction drag coefficient due to transverse curvature is given by

$$\Delta C_{D_{F_{TC}}} = \frac{2}{r_B^2} \int_{S_T}^{S} \Gamma (\Delta C_{f_{TC}}) \, ds$$

The pressure drag coefficient for the conical frustum is obtained by integrating the longitudinal component of the local pressure coefficient over this portion of the body and then dividing the results by the free-stream dynamic pressure and the base area. Hence, the pressure drag coefficient can be written as

$$C_{D_P} = \frac{2}{r_B^2} \int_{S_T}^{S} C_{P_e} \Gamma \text{SIN } \theta_c \, ds$$

The increase in the pressure drag coefficient due to induced pressure is given by

$$C_{D_{P_{IP}}} = \frac{4}{\gamma M_\infty^2 r_B} \int_{S_T}^{S} \frac{pc}{p_\infty} \left[F_1 D_\infty \bar{X}_e + F_2 D^2 \bar{X}^2 \right] r \sin \theta_c \, ds$$

For the spherical nose cap the pressure is calculated assuming that modified Newtonian impact theory is valid. The pressure coefficient is given as

$$C_p = C_{p_M} \sin^2 \varphi$$

where C_{p_M} is the maximum pressure coefficient occurring at the stagnation point and is assumed equal to the stagnation pressure resulting from bringing the flow to rest isentropically after passing through a normal shock. The angle φ is that angle between the free-stream velocity vector and a tangent to the surface at the point being considered. The resulting pressure is integrated over this spherical nose cap and then divided by the free-stream dynamic pressure and the base area of the cone. This integration can be performed in closed form resulting in the relation

$$C_{D_N} = \frac{1}{1.4 M_\infty^2} \left[\left(\frac{6 M_\infty^2}{5} \right)^{3.5} \left(\frac{6}{7 M_\infty^2 - 1} \right)^{2.5} - 1 \right] \left(\frac{r_N}{r_B} \right)^2 \left(1 - \sin^4 \theta_c \right)$$

A value for the base drag coefficient is calculated assuming a vacuum exists at the base, as usually done at hypersonic Mach numbers, and is given by

$$C_{D_B} = \frac{2}{\gamma M_\infty^2}$$

COMPARISON OF THEORETICAL AND MEASURED DRAG COEFFICIENTS

Calculations have been performed to compare theoretically obtained total drag coefficients with experimentally obtained data. Most of the data were obtained in the NOL ballistics range facilities, although some wind-tunnel data are also used. Tests have been chosen so that comparisons can be made over a variation of Mach number, Reynolds number, nose-to-base radius ratio, and wall-to-stagnation temperature ratio. Although there are data with some variation in cone angle, this variation is small. For all of the calculations it was assumed that the base pressure was constant over the base, and equal to one tenth of the free-stream static pressure. The agreement between computed and measured drag coefficients is very good, with the exception of one set of data which will be discussed later. The following is a detailed description of all of the various comparisons.

A comparison between calculated and measured drag coefficients for a 6.3-degree half-angle cone is presented in figure 1. These data were obtained at nominal Mach numbers of 9 and 13. Three curves are shown in figure 1. The data at Mach number 9 were presented in reference (7), while the data at Mach number 13 were presented in reference (8). The blunted cones used in these tests had half angles of 6.3 degrees and nose-to-base radius ratios of approximately 0.03 and 0.30. Calculations were performed for each set of data for the conditions indicated in figure 1. Data from tests of the most blunt cone are indicated by the square symbols. Agreement between the calculated values and the experimental values is seen to be good over a Reynolds number range from 2×10^5 to approximately 3×10^6. These Reynolds numbers are based on free-stream properties and axial length of the body. Data for the sharper configuration, tested over approximately this same Reynolds number range, are seen to be consistently higher than the calculated values by approximately 13 percent. These data have been reviewed with the author of reference (7). It was determined that one possible source of this deviation could have resulted from the nose bluntness being larger than reported. The models used in these tests had a design nose diameter of only 0.007 inch. This was extremely difficult to maintain during manufacturing both in size and shape. Further, a nose of this size is very susceptible to blunting during flight due to aerodynamic heating. An inspection of some shadowgraphs made during these tests revealed that nose diameters could be as large as 0.020 inch. Calculations have been made for a nose-to-base radius ratio of 0.1 and are shown as the dotted curve in figure 1. It is seen that this curve is in much better agreement with the data. A review of reference (7) also reveals that some difficulty was encountered in reducing the measured drag coefficients, which were obtained at angles of attack, to equivalent zero angle-of-attack coefficients. It should be noticed, however, that good agreement was obtained over nearly the same Reynolds number range between calculated and measured drag coefficients presented in figure 2. The data in figure 2 will be discussed in more detail later.

The two groups of data in figure 1, which were reported in reference (8), are at Reynolds numbers near the free-stream transition Reynolds number. The value of the free-stream transition Reynolds number, as obtained from reference (8), is indicated by the side of each curve. These transition Reynolds numbers were also used in the calculations. All data and calculations at Reynolds numbers below the indicated transition Reynolds number are for completely laminar boundary layer over the body. Data shown at Reynolds numbers above transition Reynolds number had transition occurring at some point on the body and, hence, both laminar and turbulent flow were present. The agreement between the calculated drag coefficients and the experimental data for these higher Reynolds numbers is good for both the Mach number 9 and the Mach number 13 cases.

The comparison between calculated drag coefficients and data presented in reference (9) is shown in figure 2. These data cover a Reynolds number range of approximately 7×10^4 to 5×10^6 and were obtained at a free-stream Mach number of approximately 12.8. The model used for this test was a slightly blunted, 8-degree half-angle cone with a nose-to-base radius ratio of 0.035. Calculations at a Reynolds number of approximately 7×10^4 indicate that approximately 11 percent of the total drag is a result of viscous interaction effects. Viscous interaction effects which are included in the calculations represent increases in the pressure drag component and the friction drag component due to induced pressures and increases in the friction drag component due to transverse curvature. The local calculated viscous interaction parameter $\bar{\chi}_e$ at the back end of the cone has a value of 2.03 with an average value of the viscous interaction parameter over the frustum portion of the cone of 2.5. The highest Mach number for which the calculations were compared with data is approximately 15. This comparison is shown in figure 3. The data shown in this figure were taken from reference (8). The Reynolds number range for these data extends from 0.7 to 13×10^6. At free-stream Reynolds numbers based on model length greater than 5×10^6, it was assumed that transition occurred on the model. For this configuration and Mach number, a transition Reynolds number of 5×10^6 was reported in reference (8). Again, over the entire Reynolds number variation which considered for some cases all laminar flow on the body, while for other conditions it considered both laminar and turbulent flow existing on the body, it is seen that the agreement between the data and calculations is good. Figure 4 is presented to show the applicability of the program for calculating drag coefficients for cones over a wide range of nose-to-base radius ratios. The data shown in figure 3 were obtained from reference (10). The configuration used to obtain these data was a 10-degree half-angle cone, with nose-to-base radius ratio varying from zero to approximately 0.76. Again, the agreement between the calculated drag coefficients and the measured values is seen to be good.

LOCAL FLOW PROPERTIES

It is often of interest to have the longitudinal distribution of local flow properties which exist at the outer edge of the boundary layer. Also of interest is the distribution of the integrated boundary-layer characteristics, such as the momentum and displacement thickness. It was mentioned that values for these quantities are calculated along the length of the cone. As discussed by Wilson (refs. (5) and (6)), slightly blunting a slender cone flying at hypersonic speeds can significantly affect the values of the local flow properties over that for a sharp cone. Over the portion of the cone experiencing a strong entropy gradient, the local Mach number will be much below the value for an inviscid sharp cone. The local Mach number can be used to indicate the "swallowing length," or the distance required for the boundary layer to "swallow" the variable entropy layer. The swallowing length can be defined as that distance required for the local Mach number to reach some arbitrarily chosen fraction of the local inviscid cone Mach number, say 99 percent. To illustrate the effect nose blunting has on the local Mach number, the distribution of the local Mach number at the outer edge of the boundary layer on a 5-degree half-angle cone has been calculated and presented in figure 5. These calculations were performed for a sharp cone and for two slightly blunted cones. The free-stream Mach number and slant-length Reynolds number used in these calculations were 12 and 1 million, respectively.

To illustrate the effect of blunting on integrated boundary-layer characteristics, the results of calculations of the local momentum-thickness Reynolds number distribution is shown in figure 6.

From these two figures it is seen that slight blunting reduced the value of both the local Mach number and momentum-thickness Reynolds number at any given point along the surface of the cone.

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(10) Harris, J. E., "Force-Coefficient and Moment-Coefficient Correlations and Air-Helium Simulation for Spherically Blunted Cones," NASA TN D-2184, 1964

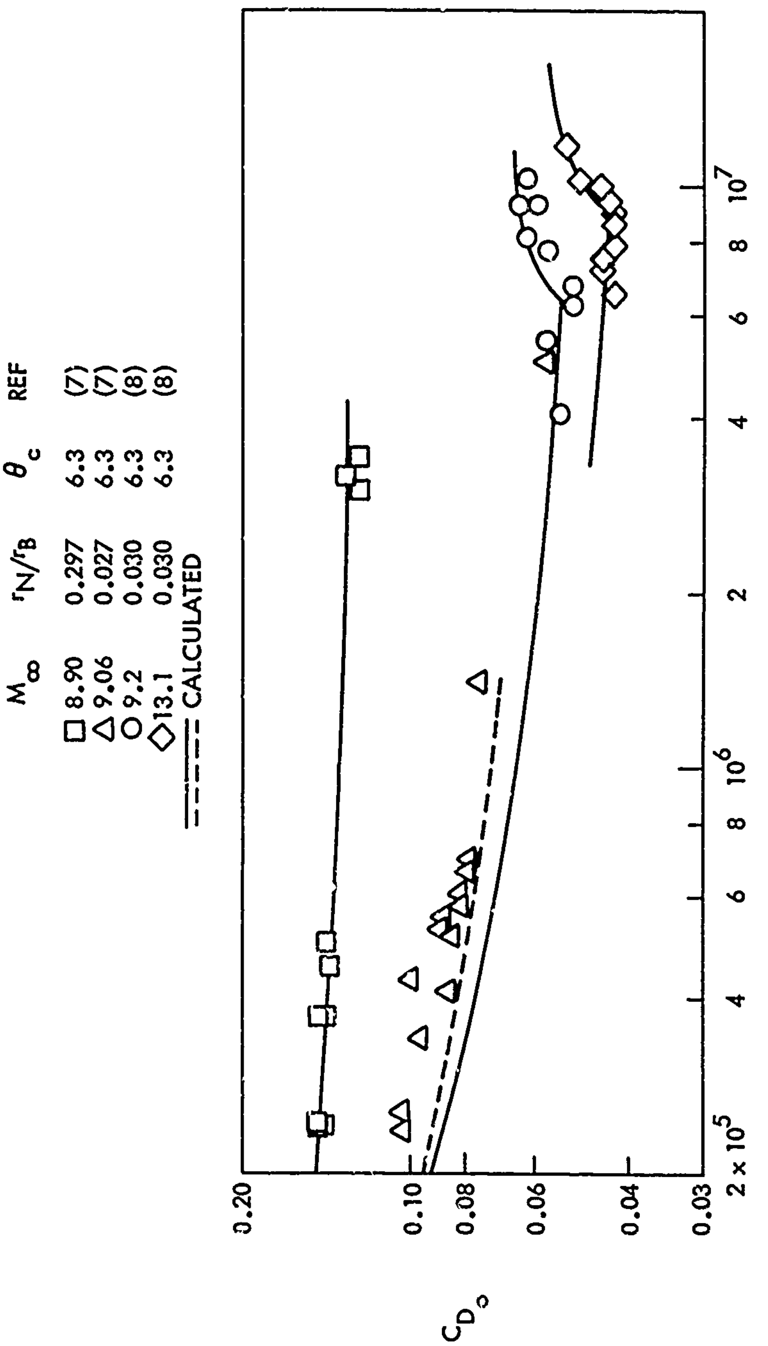

FIG. 1 VARIATION OF DRAG COEFFICIENT WITH REYNOLDS NUMBER $M_\infty = 9$ AND 13, $\theta_c = 6.3$ DEGREES

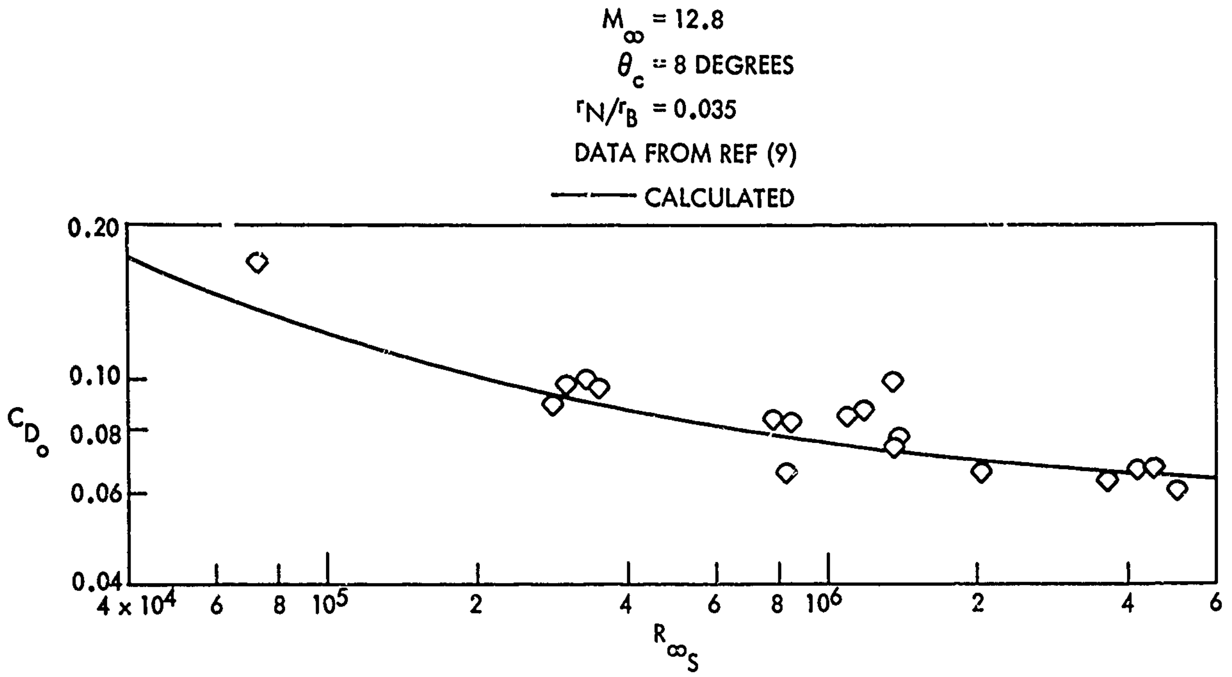

FIG.2 VARIATION OF DRAG COEFFICIENT WITH REYNOLDS NUMBER $M_\infty = 12.8$, $\theta_c = 8$ DEGREES

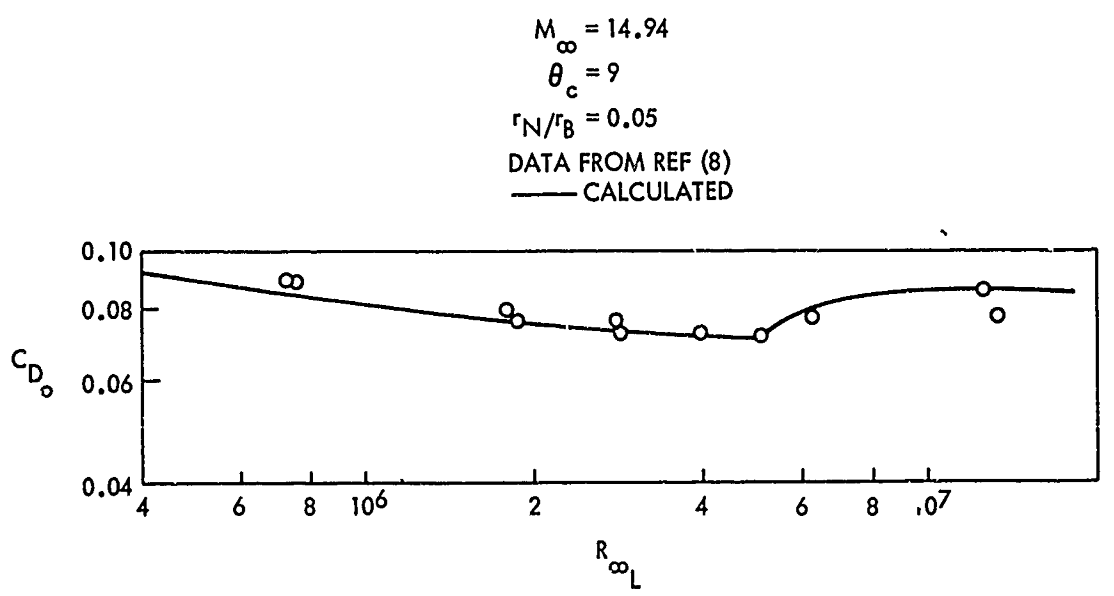

FIG.3 VARIATION OF DRAG COEFFICIENT WITH REYNOLDS NUMBER $M_\infty = 15$, $\theta_c = 9$ DEGREES

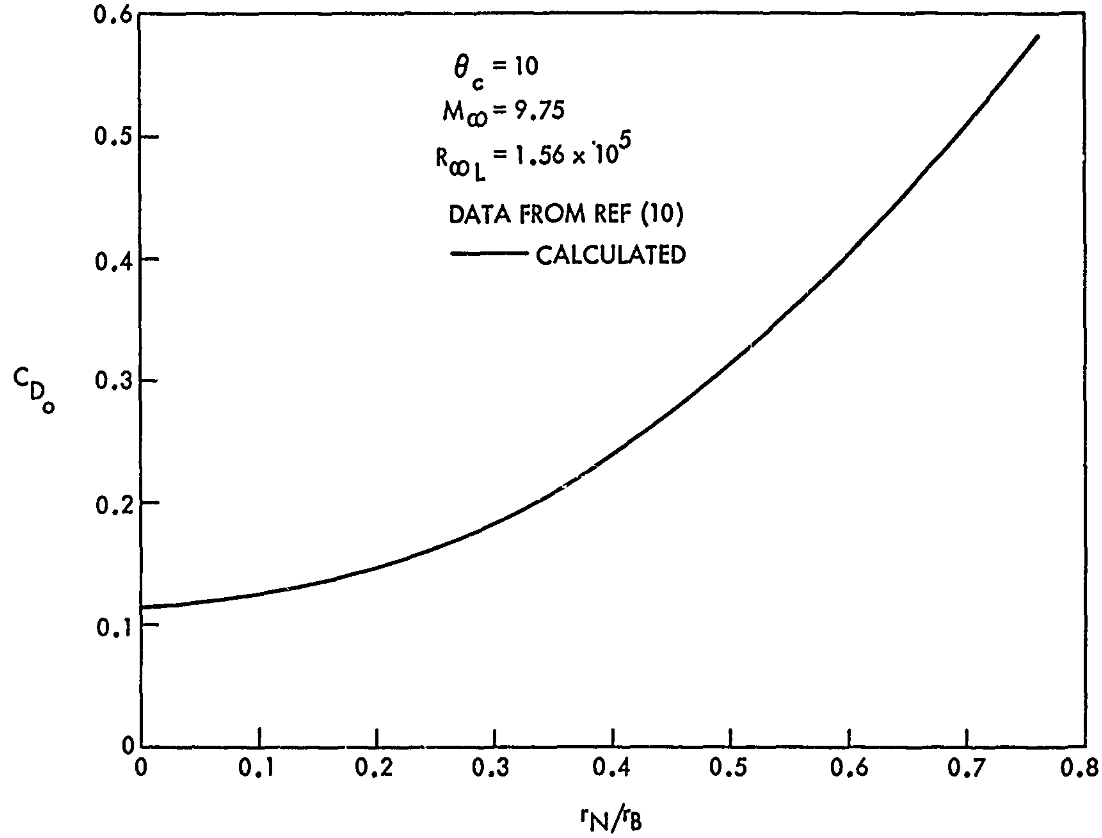

FIG.4 VARIATION OF DRAG COEFFICIENT WITH BLUNTNESS RATIO $M_\infty = 9.75$, $\theta_c = 10$ DEGREES

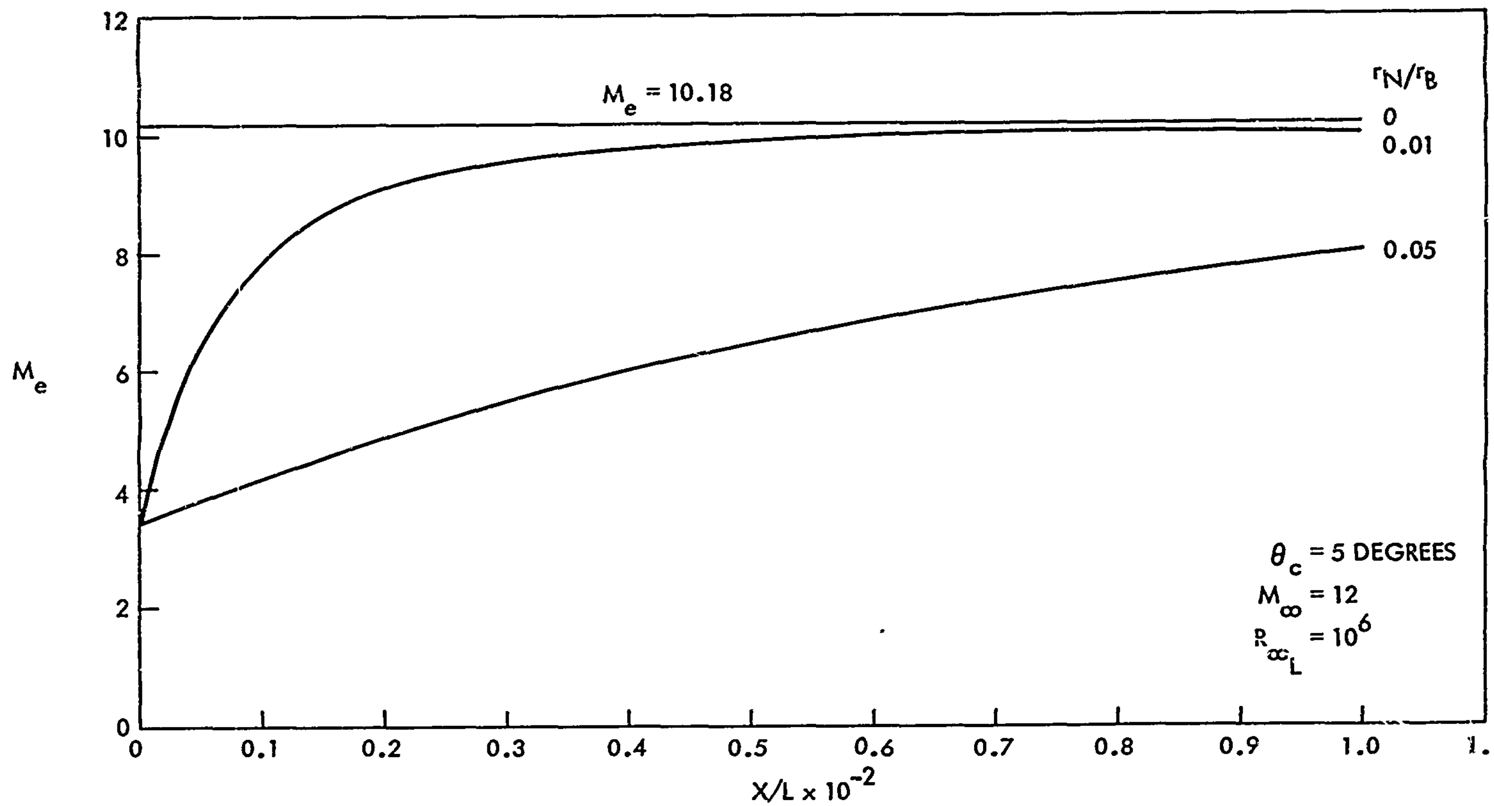

FIG.5 VARIATION OF LOCAL MACH NUMBER DISTRIBUTION WITH NOSE BLUNTNESS

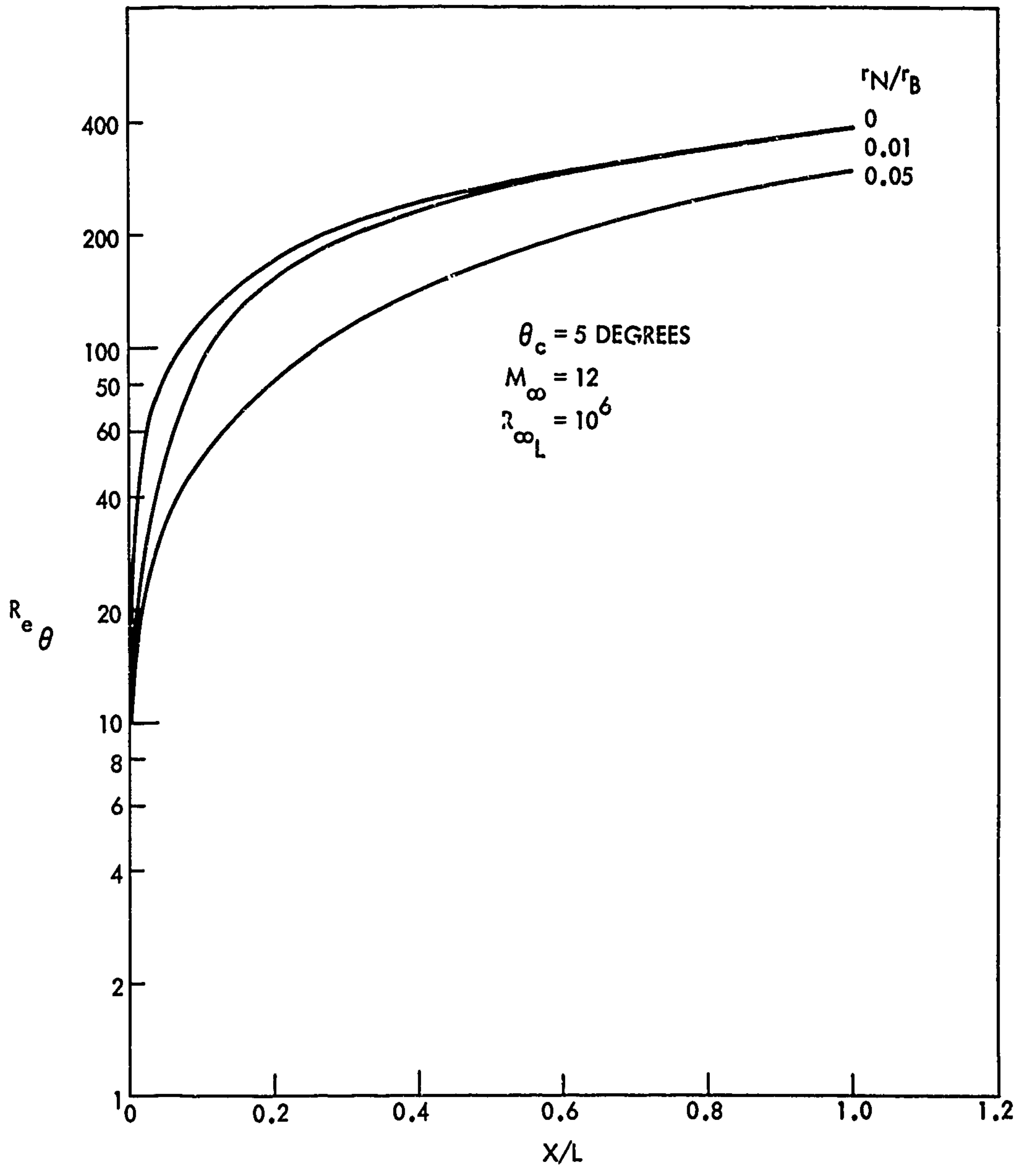

FIG.6 VARIATION OF LOCAL MOMENTUM THICKNESS REYNOLDS NUMBER DISTRIBUTION WITH NOSE BLUNTNESS

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APPENDIX A

This appendix includes a description of the details of the program as it is presently coded for use on an IBM 7090. Included in this description is the required input and the input format for the program. Also included is a cross listing of the symbols used in the text, with those appearing in the Fortran listing and those appearing in the program output. Further, there is a listing of the definitions of the symbols used in the program output.

This program is coded in Fortran IV and runs under the IBSYS - IBJOB monitor version 13. Pertinent comment cards have been inserted into the program listing to aid in relating program statements to equation in the text or given references. This was done to make any desired modification of the program as easy as possible.

This program will compile and run the test case (output in Appendix B) on an IBM 7090 in 1.53 minutes.

PROGRAM INPUT

Card 1.

IDEN	SIGMA	EMIN	TIN	TW	RORPIN
2A6	E12.6	E12.6	E12.6	E12.6	E12.6

Card 2.

RNRB	RB	RLTR
E12.6	E12.6	E12.6

SYMBOLS	Definition of Symbols
IDEN	For identification purposes only
SIGMA	Cone half-angle (degrees)
EMIN	Free-stream Mach number
TIN	Free-stream temperature (degrees Rankine)
TW	Wall temperature (degrees Rankine)
RORPIN	Free-stream Reynolds number based on axial length (inches) or free-stream pressure (atmospheres)
RNRB	Ratio of nose-to-base radii
RB	Base radius (inch)
RLTR	Free-stream transition Reynolds number based on axial length (inch)

Runs may be stacked with a blank card after last run.

INTERNAL AND EXTERNAL COMPUTER SYMBOLS

Symbol	Computer Symbol	Output Symbol
M_c	EMC	MC
M_∞	EMIN	M(INF)
γ	GAM	
P_c	PC	PC
P_∞	PIN	P(INF)
r_B	RB	RB
$R_{L_\infty}(tr)$	RLTR	RL(TR)
r_N/r_B	RNRB	RN/RB
σ	SIGMA	SIGMA
T_∞	TIN	T(INF)
T_w	TW	T(WALL)
T_c	TC	TC
C_f	CF	CF
$\bar{X}_1$	CIBAR1	CIBAR1
δ	DELTA	DELTA
M_1	M1	M1
R_{x_c}	RC	RXC
R_{s_1}	RES	RS1
R_{θ_c}	RTHC	RTHC
R_{θ_1}	RTH1	RTH1
S	S	S
T_1	T1	T1
X	X	X
C_{D_B}	CDB	CD(BASE)(VACUUM)
$C_{D_{F_L}}$	CDFL	CDF(L)
$C_{D_{f_T}}$	CDFT	CDF(T)
$C_{D_f}(total)$	CDFTTL	CDF(TOTAL)
C_{D_N}	CDN	CD(NOSE)
$C_{D_{P_L}}$	CDPL	CDP(L)
$C_{D_{P_T}}$	CDPT	CDP(T)
$C_{D_P}(total)$	CDPTTL	CDP(TOTAL)
$C_D(total)$	CDTTL	CD(TOTAL) excluding base drag
$C_D(total)$	CDTTLB	CD(TOTAL) including base drag

Internal and External Computer Symbols - continued

Symbol	Computer Symbol	Output Symbol
$\Delta C_{D_f}(IP)$	DCDFIP	D CDF(IP)(L)
$\Delta C_{D_F}(TC)$	DCDFTC	D CDF(TC)(L)
$\Delta C_{D_p}(IP)$	DCDPIP	D CDP(IP)(L)
$\bar{\chi}_A$	CIBARA	CHIBAR AVG(L)

INTERNAL COMPUTER SYMBOLS

Symbol	Computer Symbol	
δ/θ	DOVTH	Defined EQ. (12)(Ref.(6.))
$d(\delta/\theta-H)/dM_1$	DTHDM1	Defined EQ. (13)(Ref.(6.))
$\gamma-1$	GM1	
$\gamma+1$	GP1	
ω	OMEGA	Shock wave angle for sharp cone
ω_s	OMEGAS	Local shock wave angle for blunt cone
Pc/P_∞	PCPIN	Ratio cone pressure to free-stream pressure
π	PI	
R_{BC}	RBC	Reynolds number based on cone properties and tip radius of curvature
r_n	RN	Nose radius
S_T	ST	Distance along the surface of nose from stagnation to tangency point
T'/T_1	TPT1	Defined EQ. (4)(Ref.(5.))
T_{T_1}	TT1	Stagnation temperature at the outer edge of boundary layer
μ'/μ_w	XMU1MW	
μ'/μ_1	XMPM1	
μ_1/μ_c	XM1MC	
F_1	F1	Function defined by EQ. (13)(Ref.(5.))
ξ	XRRR	$R_c R_{\theta_c}/R_{B_c}^2 = X\theta/r_N^2$
$2\xi/F_2$	YRRR	Integrand in EQ. (20)(Ref.(5.))
F_2	F2	Function defined by EQ. (16)(Ref.(5.))
$SIN^2\omega_s$	SINWS2	
$COS^2\omega_s$	COSWS2	
$TAN^2\omega_s$	TANWS2	
$TAN^2\omega$	TANW2	

PROGRAM OUTPUT

SYMBOLS	Definition of Symbols
P(INF)	Free-stream pressure (atmospheres)
T(INF)	Free-stream temperature (degrees Rankine)
M(INF)	Free-stream Mach number
PC	Inviscid sharp cone pressure (atmospheres)
TC	Inviscid sharp cone temperature (degrees Rankine)
MC	Inviscid sharp cone Mach number
SIGMA	Cone half-angle (degrees)
T(WALL)	Wall temperature (degrees Rankine)
RN/RB	Ratio of nose-to-base radii
RB	Base radius (inch)
RL(INF)	Free-stream Reynolds number based on axial length
RL(TR)	Free-stream transition Reynolds number based on axial distance from stagnation point
D CDP(IP)(L)	Incremental increase in the pressure drag coefficient due to induced pressure for the laminar portion of the boundary layer
D CDF(TC)(L)	Incremental increase in the skin-friction drag coefficient due to transverse curvature for laminar portion of the boundary layer
D CDF(IP)(L)	Incremental increase in the skin-friction drag coefficient due to induced pressure for laminar portion of the boundary layer
CHIBAR AVG(L)	Average value of viscous interaction parameter, $(\bar{\chi})$ for laminar portion
CDF(L)	Skin-friction drag coefficient for laminar portion of boundary layer
CDP(L)	Pressure drag coefficient for area wetted by laminar boundary layer
CD(NOSE)	Pressure drag coefficient for spherical nose cap
CDF(TOTAL)	Total skin-friction drag coefficient (sum of all skin-friction drag coefficient components)
CDP(TOTAL)	Total pressure drag coefficient (sum of all pressure drag coefficient components)
CD(BASE)(VACUUM)	Base drag coefficient assuming vacuum at the base

CD(TOTAL) excluding base drag	Sum of all drag coefficient components except base drag coefficient
CD(TOTAL) including base drag	Sum of all drag coefficient components
X	Distance along cone surface measured from hypothetical apex (inch)
S	Distance along cone surface measured from stagnation point (inch)
M1	Local Mach number at outer edge of boundary layer
CF	Local skin-friction coefficient
T1	Local temperature at outer edge of boundary layer (degrees Rankine)
DELTA(δ)	Boundary-layer thickness (inch)
RXC	Reynolds number based on inviscid sharp cone properties and X
RTHC	Reynolds number based on inviscid sharp cone properties and boundary-layer momentum thickness
RTH1	Reynolds number based on local properties and boundary-layer momentum thickness
RS1	Reynolds number based on local properties at outer edge of boundary layer and S
CHIBAR1	Local value of the viscous interaction parameter $\bar{\chi}$ defined by

$$\bar{\chi} = \frac{M_1^3\sqrt{C}}{\sqrt{RS1}}$$

$$\text{where } C = \frac{\mu_w}{\mu_1} \Big/ \frac{T_w}{T_1}$$

PROGRAM LISTING

```
$IBFTC DRAG    DD,DECK
C       THIS PROGRAM IS CODED IN FORTRAN IV AND RUNS UNDER THE IBSYS-
C       IBJOB MONITOR VERSION 13.
C
C       MAIN PROGRAM
C
C       INPUT CONSIST OF 2 CARDS PER ROUND.
C       FIRST CARD  - FORMAT(2A6,5E12.6)
C       IDEN   -  IDENTIFICATION (MAX. 12 CHARACTERS)
C       SIGMA -  CONE HALF-ANGLE  (DEGREES)
C       EMIN   -  FREE STREAM MACH NO.
C       TIN    -  FREE STREAM TEMPERATURE  (RANKINE)
C       TW     -  WALL TEMPERATURE  (RANKINE)
C       RORPIN-  FREE STREAM REYNOLDS NUMBER BASED ON AXIAL LENGTH IN
C                INCHES (OR)  FREE STREAM PRESSURE (ATMOSPHERES)
C
C       NOTE - IF RORPIN LESS THAN 100. PROGRAMS ASSUMES PRESSURE.
C              IF RORPIN GREATER THAN 100. PROGRAM ASSUMES REYNOLDS NUM.
C
C       SECOND CARD  - FORMAT(6E12.6)
C       RNRB   -  RATIO NOSE TO BASE RADIUS.
C       RB     -  BASE RADIUS  (INCHES)
C       RLTR   -  FREE STREAM TRANSITION REYNOLDS NO. BASED ON AXIAL LENGTH
C
C       IF AN ALL TURBULENT RUN IS DESIRED SET RLTR EQUAL TO A SMALL
C       VALUE, SAY 100.
C       ROUNDS MAY BE STACKED - LAST ROUND SHOULD BE FOLLOWED WITH A BLANK CARD.
C
C       PROGRAM OPERATING MODES
C       MODE=1  - LAMINAR
C       MODE=2  - LAMINAR-TURBULENT
C       MODE=3  - TURBULENT
C
C       PROGRAM CONTROL VARIABLES
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
C       PROGRAM INPUT VALUES
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
C       PROGRAM NONDIMENSIONED OUTPUT VARIABLES
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
C       PROGRAM DIMENSIONED OUTPUT VARIABLES
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
C       PROGRAM NONDIMENSIONED INTERNAL VARIABLES
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,      RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
C       PROGRAM DIMENSIONED INTERNAL VARIABLES
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
C
C       SINCE A CONSTANT PRESSURE ON THE CONICAL SURFACE EQUAL TO THE
C       INVISCID SHARP CONE PRESSURE IS ASSUMED, WE SET P1=PC AND P1/PIN
C       =PC/PIN USING AN EQUIVALENCE STATEMENT.
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
```

```
C
C     READ INPUT FIRST CARD
    5 READ(5,10) IDEN,SIGMA,EMIN,TIN,TW,RORPIN
   10 FORMAT(2A6,5E12.6)
      IF(SIGMA.EQ.0.) STOP
C
C     READ INPUT  SECOND CARD
      READ(5,15) RNRB,RB,RLTR
   15 FORMAT(6E12.6)
C
C     SETUP PROGRAM CONTROLS,CONSTANTS AND UNIT CONVERSIONS
      ITRBLE=0
      KEY=0
      RN=RNRB*RB
C
C     SET GAMMA = 1.4
      GAM=1.4
      GM1=GAM-1.
      GP1=GAM+1.
      PI=3.14159
      SIGMA=SIGMA/57.29578
      DELW=4./57.29578
      IQUIT=0
C
C     CALCULATE GEOMETRIC CHARACTERISTICS OF SPHERICALLY BLUNTED CONE
      SMAX=(RN*(PI/2.-SIGMA)+(RB-RN*SIN(PI/2.-SIGMA))/SIN(SIGMA))
      ST=RN*(PI/2.-SIGMA)
      AXIAL=RN*(1.-SIN(SIGMA))+(RB-RN*SIN(PI/2.-SIGMA))*COS(SIGMA)
     1/SIN(SIGMA)
      PIN=RORPIN
      IF(RORPIN.LT.100.) GO TO 25
      PIN=RORPIN/(222.*EMIN*AXIAL*1.E6*(TIN+198.6)/TIN**2)
C
C     CALCULATE INVISCID SHARP CONE PROPERTIES
   25 CALL PCMCTC
      TANW2=TAN(OMEGA)**2
      MODE=1
      IF(RLTR.GT.0.) MODE=2
      GO TO (40,30),MODE
C
C     CALCULATE S VALUE WHERE TRANSITION WILL OCCUR IF RLTR NOT ZERO
   30 SMAXT=RN*(PI/2.-SIGMA)+(RLTR*TIN**2*1.E-6/(222.*EMIN*PIN*(TIN+
     1198.6))-RN*(1.-SIN(SIGMA)))/COS(SIGMA)
   33 IF(SMAXT.LT.ST) SMAXT=ST
      IF(SMAXT.LT.SMAX) GO TO 35
      MODE=1
      GO TO 40
   35 SMAX=SMAXT
C
C     LAMINAR BOUNDARY LAYER CALCULATIONS
   40 CALL LAMINR
      IF(ITRBLE.GT.0) GO TO 5
C
C     SETUP PROGRAM CONTROLS AND CONSTANTS
      DELS=S(1)-ST
```

```
      N1=1
      CDFTTL=0.
      CDPTTL=0.
      IF(MODE.EQ.2.AND.N.EQ.1) GO TO 60
C
C     CALCULATE VISCOUS INTERACTION EFFECTS AND DRAG COEFFICIENT
C     COMPONENTS FOR LAMINAR PORTION
      CONST=RB**2*(RNRB**2*(2.*(1.-SIN(SIGMA))-COS(SIGMA)**2/SIN(SIGMA))
     1+1./SIN(SIGMA))
      XF1=.8992-.1049*EMIN*SIGMA
      XF2=.6192-.3822*EMIN*SIGMA+.0798*EMIN**2*SIGMA**2
      DIN=.968*TW/(EMIN**2*TIN)+.145*GM1
      CALL SUMUP
C
C     SUM LAMINAR DRAG COMPONENTS, SETUP PROGRAM CONTROLS AND ETC.
      N1=N
      CDFL=CDF
      CDPL=CDP
      CDFTTL=CDFL+DCDFIP+DCDFTC
      CDPTTL=CDPL+DCDPIP
      IF(MODE.EQ.1) GO TO 70
      N1=N
   60 SMAX=RN*(PI/2.-SIGMA)+(RB-RN*SIN(PI/2.-SIGMA))/SIN(SIGMA)
      IF(N.EQ.1) MODE=3
      XMAX=SMAX-RN*(PI/2.-SIGMA)+RN/TAN(SIGMA)
      RFINAL=222.*EMC*PC*(TC+198.6)*XMAX*1.E6/TC**2
      DELRC=(RFINAL-RC(N))*XMAX/((XMAX-X(N))*100.)
C
C     TURBULENT BOUNDARY LAYER CALCULATIONS
      CALL TURB
      IF(ITRBLE.GT.0) GO TO 5
C
C     CALCULATE DRAG COEFFICIENT COMPONENTS FOR TURBULENT PORTION
      DELS=S(N1+1)-S(N1)
      CALL SUMUP
      CDFT=CDF
      CDPT=CDP
      CDFTTL=CDFTTL+CDFT
      CDPTTL=CDPTTL+CDPT
C
C     CALCULATE DRAG COEFFICIENT FOR SPHERICAL NOSE CAP
   70 CDN=((6.*EMIN**2/5.)**3.5*(6./(7.*EMIN**2-1.))**2.5-1.)*RNRB**2*
     1(1.-SIN(SIGMA)**4)/(1.4*EMIN**2)
C
C     CALCULATE BASE DRAG COEFFICIENT  (ASSUME VACCUUM)
      CDB=1./(GAM/2.*EMIN**2)
C
C     SUM UP LAMINAR AND TURBULENT COMPONENTS TO FORM TOTALS
      CDTTL=CDFTTL+CDPTTL+CDN
      CDTTLB=CDTTL+CDB
C
C     PRINT RESULTS
      CALL OUTPUT
      GO TO 5
       END
```

```
$IBFTC CONPRO  DD
C     THIS SUBROUTINE CALCULATES INVISCID SHARP CONE PROPERTIES
      SUBROUTINE PCMCTC
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,IW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,      RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,,PT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
      XKC=EMIN*SIGMA
      GP3=GAM+3.
      XKS=GP1*XKC/GP3+SQRT((GP1/GP3)**2*XKC**2+2./GP3)
C
C     CALCULATE CONE TEMPERATURE FROM REF. 3
      IF(EMIN*SIN(SIGMA).GT.1.) GO TO 10
      TCTIN=1.+.35*(EMIN*SIN(SIGMA))**1.5
      GO TO 25
   10 TCTIN=(1.+EXP(-1.-1.52*EMIN*SIN(SIGMA)))*(1.+(EMIN*SIN(SIGMA))**2/
     14.)
C
C     CALCULATE CONE PRESSURE FROM REF. 4
   25 PCPIN=1.+.7*EMIN**2*4.*SIN(SIGMA)**2*(2.5+8.*SQRT(EMIN**2-1.)*SIN
     1(SIGMA))/(1.+16.*SQRT(EMIN**2-1.)*SIN(SIGMA))
      PC=PCPIN*PIN
C
C     CALCULATE CONE MACH NUMBER FROM REF. 3
      UCUIN=COS(SIGMA)*SQRT(1.-SIN(SIGMA)/EMIN)
      EMC=UCUIN*EMIN/SQRT(TCTIN)
   40 TC=TCTIN*TIN
      CPC=(PCPIN-1.)/(GAM/2.*EMIN**2)
C
C     CALCULATE SHOCK WAVE ANGLE FOR SHARP CONE
      OMEGA=XKS/EMIN
      RETURN
       END
```

```
$IBFTC LAMNR.  DD,DECK
      SUBROUTINE LAMINR
C     THIS ROUTINE CALCULATES LOCAL PROPERTIES FOR THE LAMINAR PORTION
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,       RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
C
C     FUNCTION STATEMENT FOR LINEAR INTERPOLATION
      XINT(XPT,X1,X2,Y1,Y2)=Y1+(Y2-Y1)*(XPT-X1)/(X2-X1)
      IFEW=0
      IMANY=0
      IF(RN.GT.0.) GO TO 1
C
C     LAMINAR BOUNDARY LAYER CALCULATIONS FOR SHARP NOSED CONE
C     CALCULATE 100 POINTS OR EVERY .01 INCHES ALONG BODY
  195 DELX=SMAX/100.
      IF(DELX.LT..01) DELX=.01
      X(1)=0.
      N=101
C
C     CALCULATE T(PRIME)/T(C)
      TPTC=1.+.076*GM1*EMC**2+.481*(TW/TC-1.)
C
C     CALCULATE MU(PRIME)/MU(C)
      XMPMC=(TC+198.6)*TPTC*SQRT(TPTC)/(TPTC*TC+198.6)
C
C     CALCULATE F(2)  EQ. (23), REF. 5
      F2=.441*XMPMC/TPTC
      DO 200 J=1,101
C
C     CALCULATE REYNOLDS NUMBER BASED ON CONE PROPERTIES AND X
      RC(J)=222.*EMC*PC*X(J)*(TC+198.6)*1.E6/TC**2
C
C     CALCULATE R THETA(C)  EQ. (24), REF 5
      RTHC(J)=SQRT(F2*RC(J)/3.)
C
C     CALCULATE LOCAL SKIN FRICTION COEFFICIENT  EQ. (26), REF 5
      CF(J)=F2/RTHC(J)
C
C     CALCULATE BOUNDARY LAYER THICKNESS  EQ. (5), REF 5
      DELTA(J)=(6.1*TPTC+2.9)*RTHC(J)*X(J)/RC(J)
      EM1(J)=EMC
      T1(J)=TC
      RTH1(J)=RTHC(J)
      RES(J)=RC(J)
      CE=(T1(J)+198.6)*SQRT(TW/T1(J))/(TW+198.6)
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```
C
C     CALCULATE LOCAL CHI BAR PARAMETER
      CIBAR1(J)=EMC**3*SQRT(CE)/SQRT(RES(J))
      S(J)=X(J)
      IF(X(J).GE.SMAX) GO TO 150
      X(J+1)=X(J)+DELX
  200 CONTINUE
      J=101
      GO TO 150
C
C     LAMINAR BOUNDARY LAYER CALCULATIONS FOR BLUNTED CONE.
    1 ITRY=0
      XLIMIT=1.
      OMEGAS(1)=PI/2.
C
C     CALCULATE REYNOLDS NUMBER BASED ON CONE PROPERTIES AND NOSE RADIUS
      RBC=222.*PC*EMC*RN*((TC+198.6)/TC**2)*1.E6
C
C     CALCULATE REYNOLDS NUMBER BASED ON CONE PROPERTIES AND BOUNDARY-
C     LAYER MOMENTUM THICKNESS AT POINT OF TANGENCY.
      RTHCN=6.48*SQRT(1.5*RBC)
C
C     CALCULATE REYNOLDS NUMBER BASED ON CONE PROPERTIES AND DISTANCE
C     ALONG CONE SURFACE MEASURED FROM APEX TO TANGENCY POINT.
      RCN=222.*PC*EMC*RN*1.E6*(TC+198.6)/(TC**2*TAN(SIGMA))
C
C     CALCULATE BOUNDARY-LAYER GROWTH XI(NOSE) OVER THE NOSE BY METHOD
C     OF REF. 12 IN REF. 5.
      XRRRN=43./SQRT(RBC)
    5 IQUIT=0
      KODE=0
      DO 100 I=1,440
C
C     STARTING WITH PI/2 VARY OMEGA(S) IN INCREMENTS OF DELTA OMEGA(S)
   10 OMEGAS(I+1)=OMEGAS(I)-DELW
   20 SINWS2=SIN(OMEGAS(I+1))**2
      TANWS2=TAN(OMEGAS(I+1))**2
      COSWS2=COS(OMEGAS(I+1))**2
C
C     CALCULATE LOCAL MACH NO. FROM EQ. (11) REF 5.
      TEMP1=(GP1/(2.*GAM*EMIN**2*SINWS2-GM1))**(1./GAM)
      TEMP2=GP1*EMIN**2*SINWS2*(2.+GM1*EMIN**2)
      TEMP3=2.*(2.+GM1*EMIN**2*SINWS2)
      EM1TMP=SQRT(((TEMP1*TEMP2/TEMP3)/P1PIN**(GM1/GAM)-1.)/(GM1/2.))
C
C     CALCULATE XI FROM EQ. (21), REF 5.
      TEMP4=SQRT((2.+GM1*EMIN**2)/(2.+GM1*EM1TMP**2))
      XRRR(I)=.1755*EMIN*TEMP4/(P1PIN*SIN(SIGMA)*EM1TMP*(TANWS2-TANW2))
      IF(I.LE.1.OR.(XRRR(I)-XRRR(I-1)).LE.XLIMIT) GO TO 30
      DELW=DELW/2.
      GO TO 10
C
C     CALCULATE F(1) EQ. (13), REF 5.
   30 TEMP5=2.+GM1*EM1TMP**2-6.41
      TEMP6=EM1TMP**2*TANWS2/(2.*COSWS2*(TANWS2-TANW2))
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      TEMP7=(2.*GAM*EMIN**2*SINWS2-GM1)*(2.+GM1*EMIN**2*SINWS2)/
     1(EMIN**2*SINWS2-1.)**2
      TEMP8=1.+GM1*EM1TMP**2
      F1TMP=TEMP5/(TEMP6*TEMP7-TEMP8)
C
C     CALCULATE T(1) EQ. (18), REF 5.
      T1TMP=TC*(2.+GM1*EMC**2)/(2.+GM1*EM1TMP**2)
C
C     CALCULATE T(PRIME)/T(1) EQ. (4), REF 5.
      TPT1=1.+.076*GM1*EM1TMP**2+.481*(TW/T1TMP-1.)
C
C     CALCULATE MU(PRIME)/MU(1) FROM SUTHERLANDS VISCOSITY LAW.
      XMPM1=(T1TMP+198.6)*TPT1**1.5/(TPT1*T1TMP+198.6)
C
C     CALCULATE MU(1)/MU(C) FROM SUTHERLANDS VISCOSITY LAW.
      XM1MC=(TC+198.6)*(T1TMP/TC)**1.5/(T1TMP+198.6)
C
C     CALCULATE F(2) USING EQS. (16) AND (17), REF 5.
      F2=.441*EMC*SQRT(T1TMP/TC)*XM1MC*XMPM1/(TPT1*EM1TMP*(1.+F1TMP))
C
C     CALCULATE INTEGRAND IN EQ. (20), REF 5.
      YRRR(I)=2.*XRRR(I)/F2
      IF(KODE.GT.0) GO TO 50
C
C     IF XI IS BELOW THE LOWER LIMIT (XI(NOSE)), KEEP STEPPING OMEGA(S)
C     UNTIL XI EQUALS OR EXCEEDS LOWER LIMIT, INTERPOLATE IF NECESSARY.
      IF(XRRR(I).LE.XRRRN) GO TO 100
      IF(I.GT.1) GO TO 40
      DELW=DELW/2.
      GO TO 10
   40 YRRR(I-1)=XINT(XRRRN,XRRR(I-1),XRRR(I),YRRR(I-1),YRRR(I))
      XRRR(I-1)=XRRRN
      J=0
      KODE=1
      AREA=0
   50 J=J+1
C
C     USING TRAPEZOIDAL RULE, INTEGRATE THE INTEGRAL IN EQ. (20), REF 5.
      AREA=AREA+(YRRR(I)+YRRR(I-1))/2.*(XRRR(I)-XRRR(I-1))
C
C     CALCULATE R(C) EQ. (20), REF 5
      RC(J)=RBC*(3.*RBC*AREA+1./TAN(SIGMA)**3)**(1./3.)
C
C     CALCULATE X FROM R(C) AND CONE PROPERTIES.
      X(J)=RC(J)/(222.*PC*EMC*1.E6*(TC+198.6)/TC**2)
C
C     CALCULATE S USING X AND BODY GEOMETRY.
      S(J)=RN*(PI/2.-SIGMA)+(X(J)-RN/TAN(SIGMA))
      EM1(J)=EM1TMP
C
C     CALCULATE R THETA(C) USING R(C), EQ. (20) AND EQ(21), REF 5.
      RTHC(J)=XRRR(I)*RBC**2/RC(J)
      T1(J)=T1TMP
C
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C     CALCULATE R THETA(1) USING EQ. (22), REF. 5.
      RTH1(J)=RTHC(J)*EM1(J)*(T1(J)+198.6)*(TC/T1(J))**2/(EMC*(TC+198.6
     1 ))
C
C     CALCULATE REYNOLDS NUMBER BASED ON LOCAL PROPERTIES AND S.
      RES(J)=222.*P1*EM1(J)*S(J)*(T1(J)+198.6)*1.E6/T1(J)**2
C
C     CALCULATE LOCAL SKIN-FRICTION COEFFICIENT EQ. (3), REF. 5.
      CF(J)=.441*XMPM1/(RTH1(J)*TPT1)
      CE=(T1(J)+198.6)*SQRT(TW/T1(J))/(TW+198.6)
C
C     CALCULATE LOCAL CHI BAR PARAMETER.
      CIBAR1(J)=EM1(J)**3*SQRT(CE)/SQRT(RES(J))
      F1(J)=F1TMP
C
C     CALCULATE BOUNDARY LAYER THICKNESS EQ. (5), REF. 5.
      DELTA(J)=(6.1*TPT1+2.9)*RTHC(J)*X(J)/RC(J)
   54 IF(S(J)-SMAX) 100,150,60
   55 DELW=DELW/5.
      J=J-1
      AREA=AREA-(YRRR(I)+YRRR(I-1))/2.*(XRRR(I)-XRRR(I-1))
      IQUIT=1
      GO TO 10
C
C     CHECKS TO CONTROL NUMBER OF LOCAL VALUES CALCULATED OVER THE
C     LAMINAR PORTION.
C     IF ALL TURBULENT RUN, CALCULATE ONLY ONE LAMINAR POINT.
C     IF LAMINAR-TURBULENT RUN, CALCULATE MINIMUM 15 LAMINAR POINTS
C     UNLESS S(TR) LESS THAN SMAX/3.
C     IF ALL LAMINAR RUN, CALCULATE MINIMUM 25 POINTS WHEN FEASIBLE.
   60 IF(MODE.EQ.2.AND.J.EQ.1) GO TO 150
      IF(MODE.EQ.2.AND.J.GT.15) GO TO 170
      IF(MODE.EQ.2.AND.S(J).GT.(SMAX/3.)) GO TO 115
      IF(MODE.EQ.1.AND.J.LT.25) GO TO 115
      IF(IQUIT.GT.0) GO TO 170
      GO TO 55
  100 CONTINUE
C
C     INCREASE INTEGRATION INTERVAL TO CALCULATE FEWER POINTS.
C     QUIT AFTER 5 TRIES.
      IF(IFEW.EQ.1) GO TO 121
      IF(ITRY.GT.5) GO TO 106
      ITRY=ITRY+1
      IMANY=1
      XLIMIT=4.*XLIMIT
      DELW=4./57.29578
      GO TO 5
  106 WRITE(6,110) IDEN
  110 FORMAT(16H1IDENTIFICATION 2A6,10X,13HPROGRAM STOP    /
     180H0THERE ARE TOO MANY LAMINAR POINTS BEING CALCULATED - RN/RB PRO
     2BABLY TOO SMALL -   )
  111 ITRBLE=1
      N=J
      N1=N
      CALL OUTPUT
```

```
      IF(IMANY.NE.1) GO TO 150
      SIGMA=SIGMA/57.295
      ITRBLE=0
      WRITE(6,113)
  113 FORMAT(39H0THIS RUN WILL BE REPEATED WITH RN/RB=0   )
      RN=0.
      RNRB=0.
      GO TO 195
C
C     DECREASE INTEGRATION INTERVAL TO CALCULATE MORE POINTS.
C     QUIT AFTER 5 TRIES.
  115 IF(IMANY.EQ.1) GO TO 106
      IF(ITRY.GT.5) GO TO 121
      ITRY=ITRY+1
      IFEW=1
      XLIMIT=XLIMIT/4.
      DELW=(4./2.**(FLOAT(ITRY)*2.))/57.29576
      GO TO 5
  121 IF(J.GT.1) GO TO 170
      WRITE(6,130) IDEN
  130 FORMAT(16H1IDENTIFICATION 2A6,10X,13HPROGRAM STOP    /
     179H0THERE ARE TOO FEW LAMINAR POINTS BEING CALCULATED - RN/RB PROB
     2ABLY TOO LARGE -    )
      GO TO 111
C
C      DO LINEAR INTERPOLATION FOR LAST POINT.
  170 CF(J)=XINT(SMAX,S(J-1),S(J),CF(J-1),CF(J))
      X(J)= XINT(SMAX,S(J-1),S(J),X(J-1),X(J))
      EM1(J)=XINT(SMAX,S(J-1),S(J),EM1(J-1),EM1(J))
      T1(J)=XINT(SMAX,S(J-1),S(J),T1(J-1),T1(J))
      RC(J)=XINT(SMAX,S(J-1),S(J),RC(J-1),RC(J))
      RTHC(J)=XINT(SMAX,S(J-1),S(J),RTHC(J-1),RTHC(J))
      RTH1(J)=XINT(SMAX,S(J-1),S(J),RTH1(J-1),RTH1(J))
      DELTA(J)=XINT(SMAX,S(J-1),S(J),DELTA(J-1),DELTA(J))
      RES(J)=XINT(SMAX,S(J-1),S(J),RES(J-1),RES(J))
      F1(J)=XINT(SMAX,S(J-1),S(J),F1(J-1),F1(J))
      CIBAR1(J)=XINT(SMAX,S(J-1),S(J),CIBAR1(J-1),CIBAR1(J))
      S(J)=SMAX
  150 N=J
      RETURN
       END
```

```
$IBFTC TURB.   DD,DECK
      SUBROUTINE TURB
C     THIS ROUTINE CALCULATES LOCAL PROPERTIES FOR THE TURBULENT PORTION
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,       RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
C
C     SET N USED IN EQ. (12) AND (13), REF. 6 EQUAL TO 7.
      DATA EN/7./
C
C     FUNCTION STATEMENT FOR LINERAR INTERPOLATION.
      XINT(XPT,X1,X2,Y1,Y2)=Y1+(Y2-Y1)*(XPT-X1)/(X2-X1)
      J=N
      DELM=.05
C
C     USING EQ. (21), REF. 6, CALCULATE R THETA(C) AT A NEW POINT USING
C     VALUES AT A PREVIOUS POINT FOR C(F), F(1), R THETA(C), R(C) AND
C     A PREDETERMINED DELTA R(C).
   10 RTHC(J+1)=RTHC(J)+(CF(J)/(2.*(1.+F1(J)))-RTHC(J)/RC(J))*DELRC
C
C     INCREMENT R(C) BY DELTA R(C).
      RC(J+1)=RC(J)+DELRC
      ISKIP=0
C
C     START ITERATION FOR LOCAL MACH NUMBER M(1) AND OMEGA(S) USING EQS.
C     (22) AND (17), REF. 6.
C
C     INCREMENT M(1) AT PREVIOUS POINT BY DELTA M(1) AND USE AS A START-
C     ING VALUE, CALL IT M(1) FIRST.
      EM1(J+1)=EM1(J)+DELM
      K=1
   30 T1(J+1)=TIN*(2.+GM1*EMIN**2)/(2.+GM1*EM1(J+1)**2)
      TT1=T1(J+1)*(1.+GM1*EM1(J+1)**2/2.)
C
C     CALCULATE OMEGA(S) FROM EQ. (22), REF. 6.
      DTH=(EN+1.)*(EN+2.)/(EN+2.*(TT1-TW)/TT1)-(EN+2.)*(1.-(TT1-TW)
     1/TT1)/EN+GM1*EM1(J+1)**2*(.34+.18*(1.-(TT1-TW)/TT1))/2.
      IF(ISKIP.LT.0) GO TO 70
      TEMP1=1.125*EMIN*SQRT((2.+GM1*EMIN**2)/(2.+GM1*EM1(J+1)**2))/
     1(SIN(SIGMA)*P1PIN*EM1(J+1))
      TEMP2=TEMP1/(DTH*RC(J+1)*RTHC(J+1)/RBC**2)
      TEMP3=SQRT(TEMP2+TANW2)
      OMEGAS(J+1)=ATAN(TEMP3)
C
C     PLUG OMEGA(S) INTO EQ. (17) REF. 6, AND CALCULATE A NEW M(1), CALL
C     IT M(1) SECOND
```

```
      SINWS2=SIN(OMEGAS(J+1))**2
      COSWS2=COS(OMEGAS(J+1))**2
      TEMP1=GP1/(2.*GAM*EMIN**2*SINWS2-GM1)
      IF(TEMP1.GT.0.) GO TO 40
      EM1(J+1)=2.*EM1(J)-EM1(J-1)
      OMEGAS(J+1)=2.*OMEGAS(J)-OMEGAS(J-1)
      ISKIP=-1
      GO TO 30
   40 TEMP2=TEMP1**(1./GAM)
      TEMP3=GP1*EMIN**2*SINWS2*(2.+GM1*EMIN**2)/(2.*(2.+GM1*EMIN**2*SINW
     1S2))
      TEMP4=(TEMP2*TEMP3/P1PIN**(GM1/GAM)-1.)*(2./GM1)
      EM1TMP=SQRT(TEMP4)
      DEL1=EM1TMP-EM1(J+1)
C
C     COMPARE THE M(1) FIRST AND M(1) SECOND.
C     1) IF ABS(M(1) FIRST-M(1) SECOND) LESS THAN .001 ACCEPT THE VALUE
C     2) IF GREATER THAN .001 SET M(1) FIRST =(M(1) FIRST +M(1) SECOND)/2
C        AND TRY AGAIN.
C     3) IF ITERATION FAILS AFTER 100 PASSES, PRINT WARNING, ACCEPT
C        CURRENT VALUE AND CONTINUE TO NEXT POINT.
      IF( ABS(DEL1).LE.1.E-3) GO TO 60
      EM1(J+1)=(EM1(J+1)+EM1TMP)/2.
      K=K+1
      IF(K.LE.100) GO TO 30
      WRITE(6,50) IDEN,X(J)
   50 FORMAT(16H0IDENTIFICATION 2A6/91H0WARNING - SUBPROGRAM TURB - ITER
     *ATION FOR OMEGAS AND M1 FAILED AFTER 100 ITERATIONS AT X= 1PE11.2)
   60 EM1(J+1)=EM1TMP
      ISKIP=-1
      GO TO 30
   70 J=J+1
C
C     CALCULATE T(PRIME)/T(1)
      TPT1=(1.+.110*EM1(J)**2)*(1.-(.276+.0148*EM1(J))*(TT1-TW)/TT1-.449
     1*((TT1-TW)/TT1)**3)
C
C     CALCULATE MU(1)/MU(WALL)
      XMU1MW=(T1(J)/TW)**1.5*(TW/T1(J)+198.7/T1(J))/(1.+198.7/T1(J))
C
C     CALCULATE R THETA(1) EQ. (22), REF. 5
      RTH1(J)=RTHC(J)*EM1(J)*(T1(J)+198.6)*(TC/T1(J))**2/(EMC*(TC+198.6
     1 ))
C
C     CALCULATE THE DERIVATIVE D(DELTA/THETA-H)/DM1 FROM EQ. (14), REF.
C     6.  NOTE - EQ. IS INCORRECT IN REPORT. (TT1-TW)/TT1 SHOULD READ
C     TW/TT1.
      DTHDM1=GM1*EM1(J)*(.34+.18*TW/TT1)
C
C     CALCULATE F(1) EQ.(19), REF. 6.
      TEMP1=(2.+GM1*EM1(J)**2)-DTH
      TEMP2=1.+GM1*EM1(J)**2+EM1(J)*(2.+GM1*EM1(J)**2)/(2.*DTH)*DTHDM1
      TEMP3=EM1(J)**2*TANWS2/COSWS2*(2.*GAM*EMIN**2*SINWS2-GM1)*(2.+GM1
     1*EMIN**2*SINWS2)/(2.*(TANWS2-TANW2)*(EMIN**2*SINWS2-1 )**2)
      F1(J)=-TEMP1/(TEMP2-TEMP3)
```

```
C
C     CALCULATE X FROM R(C) AND CONE PROPERTIES.
      X(J)=RC(J)/(222.*PC*EMC*1.E6*(TC+198.6)/TC**2)
C
C     CALCULATE S USING X AND BODY GEOMETRY.
      S(J)=RN*(PI/2.-SIGMA)+X(J)-RN/TAN(SIGMA)
C
C     CALCULATE REYNOLDS NUMBER BASED ON LOCAL PROPERTIES AND S.
      RES(J)=222.*P1*EM1(J)*S(J)*(T1(J)+198.6)*1.E6/T1(J)**2
C
C     CALCULATE DELTA/THETA EQ. (12), REF. 6.
      DOVTH=(EN+1.)*(EN+2.)/(EN+2.*(TT1-TW)/TT1)+GM1*EM1(J)**2*(1.34
     1+1.38*(1.-(TT1-TW)/TT1))/2.
C
C     CALCULATE DELTA
      DELTA(J)=DOVTH*RTHC(J)*X(J)/RC(J)
C
C     CALL SUBROUTINE TO CALCULATE LOCAL C(F).
      CALL CFCALC(J)
      DELM=EM1(J)-EM1(J-1)
      IF(S(J)-SMAX) 10,90,80
C
C     INTERPOLATE FOR LAST TURBULENT POINT ON BODY.
   80 CF(J)=XINT(SMAX,S(J-1),S(J),CF(J-1),CF(J))
      X(J)= XINT(SMAX,S(J-1),S(J),X(J-1),X(J))
      EM1(J)=XINT(SMAX,S(J-1),S(J),EM1(J-1),EM1(J))
      T1(J)=XINT(SMAX,S(J-1),S(J),T1(J-1),T1(J))
      RC(J)=XINT(SMAX,S(J-1),S(J),RC(J-1),RC(J))
      RTHC(J)=XINT(SMAX,S(J-1),S(J),RTHC(J-1),RTHC(J))
      RTH1(J)=XINT(SMAX,S(J-1),S(J),RTH1(J-1),RTH1(J))
      DELTA(J)=XINT(SMAX,S(J-1),S(J),DELTA(J-1),DELTA(J))
      RES(J)=XINT(SMAX,S(J-1),S(J),RES(J-1),RES(J))
      S(J)=SMAX
   90 N=J
      RETURN
       END
```

```
$IBFTC SUMUP.  DD
      SUBROUTINE SUMUP
      DIMENSION SUM(6)
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,       RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
      DO 10 I=1,6
   10 SUM(I)=0.
C
C     USE RECTANGULAR INTEGRATION FOR THE FOLLOWING INTEGRALS.

      DO 20 I=N1,N
      TERM1=RN+(S(I)-ST)*SIN(SIGMA)
      TERM=P1PIN*(EM1(I)/EMIN)**2*TERM1*COS(SIGMA)*DELS
C
C     EVALUATE INTEGRAL FOR PRESSURE DRAG COEFFICIENT.
      SUM(1)=SUM(1)+CPC*TERM1*SIN(SIGMA)*DELS
C
C     EVALUATE INTEGRAL FOR SKIN FRICTION DRAG COEFFICIENT.
      SUM(2)=SUM(2)+TERM*CF(I)
      IF(MODE.EQ.2.AND.N1.NE.1) GO TO 20
      IF(MODE.EQ.3) GO TO 20
C
C     FOR LAMINAR FLOW ONLY.
      DE=.968*TW/(EM1(I)**2*T1(I))+.145*GM1
C
C     EVALUATE INTEGRAL FOR AVERAGE LOCAL CHI BAR PARAMETER.
      SUM(3)=SUM(3)+TERM1*CIBAR1(I)*DELS
C
C     EVALUATE INTEGRAL FOR INCREMENTAL INCREASE IN THE SKIN FRICTION
C     DRAG COEFFICIENT DUE TO TRANSVERSE CURVATURE.
      SUM(4)=SUM(4)+TERM*(CF(I)*(.517+.913*TW/T1(I)+.121*GM1*EM1(I)**2)
     1*CIBAR1(I)/(EM1(I)**3*TAN(SIGMA)*SQRT(3.)))
C
C     EVALUATE INTEGRAL FOR INCREMENTAL INCREASE IN THE SKIN FRICTION
C     DRAG COEFFICIENT DUE TO INDUCED PRESSURE.
      SUM(5)=SUM(5)+TERM*(CF(I)*(-1.152+.733*TW/T1(I)+(.528*GAM-.126)
     1*  EM1(I)**2)*DE*XF1*CIBAR1(I)/(GAM*EM1(I)**2))
C
C     EVALUATE INTEGRAL FOR INCREMENTAL INCREASE IN THE PRESSURE DRAG
C     COEFFICIENT DUE TO INDUCED PRESSURE.
      SUM(6)=SUM(6)+PCPIN*(XF1*DIN*CIBAR1(I)+XF2*DIN**2*CIBAR1(I)**2)
     1*TERM1*SIN(SIGMA)*DELS
   20 DELS=S(I+1)-S(I)
      IF(MODE.EQ.2.AND.N1.NE.1) GO TO 30
      IF(MODE.EQ.3) GO TO 30
```

```
      CIBARA=2.*SUM(3)/CONST
      DCDFTC=2.*SUM(4)/RB**2
      DCDFIP=2.*SUM(5)/RB**2
      DCDPIP=4.*SUM(6)/(GAM*EMIN**2*RB**2)
   30 CDP=2.*SUM(1)/RB**2
      CDF=2.*SUM(2)/RB**2
      RETURN
       END
```

```
$IBFTC CFALT.  DD
      SUBROUTINE CFALT(J)
C     THIS ROUTINE CALCULATES A LOCAL SKIN FRICTION COEFFICIENT FOR
C     TURBULENT FLOW WHENEVER THE ITERATION IN SUBROUTINE CFCALC FAILS
C     TO CONVERGE.  THE METHOD USED IS CONSIDERED SOMEWHAT LESS ACCURATE
C     THAN THE ITERATIVE METHOD.
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,       RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
      TERM1=ALOG10(2.*XMU1MW*RTH1(J))
      TERM2=(.8686+TERM1)*TERM1*TPT1
      CF(J)=.05856/TERM2
      IF(KEY.EQ.10) WRITE(6,5)
    5 FORMAT(1H1)
      KEY=20
      WRITE(6,10)
   10 FORMAT(40H ALTERNATE METHOD USED TO CALCULATE C(F) )
      RETURN
       END
```

```
$IBFTC CF.     DD
      SUBROUTINE CFCALC(J)
C     THIS ROUTINE CALCULATES LOCAL SKIN FRICTION COEFFICIENT FOR
C     TURBULENT FLOW.
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,      RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
C
C     SET PRANDTL NUMBER USED IN  EQ. (6), REF. 6 EQUAL TO .75
      DATA PR/0.75/
C
C     START ITERATION FOR C(BIG F) AND ETA(BIG F)
C     IF THIS IS THE FIRST PASS THRU, SET ETA(BIG F) = .5
C     AS A FIRST APPROXIMATION.  CALL IT ETAF1
      IF(KEY.EQ.0) ETAF1=.50
      KEY=10
C
C     CALCULATE BETA FROM EQ. (2), REF. 6.
      BETA=GM1*EM1(J)**2/(2.+GM1*EM1(J)**2)
C
C     CALCULATE RECOVERY TEMPERATURE TE1  EQ. (6), REF. 6
      TE1=(1.+PR**(1./3.)*GM1*EM1(J)**2/2.)*T1(J)
C
C     CALCULATE SUBLAYER PARAMETER S  EQ. (5), REF. 6
      SS=11.5+6.6*(TE1-TW)/TE1
C
C     CALCULATE PHI FROM DEFINITION PAGE 4, REF. 6
      PHI=SQRT(4.*BETA*(1.-(TT1-TW)/TT1)+((TT1-TW)/TT1)**2)
C
C     CALCULATE ETA FROM DEFINATION PAGE 3, REF. 6
      ETA=(2.*BETA-(TT1-TW)/TT1)/PHI
      KOUNT=1
   10 IF(ABS(ETAF1).LT.1.) GO TO 15
C
C     IF ITERATION HAS FAILED, USE ALTERNATE METHOD TO CALCULATE LOCAL
C     SKIN FRICTION COEFFICIENT.
   11 CALL CFALT(J)
      ETAF1=.5
      GO TO 70
C
C     CALCULATE C(BIG F) EQ. 10, REF. 6
   15 CBF=((.242*(ARSIN(ETA)-ARSIN(ETAF1)))/(-1.968+ALOG10(23.*XMU1MW*
     1RTH1(J)/SS)))**2/(BETA*TT1/T1(J))
C
C     PLUG CALCULATED VALUE FOR C(BIG F) INTO DEFINITION FOR ETA(BIG F)
C     PAGE 3, REF. 6.  CALL IT ETAF2
```

```
      ETAF2=(2.*BETA*SS*SQRT(TW*CBF/(T1(J)*2.))-(TT1-TW)/TT1)/PHI
C
C       COMPARE ETAF2 WITH ETAF1
C       IS ABSOLUTE DIFFERENCE LESS THAN .00001
C       IF YES  STOP ITERATION
C       IF NO  SET ETAF1=(ETAF2+ETAF1)/2. AND CONTINUE
      IF(ABS(ETAF2-ETAF1).LE.1.E-5) GO TO 50
      ETAF1=(ETAF2+ETAF1)/2.
      IF(KOUNT.GT.1000) GO TO 20
      KOUNT=KOUNT+1
      GO TO 10
   20 WRITE(6,30) IDEN,X(J)
   30 FORMAT(16H0IDENTIFICATION 2A6/91H WARNING - SUBPROGRAM CFCALC - IT
     *ERATION FOR ETAF AND CF FAILED AFTER 1000 ITERATION AT X= 1PE11.2)
   50 XRAY=1.-ETAF2**2
      IF(XRAY.GE.0.) GO TO 60
      GO TO 11
C
C      USING CALCULATED VALUES FOR ETA(BIG F) AND C(BIG F) SOLVE EQ. (9),
C      REF. 6 FOR LOCAL SKIN FRICTION C(SMALL F).
C      NOTE - EQ. (9) REF. 6 IS INCORRECTLY WRITTEN IN THE REPORT, THE
C      THIRD TERM IN THE NUMERATOR AND DENOMINATOR SHOULD BE MULTIPLIED
C      BY SUBLAYER PARAMETER S.
   60 TERM1=-1.968+ALOG10(23.*XMU1MW*RTH1(J)/SS)+.242*SS*SQRT(2.*BETA*
     1TW/TT1)/(PHI*SQRT(XRAY))
      TERM2=TERM1+1.968-1.099
      CF(J)=CBF*(TERM1/TERM2)
      ETAF1=ETAF2
   70 RETURN
       END
```

```
$IBFTC OUTPT.  DD
      SUBROUTINE OUTPUT
      COMMON DELM,DELRC,DELW,IQUIT,ISKIP,ITRBLE,ITRY,K,KODE,KEY,
     * LINES,MODE,N,N1,XLIMIT
      COMMON EMC,EMIN,GAM,IDEN(2),PC,PIN,RB,RLTR,RNRB,SIGMA,TIN,TW
      COMMON CDB,CDF,CDFL,CDFT,CDFTTL,CDN,CDP,CDPL,CDPT,CDPTTL,CDTTL,
     *CDTTLB,DCDFIP,DCDFTC,DCDPIP,CIBARA,TC
      COMMON CF(500),CIBAR1(500),DELTA(500),EM1(500),RC(500),
     *RES(500),RTHC(500),RTH1(500),S(500),T1(500),X(500)
      COMMON CONST,CPC,COSWS2,DELS,DIN,DOVTH,DTHDM1,GM1,GP1,
     * OMEGA,PCPIN,PI,       RBC,RCTR,RN,SINWS2,SMAX,SMAXT,
     *ST,TANW2,TANWS2,TPT1,TT1,XF1,XF2,XMAX,XMPM1,XMU1MW,XM1MC
      COMMON F1(500),OMEGAS(500),XRRR(750),YRRR(750)
      EQUIVALENCE (PC,P1),(PCPIN,P1PIN)
      AXIAL=RN*(1.-SIN(SIGMA))+(RB-RN*SIN(PI/2.-SIGMA))*COS(SIGMA)
     1/SIN(SIGMA)
      RLIN=222.*PIN*EMIN*AXIAL*1.E6*(TIN+198.6)/TIN**2
      SIGMA=SIGMA*57.29578
      LINES=0
      GO TO (10,30,40),MODE
   10 WRITE(6,20) IDEN
   20 FORMAT(16H1IDENTIFICATION  2A6,12X,14H  LAMINAR ONLY  )
      GO TO 50
   30 WRITE(6,35) IDEN
   35 FORMAT(16H1IDENTIFICATION  2A6,12X,19H  LAMINAR-TURBULENT   )
      GO TO 50
   40 WRITE(6,45) IDEN
   45 FORMAT(16H1IDENTIFICATION  2A6,12X,11H  TURBULENT  )
   50 WRITE(6,60) PIN,TIN,EMIN,PC,TC,EMC,SIGMA,TW,RNRB,RB,RLIN,RLTR
   60 FORMAT(1H0 12X 9HP (INF)= 1PE13.6,7X,9HT (INF)= 1PE13.6,7X,9HM (IN
     1F)= 1PE13.6/1H0 17X 4HPC= 1PE13.6,12X,4HTC= 1PE13.6,12X,4HMC= 1PE1
     23.6/1H0, 14X,7HSIGMA= 1PE13.6,6X,10HT (WALL)= 1PE13.6,9X,7HRN/RB=
     31PE13.6/1H0,17X,4HRB= 1PE13.6,6X,10HRL (INF)= 1PE13.6,
     4 7X,9HRL (TR)= 1PE13.6)
      LINES=LINES+9
      IF(ITRBLE.GT.0) GO TO 119
      GO TO (65,65,100), MODE
   65 WRITE(6,70) DCDPIP,DCDFTC,DCDFIP,CIBARA,CDFL,CDPL
   70 FORMAT(1H0,7X,14HD CDP(IP)(L)= 1PE13.6,2X,14HD CDF(TC)(L)= 1PE13.6
     1,2X,14H D CDF(IP)(L)= 1PE13.6/1H0,6X,15HCHIBAR AVG(L)= 1PE13.6,8X,
     28HCDF(L)= 1PE13.6,8X,8HCDP(L)= 1PE13.6)
      LINES=LINES+4
      GO TO (100,80),MODE
   80 WRITE(6,90) CDFT,CDPT
      LINES=LINES+2
   90 FORMAT(1H042X,8HCDF(T)= 1PE13.6,8X,8HCDP(T)= 1PE13.6)
  100 WRITE(6,110)CDN,CDFTTL,CDPTTL,CDB,CDTTL,CDTTLB
  110 FORMAT(1H0,10X,11HCD (NOSE)= 1PE13.6,3X,13HCDF (TOTAL)= 1PE13.6,
     13X,13HCDP (TOTAL)= 1PE13.6/1H0,2X,19HCD (BASE)(VACUUM)= 1PE13.6,4X
     2 12HCD (TOTAL)= 1PE13.6,4X,12HCD (TOTAL)= 1PE13.6/1H 41X,48HEXCLUD
     3ING BASE DRAG          INCLUDING BASE DRAG/1H0)
      LINES=LINES+7
      GO TO (119,119,111), MODE
  111 WRITE(6,115)
  115 FORMAT(1H0 5X, 1HX, 10X 1HS 9X 2HM1 9X 2HCF 11X 2HT1 8X 5HDELTA 8X
```

```
     13HRXC 10X 4HRTHC 9X 4HRTH1 8X 3HRS1   )
      GO TO 125
  119 WRITE(6,120)
  120 FORMAT(1H0 5X, 1HX 10X 1HS 9X 2HM1 9X 2HCF 11X 2HT1 8X 5HDELTA 8X
     13HRXC 10X 4HRTHC 9X 4HRTH1 8X 3HRS1 6X 7HCHIBAR1  )
  125 LINES=LINES+2
      IF(N1.EQ.1) N1=-1
      DO 220 I=1,N
      IF(I.GT.N1) GO TO 140
      WRITE(6,130) X(I),S(I),EM1(I),CF(I),T1(I),DELTA(I),RC(I),RTHC(I),
     1RTH1(I),RES(I),CIBAR1(I)
  130 FORMAT(1P4E11.2,1P7E12.3)
      GO TO 170
  140 IF(I.GT.(N1+1)) GO TO 160
      WRITE(6,150)
  150 FORMAT(10H0TURBULENT)
  160 WRITE(6,130)X(I),S(I),EM1(I),CF(I),T1(I),DELTA(I),RC(I),RTHC(I),
     1RTH1(I),RES(I)
  170 LINES=LINES+1
      IF(LINES.LT.52) GO TO 220
      WRITE(6,180) IDEN
  180 FORMAT(16H1IDENTIFICATION  2A6,4X,9HCONTINUED )
      GO TO (190,190,200),MODE
  190 IF(I.GT.(N1+1)) GO TO 200
      WRITE(6,120)
      GO TO 210
  200 WRITE(6,115)
  210 LINES=2
  220 CONTINUE
      RETURN
       END
$DATA
```

IDENTIFICATION CHECK RUN   LAMINAR-TURBULENT

P (INF)=	2,800000E-01	T (INF)=	5.400000E 02	M (INF)=	1.310000E 01
PC=	1.225439E 00	TC=	8.528590E 02	MC=	1.031745E 01
SIGMA=	6.300000E 00	T (WALL)=	5.400000E 02	RN/RB=	3.000000E-02
RB=	5.000000E-01	RL (INF)=	9.090164E 06	RL (TR)=	8.500000E 06
D CDP(IP)(L)=	3.475217E-04	D CDF(TU)(L)=	7.217505E-05	D CDF(IP)(L)=	2.310495E-05
CHIBAR AVG(L)=	1.996377E-01	CDF(L)=	5.283699E-03	CDP(L)=	2.622336E-02
		CDF(T)=	4.070429E-03	CDP(T)=	3.984049E-03
CD (NOSE)=	8.255762E-04	CDF (TOTAL)=	9.449407E-03	CDP (TOTAL)=	3.055493E-02
CD (BASE)(VACUUM)=	8.324523E-03	CD (TOTAL)= EXCLUDING BASE DRAG	4.082992E-02	CD (TOTAL)= INCLUDING BASE DRAG	4.915444E-02

X	S	H1	CF	T1	DELTA	RXC	RTHC	RTH1	RS1	CHIBAR1
1.51E-01	3.65E-02	3.29E 00	9.20E-03	6.011E 03	2.741E-03	6.107E 05	1.335E 03	5.057E 01	5.619E 03	7.530E-01
2.06E-01	9.21E-02	3.35E 00	6.78E-03	5.869E 03	3.575E-03	8.359E 05	1.724E 03	6.814E 01	1.476E 04	4.867E-01
2.74E-01	1.60E-01	3.42E 00	5.45E-03	5.690E 03	4.231E-03	1.110E 06	2.016E 03	8.412E 01	2.703E 04	3.817E-01
3.51E-01	2.37E-01	3.52E 00	4.52E-03	5.475E 03	4.794E-03	1.423E 06	2.249E 03	1.004E 02	4.287E 04	3.260E-01
4.37E-01	3.23E-01	3.63E 00	3.80E-03	5.227E 03	5.297E-03	1.774E 06	2.438E 03	1.179E 02	6.343E 04	2.921E-01
5.35E-01	4.21E-01	3.77E 00	3.20E-03	4.949E 03	5.754E-03	2.169E 06	2.588E 03	1.375E 02	9.063E 04	2.699E-01
6.45E-01	5.31E-01	3.93E 00	2.70E-03	4.644E 03	6.173E-03	2.616E 06	2.701E 03	1.599E 02	1.275E 05	2.547E-01
7.72E-01	6.58E-01	4.13E 00	2.27E-03	4.317E 03	6.559E-03	3.131E 06	2.775E 03	1.860E 02	1.789E 05	2.441E-01
9.21E-01	8.07E-01	4.35E 00	1.90E-03	3.970E 03	6.915E-03	3.738E 06	2.812E 03	2.170E 02	2.528E 05	2.356E-01
1.10E 00	9.38E-01	4.62E 00	1.57E-03	3.609E 03	7.249E-03	4.469E 06	2.812E 03	2.545E 02	3.627E 05	2.311E-01
1.33E 00	1.21E 00	4.93E 00	1.29E-03	3.239E 03	7.570E-03	5.378E 06	2.775E 03	3.008E 02	5.328E 05	2.268E-01
1.61E 00	1.50E 00	5.31E 00	1.04E-03	2.865E 03	7.895E-03	6.545E 06	2.705E 03	3.593E 02	8.080E 05	2.233E-01
2.00E 00	1.88E 00	5.76E 00	8.16E-04	2.493E 03	8.253E-03	8.106E 06	2.607E 03	4.357E 02	1.278E 06	2.197E-01
2.24E 00	2.13E 00	6.01E 00	7.17E-04	2.309E 03	8.465E-03	9.096E 06	2.552E 03	4.839E 02	1.637E 06	2.178E-01
2.54E 00	2.42E 00	6.30E 00	6.25E-04	2.129E 03	8.704E-03	1.029E 07	2.494E 03	5.406E 02	2.130E 06	2.155E-01
2.90E 00	2.78E 00	6.61E 00	5.40E-04	1.953E 03	8.982E-03	1.176E 07	2.433E 03	6.083E 02	2.823E 06	2.126E-01
3.35E 00	3.24E 00	6.95E 00	4.62E-04	1.782E 03	9.318E-03	1.360E 07	2.374E 03	6.907E 02	3.822E 06	2.090E-01
3.63E 00	3.51E 00	7.14E 00	4.25E-04	1.698E 03	9.516E-03	1.471E 07	2.347E 03	7.389E 02	4.486E 06	2.067E-01
3.94E 00	3.83E 00	7.33E 00	3.90E-04	1.617E 03	9.739E-03	1.599E 07	2.322E 03	7.929E 02	5.303E 06	2.042E-01
4.27E 00	4.15E 00	7.52E 00	3.60E-04	1.545E 03	9.968E-03	1.732E 07	2.301E 03	8.478E 02	6.214E 06	2.016E-01
TURBULENT										
4.31E 00	4.20E 00	8.98E 00	1.80E-03	1.114E 03	1.716E-02	1.750E 07	2.299E 03	1.464E 03	1.085E 07	
4.36E 00	4.25E 00	9.06E 00	1.74E-03	1.096E 03	1.815E-02	1.769E 07	2.401E 03	1.572E 03	1.128E 07	
4.41E 00	4.29E 00	9.13E 00	1.69E-03	1.080E 03	1.911E-02	1.787E 07	2.500E 03	1.676E 03	1.167E 07	
4.45E 00	4.34E 00	9.19E 00	1.65E-03	1.067E 03	2.003E-02	1.806E 07	2.595E 03	1.777E 03	1.205E 07	
4.50E 00	4.38E 00	9.24E 00	1.61E-03	1.055E 03	2.093E-02	1.824E 07	2.688E 03	1.874E 03	1.240E 07	
4.54E 00	4.43E 00	9.29E 00	1.58E-03	1.045E 03	2.180E-02	1.843E 07	2.778E 03	1.969E 03	1.274E 07	
4.56E 00	4.44E 00	9.30E 00	1.57E-03	1.042E 03	2.207E-02	1.849E 07	2.806E 03	1.999E 03	1.284E 07	

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
hypersonic drag						
slender cone						