A computer program for the calculation of the flow field including boundary layer effects for supersonic mixed-compression inlets at angle of attack

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A COMPUTER PROGRAM FOR THE CALCULATION OF THE FLOW FIELD INCLUDING BOUNDARY LAYER EFFECTS FOR SUPERSONIC MIXED-COMPRESSION INLETS AT ANGLE OF ATTACK

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SUMMARY

A computer program has been developed which is capable of calculating the flow field including the boundary layer for the supersonic portion of a mixed-compression aircraft inlet operating at angle of attack. The calculation procedure is based on using a zonal solution algorithm. The supersonic core flow is determined using the method of characteristics for steady three-dimensional flow. The bow shock wave and the internal shock wave system are computed using a discrete shock wave fitting procedure. The boundary layer flow adjacent to both the forebody/centerbody and the cowl is determined using an implicit finite difference algorithm. The flow in a shock wave-boundary layer interaction region is computed using an integral analysis.

The computer program has the capability to compute the internal flow field with or without the discrete fitting of the internal shock wave system. The option in which the internal shock wave system is not fitted can be employed in situations in which the strength of the internal shock wave system is weak, and thereby an acceptable solution can be obtained by smearing the internal discontinuities.

The influence of molecular transport can be included in the computation of the external flow about the forebody, and in the computation of the internal flow in which the shock waves are not discretely fitted. This is accomplished by treating the viscous and thermal diffusion terms in the governing partial differential equations as forcing functions, or correction terms, in the method of characteristics scheme.

The boundary layer computation allows for the specification of the wall temperature or normal temperature gradient at the wall. Moreover, distributed wall bleed effects can be accounted for in the analysis. Laminar, transitional, or fully turbulent boundary layer flows can be calculated.
The thermodynamic model, molecular transport properties, and turbulence model employed in the computer program are contained in a separate group of subroutines. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Dynamic viscosity is represented by Sutherland's law. Thermal conductivity is represented in terms of the dynamic viscosity and the laminar Prandtl number. Turbulent closure is achieved by use of a two-layer eddy viscosity formulation based on mixing length and velocity defect concepts. Alternative formulations may be employed by modifying the existing subroutines or by replacing them.

The contours of the centerbody and the cowl are represented by a separate subroutine. The existing subroutine has the capability to describe a variety of axisymmetric contours. Other geometries, such as those having elliptic or super-elliptic cross-sections, may be described by suitably modifying the existing subroutine or by replacing it.

A major assumption of the present analysis is that the cowl lip is contained in a given axial station. Moreover, it is assumed that both the centerbody contour and the cowl contour are smooth and have continuous first partial derivatives.

The computer program cannot:

1. compute a subsonic core flow,
2. compute the external flow field about the forebody if the bow shock wave does not exist entirely around the forebody, or
3. compute the internal flow field if the bow shock wave is ingested into the annulus.

The computer program is written in Fortran IV for CDC 6000 Series, 7000 Series, and CYBER computer systems. The program can be easily modified to be compatible with other computers.
SECTION I
INTRODUCTION

A computer program has been developed for calculating the flow field including boundary layer effects for the supersonic portion of a mixed-compression aircraft inlet operating at angle of attack. The general features of the inlet geometry and the flow field are illustrated in Figure 1. The theoretical analysis on which the computer program is based is presented by Vadyak and Hoffman (1). The present study represents an extension of an earlier investigation [(2), (3)] which was concerned solely with the computation of the supersonic core flow.

This report presents a discussion of the computer program organization, descriptions of the subroutines, a discussion of the input parameters, a brief interpretation of the output information, and sample cases to illustrate the application of the analysis.
FIGURE 1. MIXED-COMPRESSION AIRCRAFT INLET.
SECTION II
PROGRAM ORGANIZATION

1. INTRODUCTION

In this section, the program overlay structure is presented, and some general comments concerning program input and parameter initialization are made. The subroutines are identified which contain the thermodynamic model, the transport property representations, the turbulence model, and the formulations used for representing the centerbody and the cowl contours. The flow field integration options are briefly discussed, and some comments concerning program output are presented.

2. INTEGRATION OPTIONS

The computational flow regime is divided into two subregimes: the external flow field and the internal flow field (see Figure 1). If desired, only the external flow field may be computed. Alternatively, if the solution is known at the axial station of the cowl lip, the internal flow field may be determined without employing the forebody flow integration option.

The program has the capability to compute the internal flow field with or without the discrete fitting of the internal shock wave system in the supersonic core flow solution. The option in which shock waves are not discretely fitted might be employed if the strength of the internal shock wave system is relatively weak, and thereby an acceptable solution can be obtained by smearing all internal discontinuities.

The program can be executed with or without invoking the three-dimensional boundary layer calculation. The boundary layer calculation allows for the specification of distributed wall bleed and prescribed wall temperature or normal temperature gradient. Laminar, transitional, and fully turbulent boundary layer flows may be computed.

The analysis includes the influence of molecular transport in the computation of the supersonic core flow by treating the viscous and thermal diffusion terms in the governing partial differential equations as forcing functions, or correction terms, in the method of characteristics scheme. At present, the program has the capability to include the influence of molecular transport in the computation of the external flow field about the forebody, and in the computation of the internal flow field in which the shock waves are not discretely fitted. The program option in which the internal shock waves are discretely fitted does not have the capability to include the influence of molecular transport in the computation, but rather assumes the flow to be inviscid and adiabatic.
3. PROGRAM OVERLAY STRUCTURE

The overall program consists of 121 routines (16 program routines and 105 subroutines). The program is too large to be stored continuously in computer memory; hence an overlay scheme is employed. The overlay structure is presented in Figure 2. Three overlay levels are used: the resident overlay level, the primary overlay level, and the secondary overlay level.

OVERLAY (0,0)* is the resident overlay and controls the overall execution of the program. OVERLAY (0,0) calls the primary level overlays, OVERLAY (1,0), OVERLAY (2,0), OVERLAY (3,0), and OVERLAY (4,0). OVERLAY (1,0) is used for data input and parameter initialization. OVERLAY (1,0) calls the four secondary level overlays, OVERLAY (1,1), OVERLAY (1,2), OVERLAY (1,3), and OVERLAY (1,4). OVERLAY (1,1) is used for the internal generation of the supersonic core flow initial data using an approximate integration technique. OVERLAY (1,2) is employed for converting the output from OVERLAY (2,0) which generates the supersonic core flow initial data using the Jones algorithm (4). OVERLAY (1,3) is used to generate the three-dimensional boundary layer initial data for the forebody/centerbody geometry using the Adams finite difference algorithm (5). OVERLAY (1,4) is employed for the initialization of the boundary layer computational parameters.

The supersonic core flow solution is computed using the primary level overlay, OVERLAY (3,0), and the secondary level overlays, OVERLAY (3,1), OVERLAY (3,2), and OVERLAY (3,3). OVERLAY (3,0) contains the preponderance of the unit processes and the interpolation schemes. OVERLAY (3,1) contains the control logic used in performing the integration for the external flow field about the forebody. OVERLAY (3,2) contains the control logic used in determining the internal flow field in which shock waves are discretely fitted. OVERLAY (3,3) contains the control logic used in determining the internal flow field in which shock waves are not discretely fitted.

The three-dimensional boundary layer solution is computed using the primary level overlay, OVERLAY (4,0), and the four secondary level overlays, OVERLAY (4,1), OVERLAY (4,2), OVERLAY (4,3), and OVERLAY (4,4). OVERLAY (4,0) contains the overall control logic for the boundary layer computation. OVERLAY (4,1) contains the routines used for the attachment line flow solution and the three-dimensional flow solution. OVERLAY (4,2) is used for the computation of the three-dimensional shock wave-boundary layer interaction region. OVERLAY (4,3) is employed to account for boundary layer growth. OVERLAY (4,4) initializes the boundary layer solution on the cowl boundary using an approximate technique.

The computer program has a restart capability in which an internally generated restart file is retrieved from tape. When the restart option is used, control is returned to the integration control secondary level overlay which was in use at the time the initial execution was terminated [e.g., if the forebody flow was being computed, control is returned to OVERLAY (3,1)].

*Throughout the text, \( \bar{O} \) denotes the letter 0.
Figure 2. Program OVERLAY Structure.
Figure 2. Concluded.
4. DATA INPUT

The input data are entered through both namelist input and formatted read statements. Eleven namelists must always be specified: namelists LIST1 to LIST11. Namelist LIST1 contains the input parameters which specify the flow field integration options, the number of planes of symmetry, the output options, etc. Namelist LIST2 contains the parameters which specify the free-stream conditions, the vehicle orientation, and parameters associated with the specification of the initial-value plane. Namelist LIST3 specifies the number of circumferential and radial stations used in the computational mesh of the supersonic core flow solution. Namelist LIST4 specifies the thermodynamic model and the molecular transport properties. Namelist LIST5 contains the parameters which specify the centerbody and the cowl contours. Namelist LIST6 contains the parameters which specify the boundary layer computational mesh. Namelist LIST7 contains the input parameters which specify the wall temperature or its normal gradient for use in the boundary layer computation. Namelist LIST8 contains the parameters used for the specification of distributed wall bleed. Namelist LIST9 is used for specification of the turbulence model and transition criteria. Namelist LIST10 is used for specification of all convergence tolerances and iteration limits. Namelist LIST11 specifies the parameters used for debug output.

In addition to the namelist input, the two-dimensional initial-value plane for the supersonic core flow can be input by formatted read statements. Alternatively, if the forebody is conical ahead of the axial location of the initial-value plane, the initial data may be generated internally in the computer program by one of two techniques.

The initial data for the boundary layer calculation can be input by formatted read statements. Alternatively, for conical forebody flows, the boundary layer initial data for the forebody/centerbody geometry can be generated internally in the computer program by a finite difference calculation. The cowl boundary layer initial data can also be generated internally using an approximate technique.

All input data are read within routine LINK10. After the data have been entered, selected input parameters are checked for errors and consistency. If any errors are detected, appropriate messages are printed and the execution of the program is aborted. The input parameters are tested in subroutine INITIL.

It should be noted that many input parameters have default values and do not have to be specified. The default values for most of the input parameters are specified in LINK00.

After all input parameters and data have been entered, parameter initialization (for most of the subroutines) is performed in subroutine INITIL.
5. INITIAL DATA SPECIFICATION

The initial data for the supersonic core flow must be specified on a space-like plane of constant x (see Figure 1). The flow must be supersonic at every point specified. The x-coordinate axis constitutes the longitudinal axis of the centerbody and the cowl. Moreover, the mean flow direction is assumed to be in the x-coordinate direction.

If the forebody flow field is to be determined, the initial-value plane must be specified at an axial (x) station that is upstream of the forebody computational flow regime (see Figure 1). The solution is then found along the streamlines that pass through the data points specified on the initial-value plane, although some streamline addition and deletion are performed on the ensuing solution planes. The axial location of the last solution plane of the forebody flow field is adjusted to lie at the axial station of the cowl lip, and constitutes the initial-value plane for the internal flow field computation.

If only the internal flow field is to be determined, the initial-value plane must be specified at the axial station which corresponds to the x-position of the cowl lip (see Figure 1). The cowl lip is assumed to be contained in a plane of constant x. For the internal flow field integration, a point redistribution is performed on the initial-value plane. This point redistribution is required to define streamlines which lie in the stream surface formed by the cowl boundary. The solution is then found along the streamlines that pass through the redistributed points on the plane at the cowl lip axial station. It should be noted that the internal flow field cannot be computed if the bow shock wave is ingested into the annulus.

The supersonic core flow initial data may be specified externally by the user. The user supplied data are entered by a formatted read of the file ITAPI.

Alternatively, if the forebody is conical ahead of the axial location of the initial-value plane, the supersonic flow property field on the initial-value plane can be generated internally in the computer program by one of two methods. One method of internally generating the initial-value plane is by using an approximate technique which employs the Taylor-Maccoll solution for the flow about a circular cone at zero incidence. A superposition procedure is used to obtain an approximation to the flow about a circular cone at nonzero angle of attack by neglecting the cross flow effects. This superposition procedure effectively amounts to computing the flow turning angle in the meridional plane of the given solution point, and then obtaining the flow properties at that point by applying the Taylor-Maccoll solution for a cone half-angle equal to the flow turning angle. It must be emphasized that this is only an approximate technique, giving the well accepted Taylor-Maccoll solution at zero incidence, but becoming increasingly less accurate as the angle of attack is increased. Subroutines LINK11, TMCONE, INTEGR, LOGIC, C0VNG, DESL, and FUNCTM are used to generate internally the supersonic core flow initial-value plane property field.

The other method of internally generating the supersonic flow initial data is based on the numerical integration algorithm developed by Jones (4). The solution obtained by Jones for the flow about a circular cone at nonzero inci-
dence has been well substantiated. For situations in which the forebody is conical up to the axial station where the initial-value plane is located, the Jones program is the recommended source for the initial data. The Jones algoritihm has been incorporated into the present computer program in OVERLAY (2,0). Routines LINK20, JONALG, FUNCTN, CHI, FA, JSHOCK, SRFACE, PMC, ZEROSN, FAI, FN, RINIT, RKSTEP, DWEG, MAINM, MINIV, INVERT, DSOLV, and BODY comprise the Jones algorithm and are used to internally generate the supersonic core flow initial-value plane property field. To make the output of the Jones algorithm compatible with the bicharacteristic scheme developed herein, data conversion is performed in subroutines LINK12, STENCL, REFLK, and BI.

If the boundary layer flow is to be computed, then the initial data must be specified for the forebody flow if the external flow is to be determined, and for the forebody/centerbody flow and the cowl flow if the internal flow is to be determined. Data for the boundary layer computation must be specified on a body normal grid. This grid will, in general, not coincide with a plane of constant x. The axial location for specification of the forebody/centerbody boundary layer initial data coincides with the axial location used for the supersonic core flow initial data specification. The axial location for specification of the cowl boundary layer initial data is always at the first computational station inside the annulus since the cowl boundary layer thickness is identically zero at the cowl lip.

The boundary layer flow initial data may be specified externally by the user. The user supplied data is entered by a formatted read of the file ITAP2 for input of the forebody/centerbody initial data, and by a formatted read of file ITAP3 for input of the cowl initial data.

Alternatively, if the forebody is conical ahead of the axial station of the initial-data plane, the forebody/centerbody boundary initial data may be generated internally in the computer program by using the finite difference algorithm developed by Adams (5). Laminar or turbulent flows may be determined using the Adams analysis. The Adams algorithm has been incorporated into the present computer program in OVERLAY (1,3). Subroutines LINK13, SADAMS, PEQS, INTER, QEFF, BINQ, and VEL comprise the Adams algorithm and are used to generate internally the forebody/centerbody boundary layer initial data. Routine LINK14 is used to initialize the appropriate parameters for the forebody/centerbody boundary layer computation.

The cowl boundary layer initial data may also be generated internally using the approximate analysis contained in routine LINK44.

6. THERMODYNAMIC MODEL

The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models can be incorporated into the computer program by suitably modifying or replacing subroutines THERMO, STAG, TGRAD, JUMP, TMFILE, LOGIC, FUNCTN, THERMH, TGRADD, and THERMD. The initial-data generation routines contained in OVERLAY (1,3) and OVERLAY (2,0) also require modification.
7. MOLECULAR TRANSPORT PROPERTIES

Both the dynamic viscosity and the thermal conductivity are assumed to be functions of the temperature only. The assumed functional form for the dynamic viscosity is given by Sutherland's law (6). The assumed functional form for the thermal conductivity is expressed in terms of the dynamic viscosity through use of the laminar Prandtl number. Other representations for the dynamic viscosity and the thermal conductivity can be incorporated into the analysis by suitably modifying or replacing subroutines TPRPS and LVIS. The initial-data generation routines in OVERLAY (1,3) also require modification.

8. TURBULENCE MODEL

A two-layer eddy viscosity formulation has been incorporated into the computer program in order to achieve mathematical closure (7). The model is based on a mixing length formulation for the inner region and a velocity defect formulation for the outer region. The model assumes isotropic turbulence and accounts for mass transfer at the wall. The turbulent eddy thermal conductivity is expressed in terms of the eddy viscosity and the turbulent Prandtl number. Alternate turbulence models may be incorporated into the analysis by suitably modifying or replacing subroutine TURB.

9. CENTERBODY AND COWL CONTOURS

The computer program developed in the present investigation assumes that both the centerbody contour and the cowl contour are axisymmetric. For the purposes of geometry description, the axial (x) domain is divided into a number of intervals. In any interval, the body radius may be specified by either tabular input, or by supplying the coefficients of a cubic polynomial written as a function of x. It is assumed that both the centerbody contour and the cowl contour are smooth and have continuous first derivatives. More arbitrary geometries, such as those having elliptic or super-elliptic cross-sections, can be incorporated into the analysis by suitably modifying or replacing subroutines BBOUNDY, GEØD, and XCURV. The initial-data generation subroutines in OVERLAY (1,1), OVERLAY (1,2), OVERLAY (1,3), and OVERLAY (2,0) also require modification for noncircular cross-sections.

10. FLOW SYMMETRY

Four flow symmetry options have been incorporated into the computer program for cases in which the boundary layer computation is not invoked. The most general case is when no planes of symmetry exist. This option is used to compute the flow field for fully three-dimensional inlets at incidence. The second case is when one plane of symmetry exists. This option is used for computing the flow field for axisymmetric inlets at incidence. The third case is when two planes of flow symmetry exist. This option is used to compute the flow field for three-dimensional inlets with two planes of geometric symmetry at zero angle of attack. The final option is when the flow is axisymmetric. This option is used to compute the flow field in axisymmetric inlets at zero incidence.
One flow symmetry option has been incorporated into the computer program for cases in which the boundary layer is to be determined. This option is for the case of one plane of flow symmetry.

11. OUTPUT

Preliminary information is printed by LINKIO. The initial-value plane for the supersonic core flow and all subsequent solution planes are printed by subroutine PRNOUT. The solution points on the space curves defined by the intersection of the internal shock wave with the solid boundaries are output by subroutine SHKRFL. In addition to the position of and the dependent variables at a solution point, the Mach number, static temperature, velocity magnitude, stagnation pressure, and stagnation temperature are also printed. The mass flow rate across every solution plane, calculated by trapezoidal rule integration in subroutine MASS, is also printed.

The initial data and subsequent solution surfaces for the boundary layer calculation are printed by subroutine DECODE. The output consists of position, velocity components, pressure, density, temperature, velocity magnitude, stagnation pressure, stagnation temperature, bleed rate, and certain integral parameters.
SECTION III
SUBROUTINE DESCRIPTIONS

1. INTRODUCTION

In this section, a brief description is given of the function of each subroutine in the computer program. This information supplements the information available in the form of comment statements within the program.

2. OVERLAY (0,0)

LINKO0. This program routine is the main control routine in OVERLAY (0,0), the resident overlay. LINKO0 first calls OVERLAY (1,0) for data input, parameter initialization, and, if desired, internal generation of the initial data. LINKO0 then calls OVERLAY (3,0) and OVERLAY (4,0) to perform the flow field integration. Most of the program constants and input parameters have their default values specified in LINKO0. Moreover, the reader and printer call numbers, denoted by IRE and IWR, respectively, are initialized in LINKO0.

BOUNDY. This subroutine is used for the specification of both the forebody/centerbody and cowl geometries. The version of BOUNDY supplied with the program assumes that both the forebody/centerbody and the cowl are axisymmetric. More arbitrary geometries can be described by suitably modifying or replacing this subroutine. If BOUNDY is replaced, the subroutine argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- XABS: x-coordinate
- Y: y-coordinate
- Z: z-coordinate
- ALPHA: polar angle defined by \( \tan^{-1}(z/y) \)
- RBODY: radius of either forebody/centerbody or cowl
- BNX: x-component of outward body normal unit vector to forebody/centerbody or cowl
- BNY: y-component of outward body normal unit vector to forebody/centerbody or cowl
- BNZ: z-component of outward body normal unit vector to forebody/centerbody or cowl
- J: If J=1, forebody/centerbody geometry is to be specified. If J=2, cowl geometry is to be specified.

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K. If K=0, read in XABS and ALPHA, and compute RBØDY and the corresponding Y and Z. If K=1, read in XABS and ALPHA, and compute RBØDY, Y, Z, BNX, BNY, and BNZ. If K=2, read in XABS, Y, and Z (coordinates of a point not on the body), and compute RBØDY, ALPHA, Y, Z, BNX, BNY, and BNZ at the point on the body where the projection of the body normal in the (y,z)-plane passes through the originally specified point.

THERMØ. This subroutine computes the temperature, sonic speed, and the thermodynamic parameter \( \xi \). The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If subroutine THERMØ is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- \( P \): pressure (\( p \))
- \( RØ \): density (\( p \))
- \( T \): temperature (\( t \))
- \( A \): sonic speed (\( a \))
- \( CØEFF \): \( \xi = (1/\rho t)(\partial p/\partial s)_\rho \), where \( s \) is the entropy per unit mass
- \( KT \): If \( KT = 1 \), compute \( T \). If \( KT \neq 1 \), do not compute \( T \).
- \( KA \): If \( KA = 1 \), compute \( A \). If \( KA \neq 1 \), do not compute \( A \).
- \( KC \): If \( KC = 1 \), compute \( CØEFF \). If \( KC \neq 1 \), do not compute \( CØEFF \).

Thermodynamic property information is supplied to subroutine THERMØ through the named common block GASI. This common block contains the following parameters: RUNIV (universal gas constant), TDT (temperature data array), WTMØL (molecular weight data array), CP (specific heat data array), NGAS1 (an integer to denote the number of elements in the TDT, WTMØL, and CP arrays), and KGAS1 (an integer to denote which gas model is to be used). These parameters are included for modifying subroutine THERMØ to include real gas effects.

STAG. This subroutine computes the Mach number, the stagnation pressure, and the stagnation temperature. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If STAG is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- \( P \): static pressure
- \( RØ \): static density
- \( T \): static temperature
- \( A \): sonic speed
- \( Q \): velocity magnitude
- \( XM \): Mach number
Thermodynamic property information is supplied to subroutine \texttt{STAG} through the named common block \texttt{GAS1}.

\texttt{THERMH}. This subroutine computes the pressure, density, temperature, and specific enthalpy. Any two variables may be computed given the remaining two. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If subroutine \texttt{THERMH} is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- $P$: pressure
- $\rho$: density
- $T$: temperature
- $H$: specific static enthalpy
- $K_{\text{OPT}}$:
  - If $K_{\text{OPT}}=1$, compute $\rho$ and $T$ given $P$ and $H$.
  - If $K_{\text{OPT}}=2$, compute $T$ and $H$ given $P$ and $\rho$.
  - If $K_{\text{OPT}}=3$, compute $\rho$ and $H$ given $P$ and $T$.
  - If $K_{\text{OPT}}=4$, compute $H$ given $P$ and $T$.
  - If $K_{\text{OPT}}=5$, compute $\rho$ and $T$ given $H$ and $P$.

Thermodynamic property information is supplied to subroutine \texttt{THERMH} through the named common block \texttt{GAS1}.

\texttt{TGRADB}. This subroutine computes the spatial gradients of temperature by using an analytically differentiated form of the thermal equation of state so that temperature derivatives can be expressed in terms of the derivatives of pressure and density. The assumed thermodynamic model is that of a thermally perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If \texttt{TGRADB} is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- $P$: pressure
- $\rho$: density
- $D_P$: first partial spatial derivative of pressure
- $D_\rho$: first partial spatial derivative of density
- $D_T$: first partial spatial derivative of temperature

Thermodynamic property information is supplied to subroutine \texttt{TGRADB} through the named common block \texttt{GAS1}.
LVIS. This subroutine computes the dynamic viscosity and its spatial gradient. The assumed functional form for dynamic viscosity is given by Sutherland's Law (6). Other transport property formulations may be incorporated into the analysis by suitably modifying or replacing this subroutine. If LVIS is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- T: static temperature
- P: static pressure
- VIS: dynamic viscosity
- DTY: first partial spatial derivative of temperature
- DPY: first partial spatial derivative of pressure
- DVISY: first partial spatial derivative of viscosity
- KOPT: if KOPT=1, compute VIS. If KOPT=2, compute DVISY.

Transport property information is supplied to subroutine LVIS through the named common block GAS2. The common block GAS2 contains the following parameters:
- TDL (temperature data array)
- VISD (viscosity data array)
- COND (thermal conductivity data array)
- NGAS2 (an integer to denote the number of elements in the TDL, VISD, and COND arrays)
- KGAS2 (an integer to denote which transport property model is to be used)

These parameters are included for modifying LVIS to use tabular data.

QUAD. This subroutine determines the three coefficients in the univariate quadratic interpolation polynomial.

GELG. This subroutine is used for solving a system of simultaneous linear equations. The system is solved using Gaussian elimination with complete pivoting. This subroutine is IBM library subroutine GELG.

SYMSIM. This subroutine solves a system of simultaneous linear equations with a symmetric coefficient matrix. The system is solved using Gaussian elimination with pivoting in the main diagonal. This subroutine is a modified version of IBM library subroutine GELS.

WTRANS. This subroutine determines the wall transpiration/suction parameters for use in the computation.

CONVRT. This subroutine obtains the base axial coordinate of a point on the body given the streamwise curvilinear coordinate.

3. OVERLAY (1,0)

LINK10. This program routine is the main control routine in OVERLAY (1,0). All input parameters and initial data are entered in LINK10. In all cases, the eleven namelists LIST1 to LIST11 are entered. If the flow property field on the initial-value plane is externally specified, a formatted read is used to enter this information. After the input data have been entered, subroutine
INITIL is called for testing for input errors and performing parameter initialization. If the flow property field on the initial-value plane is to be internally generated, the appropriate subroutines are then called from subroutine INITIL. After subroutine INITIL has been called, preliminary output is printed by LINK10.

**INITIL**: This subroutine is called from routine LINK10, and is used to test for errors on selected input parameters and to perform parameter initialization. If an input parameter error is found, an appropriate message is generated and the program execution is aborted. After the selected input parameters have been tested, parameter initialization is performed. If the flow property field on the initial-value plane is to be internally generated, the appropriate subroutines are then called.

4. **OVERLAY (1,1)**

**LINK11**: This program routine is the main control routine in OVERLAY (1,1), and is used in conjunction with subroutines TMCONE, INTEGR, LOGIC, CVNVRG, DESLVL, and FUNCTM to internally generate the supersonic flow property field on the initial-value plane if the forebody is conical ahead of the initial-value plane. The internally generated initial-value plane is obtained by an approximate technique which employs the Taylor-Maccoll solution for the flow about a circular cone at zero incidence. A superposition procedure is used to obtain an approximation to the flow about a circular cone at nonzero angle of attack by neglecting the cross flow effects. This superposition procedure effectively amounts to computing the flow turning angle in the meridional plane of the given solution point, and then obtaining the flow properties at that point by applying the Taylor-Maccoll solution for a cone half-angle equal to the flow turning angle. The shock wave angle is then measured from the original streamline direction in the appropriate meridional plane. It must be emphasized that this is only an approximate technique, giving the well accepted Taylor-Maccoll solution at zero angle of attack, but becoming increasingly less accurate as the angle of attack is increased.

**TMCONE**: This subroutine is one of the subroutines used for the internal generation of the initial-value plane. TMCONE is called from routine LINK11 and performs initialization and post calculation storage of the Taylor-Maccoll solution used in computing the initial-value plane supersonic flow property field. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying this subroutine. Thermodynamic property information is supplied to subroutine TMCONE through the named common block GAS1.

**INTEGR**: This subroutine is one of the subroutines used in internally generating the supersonic flow property field on the initial-value plane. INTEGR integrates the Taylor-Maccoll equation inward towards the forebody until a point is reached where the normal component of velocity is sufficiently small.
LOGIC. This subroutine is one of the subroutines used in internally generating the supersonic flow property field on the initial-value plane. LOGIC is used to control the computation of the Taylor-Maccoll solution in a particular meridional plane. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying this subroutine. Thermodynamic property information is supplied to subroutine LOGIC through the named common block GAS1.

CONVRG. This subroutine is one of the subroutines used in internally generating the supersonic flow property field on the initial-value plane. CONVRG is used in testing if the normal component of velocity has vanished at the body in the external flow field integration.

ODESLV. This subroutine is one of the subroutines used in internally generating the supersonic flow property field on the initial-value plane. ODESLV integrates the Taylor-Maccoll equation by employing a fourth-order Runge-Kutta method.

FUNCTM. This function is used in internally generating the supersonic flow property field on the initial-value plane. FUNCTM evaluates the Taylor-Maccoll equation. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying this function. Thermodynamic property information is supplied to FUNCTM through the named common block GAS1.

5. OVERLAY (1,2)

LINK12. This program routine is the main control routine in OVERLAY (1,2) and is used in conjunction with subroutines STENCL, REFLK, and BI in converting the output of the Jones algorithm into a format which is compatible with the bicharacteristic algorithm. The Jones algorithm is contained in OVERLAY (2,0) and is used to internally generate the supersonic flow property field on the initial-value plane. The assumed thermodynamic model employed in LINK12 is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying this routine. Thermodynamic property information is supplied to routine LINK12 through the named common block GAS1.

STENCL. This subroutine is one of the subroutines used for conversion of the Jones algorithm output so that it can be used as initial data for the supersonic flow solution. STENCL determines the stencil of field points to be used in the bivariate interpolation of the initial data.

REFLK. This subroutine is one of the subroutines used for conversion of the Jones algorithm output so that it can be used as initial data for the supersonic flow solution. REFLK performs field point reflections about the plane of flow symmetry.
BI. This subroutine is one of the subroutines used for conversion of the Jones algorithm output so that it can be used as initial data for the supersonic flow solution. BI determines the coefficients of the least squares quadratic bivariate polynomial used for interpolation of the initial data. The system of normal equations which determines the polynomial coefficients is solved by calling subroutine SYMSIM.

6. _OVERLAY (1,3)

_LINK13. This program routine is the main control routine in _OVERLAY (1,3) and is used in conjunction with subroutines SADAMS, PEQSØ, INTER, CŒEFF, BINQ, and VEL to internally generate the initial data for the forebody/centerbody boundary layer computation. The initial data generation is accomplished by using the Adams finite-difference algorithm (5), which is incorporated into the computer program. _OVERLAY (1,3). The Adams algorithm generates the initial data at a specified axial location, assuming that the forebody/centerbody geometry is conical ahead of that location. It is also assumed in the analysis that the wall temperature is a specified constant, that the thermodynamic model is that of a thermally and calorically perfect gas, and that dynamic viscosity is given by Sutherland's Law (6). Other thermodynamic and molecular transport models may be incorporated into the analysis by suitably modifying the subroutines in _OVERLAY (1,3). Thermodynamic and molecular transport property information is supplied to routine _LINK13 through the named common blocks GAS1 and GAS2.

_SADAMS. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _SADAMS is the main control routine in the Adams finite-difference algorithm.

_PEQSØ. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _PEQSØ solves the system of parabolic differential equations generated in the analysis.

.INTER. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _INTER is used to perform Lagrangian interpolation.

_CŒEFF. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _CŒEFF is used to obtain the surface properties given the surface pressure distribution.

_BINQ. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _BINQ solves the system of simultaneous linear equations used in the Newton iteration scheme.

_VEL. This subroutine is one of the subroutines used for the internal generation of the forebody/centerbody boundary layer initial data. _VEL is used to interpolate the surface properties determined by subroutine _CŒEFF.
7. OVERLAY (1,4)

LINK14. This program routine is the main control routine in OVERLAY (1,4) and is used to initialize the transformed variables used in the boundary layer computations.

8. OVERLAY (2,0)

LINK20. This program routine is the main control routine in OVERLAY (2,0) and is used in conjunction with subroutines JNALG, FUNCTN, CHI, FA, JSHOCK, SRFC, PMC, ZEROSN, FAI, FN, RKINIT, RKSTEP, DWE, MAINM, MINIV, INVERT, DSOLV, and BODY to internally generate the supersonic property field on the initial-value plane if the forebody is conical ahead of the initial-value plane. The internally generated initial-value plane is obtained by using the Jones finite difference algorithm (4). The Jones algorithm has been incorporated into the computer program in OVERLAY (2,0). It is assumed that the thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying the subroutines in OVERLAY (2,0). Thermodynamic property information is supplied to routine LINK20 through the named common block GASI. All of the subroutines in OVERLAY (2,0) are used for the internal generation of the supersonic flow initial data.

JNALG. JNALG is the main control routine for the Jones algorithm.

FUNCTN. FUNCTN computes the surface residual mass flow functions which are to be minimized.

CHI. CHI computes certain output parameters.

FA. FA computes gradient parameters that are used in subroutine PMC.

JSHOCK. JSHOCK computes the flow properties immediately downstream of the bow shock wave.

SRFACE. SRFC finds the initial approximation to the surface solution.

PMC. PMC is used for numerically integrating the governing differential equations.

ZEROSN. ZEROSN is used to calculate the solution for a circular cone at zero incidence.

FAI. FAI computes the derivatives used in the Runge-Kutta integration for the zero incidence solution.

FN. FN controls the Runge-Kutta integration for the zero incidence solution.

RKINIT. RKINIT computes functions used in the zero incidence solution.
RKSTEP. RKSTEP performs one Runge-Kutta integration step for the zero incidence solution.

DWEG. DWEG is used for computing zeros of an equation.

MAINM. MAINM performs functional minimization applied for obtaining a minimum normal velocity at the body surface.

MINIV. MINIV is used for functional minimization.

INVERT. INVERT is used to perform matrix inversion.

DSOLV. DSOLV uses Gaussian elimination for solving systems of linear equations.

BODY. BODY is used to define conical geometries.

9. ØVERLAY (3,0)

LINK30. This program routine is the main control routine in ØVERLAY (3,0). LINK30 calls the supersonic flow integration control overlays, ØVERLAY (3,1), ØVERLAY (3,2), and ØVERLAY (3,3). If a program restart is specified, the last secondary level overlay that was in use at the time the initial execution was terminated is called.

REDIST. This subroutine is used to perform point redistribution on the solution plane at the axial station of the cowl lip. This point redistribution is required to obtain a uniform point distribution and to obtain streamlines which lie in the stream surface formed by the cowl boundary. The redistributed points are arranged symmetrically in the computed sector. These points lie on rays which have equal angular increments from one another, with the points on each ray being spaced at equal radial increments. The flow properties at these points are obtained by bivariate interpolation. If the viscous flow option is specified and the internal flow field integration option in which shock waves are not discretely fitted is specified, point redistribution is also performed on the forebody flow field solution plane immediately upstream of the solution plane located at the cowl lip axial station.

STNSEL. This subroutine is employed to determine the solution point on a given solution plane that is nearest to an arbitrary point whose coordinates are supplied in the argument list. After the proper solution point has been determined by a search of the computed sector, it is used as the base point of the nine point stencil used in formulating the quadratic bivariate interpolation polynomial. STNSEL calls subroutine BIPTS in the course of determining the proper solution point and in formulating the interpolation polynomial coefficients.

REFLEK. This subroutine performs reflections, about the coordinate axes, of the solution points in the computed sector on a given solution plane when flow symmetry exists. The solution point reflections are required to obtain
the appropriate fit point stencils used in formulating the univariate, bi-
variate, and trivariate interpolation polynomials. REFLEK is used to reflect
points for the case of one plane of flow symmetry, the case of two planes of
flow symmetry, and the axisymmetric flow case. Both streamline and shock wave
points are reflected in REFLEK.

XSTEP. This subroutine determines the axial marching step allowed by the
Courant-Friedrichs-Lewy (CFL) stability criterion. Except in the vicinity of
an internal shock wave intersection with a solid boundary, the marching step
computed by XSTEP is that used to regulate the distance between successive
solution planes. In the vicinity of an internal shock wave-solid boundary in-
tersection, special constraints are used to determine the marching step. XSTEP
applies the CFL stability criterion to all streamline points in the computed
sector. The actual marching step is taken as the allowable x-step at the most
restrictive point. The stability criterion is not applied to the shock wave
points. Moreover, the internal flow field shock wave points are ignored in de-
fining the convex hull of the finite difference network when application of the
stability criterion is made to a streamline point.

MASS. This subroutine is used to compute the mass flow rate across a given
solution plane. The mass flow rate is numerically ascertained by a trapezoidal
rule integration procedure in which the incremental mass flow rate is computed
through an elemental triangle formed by three adjacent points. The sum of these
incremental mass flow rates is the total mass flow rate. If flow symmetry exists,
only the mass flow rate in the computed sector is found by integration. The mass
flow rate across the entire plane is then obtained by use of an appropriate multi-
plier. Special logic is used to trace the internal shock wave in the integration
procedure when the mass flow rate across an internal flow field solution plane is
being computed.

PRNOUT. This subroutine is used to print the supersonic flow integration
results for all solution planes. Both the external flow field and the internal
flow field solution planes are printed by PRNOUT. In addition, the initial-
value plane, the redistributed data plane at the cowl lip axial station, and
the restart plane are output by PRNOUT. Three print options (specified in the
input by the input parameter KPRINT) are available: body streamline points and
shock wave points, all solution points, and all solution points and shock wave
parameters (incident normal Mach number and shock wave surface normal unit vector
components). The solution points along the space curves formed by the intersections
of the internal shock wave with the solid boundaries are not printed by subroutine
PRNOUT. They are printed by subroutine SHKRFL.

UNIPT. This subroutine selects the fit points used in formulating the
univariate interpolation polynomials that are used to describe the shock wave
radius and the shock wave angle along the curve defined by the intersection of
the shock wave with a given solution plane. Three adjacent shock wave solution
points constitute the fit point stencil in regions that are away from an internal
shock wave-solid boundary intersection. In the region of an intersection, the
fit point stencil may be appropriately expanded to be in accord with the Courant-
Friedrichs-Lewy (CFL) stability criterion.
UNIFIT. This subroutine is used to determine the coefficients in the quadratic univariate interpolation polynomial. The three coefficients in this polynomial are determined by a fit to three data points which are supplied to UNIFIT through the call statement. Subroutine GELG is called to solve the system of simultaneous linear equations that determines the coefficients.

BIPTS. This subroutine selects the fit points used in formulating the quadratic bivariate interpolation polynomials that are used for intraplanar flow property determination. A base point and its eight immediate neighbors constitute the fit point array. Two types of fit point stencils are used: interior point and boundary point. A boundary point stencil is employed when the interpolation base point (the fit point nearest to the interpolated point) is on the shock wave. Special logic is used to ensure that no point stencil bridges the shock wave.

BIFIT. This subroutine is used to determine the coefficients in the quadratic bivariate interpolation polynomial. The six coefficients in this polynomial are determined by a least squares fit of nine data points which are supplied to BIFIT through the named common block FITPTS. Subroutine SYMSIM is called to solve the system of simultaneous linear equations (normal equations) which determines the coefficients in the interpolation polynomial. This system of linear equations has a symmetric coefficient matrix.

TRIPTS. This subroutine selects the fit points used in formulating both the linear trivariate interpolation polynomial and the quadratic trivariate interpolation polynomial. Four solution points are used in formulating the linear trivariate interpolation polynomial. Fourteen solution points are used in formulating the quadratic trivariate interpolation polynomial. The linear polynomial is used for flow property interpolation on the upstream side of the shock wave surface. The quadratic polynomial is used for flow property interpolation on both the downstream side of the shock wave surface and on the stream surface formed by a solid boundary.

TRIFTU. This subroutine is used to determine the coefficients in the linear trivariate interpolation polynomial. The four coefficients in this polynomial are determined by a fit to four data points which are supplied to TRIFTU through the named common block FITPTS. Subroutine GELG is called to solve the system of simultaneous linear equations which determine the coefficients.

TRIFTD. This subroutine is used to determine the coefficients in the quadratic trivariate interpolation polynomial. The eight coefficients in this polynomial are determined by a least squares fit of fourteen data points which are supplied to TRIFTD through the named common block FITPTS. Subroutine SYMSIM is called to solve the system of simultaneous linear equations (normal equations) which determines the coefficients. This system of equations has a symmetric coefficient matrix.

SHKINT. This subroutine is used to evaluate the univariate interpolation polynomials that are employed in describing the shock wave radius and the shock wave angle along the curve that is defined by the intersection of the shock wave with a given solution plane. The interpolation polynomial coefficients are
supplied to SHKINT through the named common block SINTRP. The independent variable is the polar angle Theta, which is transmitted through the subroutine call statement.

PRPINT. This subroutine is used to evaluate the bivariate and trivariate interpolation polynomials that are used for flow property determination on solution planes, shock waves, and solid boundary stream surfaces. The interpolation polynomial coefficients are supplied to PRPINT through the named common block INTRP. The independent variables are the three position coordinates XA, Y, and Z, which are transmitted through the subroutine call statement.

FDERIV. This subroutine is used to compute the first partial derivatives of the flow properties on a solution plane, a shock wave, or a solid boundary stream surface. The derivatives are obtained by evaluating an analytically differentiated form of the appropriate interpolation polynomial. The interpolation polynomial coefficients are transmitted to FDERIV through the named common block INTRP. The independent variables are the three position coordinates XA, Y, and Z, which are transmitted through the subroutine call statement.

VECTR. This subroutine is used in conjunction with subroutine SHOCK to determine the components of the unit vector \( \mathbf{b} \) which is used in the parameterization of the wave surface compatibility relation. The unit vector \( \mathbf{b} \) is orthogonal to the velocity vector that is downstream of the shock wave at the shock wave solution point, and has its projection on the \((y,z)\)-plane lie in the meridional plane which passes through the shock wave solution point.

PLANAR. This subroutine is used to compute the parameters employed in the formulation that represents the shock wave surface. This formulation is then used in determining the intersection point of either a streamline or a bicharacteristic with the shock wave surface. Additionally, PLANAR initializes some parameters used in determining the intersection point of a bicharacteristic with the stream surface formed by a solid boundary.

INTSCT. This subroutine is used to compute the intersection point of either a streamline with the shock wave surface, or the intersection point of a bicharacteristic with either the shock wave surface or the stream surface formed by a solid boundary. The determination of the intersection point coordinates is performed in an iteration loop which uses the secant method to relax the difference in the radius of the point of intersection obtained from integration of the equation for a streamline or bicharacteristic and that obtained from the appropriate surface formulation.

FUNCT. This subroutine is used in conjunction with subroutine INTSCT to determine a streamline-shock wave intersection point, or the intersection point of a bicharacteristic with either a shock wave or a solid boundary. The axial position of the assumed intersection point is supplied to FUNCT through the subroutine call statement. From the given axial position, FUNCT computes the corresponding \( y \) and \( z \) coordinates of the assumed intersection point by both integrating the equation for a streamline or bicharacteristic, and by evaluating the appropriate surface formulation. The difference in the radius obtained from the streamline or bicharacteristic equation integration and that obtained from
the surface formulation is reduced to within a specified tolerance of zero by
the iteration method used in subroutine INTSCT.

RADIUS. This subroutine is used to compute the radius of a point on the
shock wave surface or on the stream surface formed by a solid boundary. The
axial position and the polar angle of the point are supplied to RADIUS through
the subroutine call statement. To obtain the shock wave radius at the desired
point, a linear interpolation is performed in the meridional plane of the point
between two space curves which are defined by either a shock-wave solution plane
intersection or by a shock wave-solid boundary intersection. To obtain the body
radius at the desired point, subroutine BOUNDY is called.

XFIT. This subroutine is used to curve fit, as a function of the polar
angle, the axial (x) position of an internal shock wave-solid boundary inter-
section. A quadratic polynomial expressed in terms of the polar angle is used
for this representation.

FRCFNS. This subroutine is used to compute the molecular transport forcing
terms used in both the governing equations and the compatibility relations.
FRCFNS is called by subroutines SOLVE and SHOCK. The molecular transport terms
can be included in the computation of the external flow field about the forebody
or in the computation of the internal flow field in which shock waves are not
discretely fitted. The program option in which internal shock waves are dis-
cretely fitted does not have the capability to include the influence of molecu-
lar-diffusion in the computation, but rather assumes the flow to be inviscid
and adiabatic.

SOLN. This subroutine calls subroutines LOCATE and SOLVE for computing
either a solid-boundary solution point or an interior solution point.

LOCATE. This subroutine is used to compute the locations of and the flow
properties at the streamline and bicharacteristic intersection points for the
standard interior point, standard solid boundary point, shock-modified interior
point, and shock-modified solid boundary point unit processes. The point loca-
tions and flow properties at these points are transmitted to subroutine SOLVE
through the named common blocks RELAY1 and RELAY2. Subroutine SOLVE then solves
the system of compatibility relations to obtain the position of and the flow
properties at the solution point.

SOLVE. This subroutine is used to solve the system of compatibility equa-
tions for the standard interior point, standard solid boundary point, shock-
modified interior point, and shock-modified solid boundary point unit processes.
If the viscous and thermal diffusion terms are to be included in the computation,
SOLVE calls subroutine FRCFNS. The system of five compatibility relations is
solved by calling subroutine GELG..

SHOCK. This subroutine is used to compute the solution for all field-shock
wave points. For the bow shock wave points, the free-stream flow conditions are
used for the upstream flow properties. For the internal flow field shock wave
points, an interior or solid boundary point unit process is applied to obtain the
upstream flow properties. Body solution points on the downstream side of
the cowl lip shock wave or on the downstream side of a reflected internal shock wave are computed using the solid boundary-shock wave point unit process (subroutine BSHOCK).

**JUMP.** This subroutine employs the Rankine-Hugoniot relations to compute the downstream flow properties at a shock wave solution point. The shock wave surface normal unit vector components and the flow properties upstream of the shock wave are entered in the argument list. The computed downstream flow properties are also transmitted in the argument list. The assumed thermodynamic model is that of a thermally and calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying this subroutine. Thermodynamic property information is supplied to subroutine JUMP through the named common block GAS1.

**TGRAD.** This subroutine computes the spatial gradients of temperature by using an analytically differentiated form of the thermal equation of state so that temperature derivatives can be expressed in terms of the derivatives of pressure and density. The assumed thermodynamic model is that of a thermally perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If TGRAD is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- \( T \) temperature
- \( P \) pressure
- \( \rho \) density
- \( \partial_p, \partial_p, \partial_p \) first partial derivatives of pressure with respect to \( x, y, \) and \( z \), respectively
- \( \partial_p, \partial_p, \partial_p \) second partial derivatives of pressure with respect to \( x, y, \) and \( z \), respectively
- \( \partial_\rho, \partial_\rho, \partial_\rho \) first partial derivatives of density with respect to \( x, y, \) and \( z \), respectively
- \( \partial_\rho, \partial_\rho, \partial_\rho \) second partial derivatives of density with respect to \( x, y, \) and \( z \), respectively
- \( \partial T, \partial T, \partial T \) first partial derivatives of temperature with respect to \( x, y, \) and \( z \), respectively
- \( \partial T, \partial T, \partial T \) second partial derivatives of temperature with respect to \( x, y, \) and \( z \), respectively

Thermodynamic property information is supplied to subroutine TGRAD through the named common block GAS1.

**TPRØPS.** This subroutine computes the dynamic viscosity, the thermal conductivity, and their spatial gradients. The assumed functional form for dynamic viscosity is given by Sutherland's Law (6). The assumed functional form for thermal conductivity is expressed in terms of the dynamic viscosity and laminar Prandtl number. Other transport property formulations may be incorporated into
the analysis by suitably modifying or replacing this subroutine. If TPR@PS is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- **T**  static temperature
- **P**  static pressure
- **VIS** dynamic viscosity
- **C@N** thermal conductivity
- **DTX,DTY,DTZ** first partial derivatives of temperature with respect to x, y, and z, respectively.
- **DPX,DPY,DPZ** first partial derivatives of pressure with respect to x, y, and z, respectively.
- **DVISX,DVISY,DVISZ** first partial derivatives of viscosity with respect to x, y, and z, respectively.
- **DC@NX,DC@NY,DC@NZ** first partial derivatives of thermal conductivity with respect to x, y, and z, respectively.

Transport property information is supplied to subroutine TPR@PS through the named common block GAS2.

10. **OVERLAY (3,1)**

**LINK31.** This program routine contains the control logic used in the computation of the supersonic external flow field about the forebody. LINK31 is the main control routine in OVERLAY (3,1). OVERLAY (3,1) is a secondary level overlay which is called from routine LINK30.

**RCNTRL.** This subroutine is used to control the number of radial stations on successive solution planes in the forebody flow field integration. If a sufficient influx of mass across the bow shock wave has occurred between the current solution plane and the last solution plane where point addition or deletion was performed, a new ring of interior field points is added between the ring of shock wave points and the outermost ring of existing interior field points. If, after a number of successive point additions, a specified number of radial stations has been reached, point deletion is performed. Here, selected interior field points are deleted from the storage arrays while the bow shock wave points and the body streamline points are retained.

11. **OVERLAY (3,2)**

**LINK32.** This program routine contains the control logic used in the computation of the supersonic internal flow field in which shock waves are discretely fitted. LINK32 is the main control routine in OVERLAY (3,2). OVERLAY (3,2) is a secondary level overlay which is called from routine LINK30.
BSHOCK. This subroutine is used to compute the flow properties at a point on the body that is downstream of either the cowl lip shock wave or an internal reflected shock wave (solid body-shock wave point unit process). This subroutine is used only in the option where the internal flow field integration in which shock waves are discretely fitted is employed.

SPRJCT. This subroutine is used in the internal flow field integration to project the internal shock wave from the current initial-value plane to the current solution plane. The projected intersection of the internal shock wave with the solution plane is then used to determine which streamlines do and do not penetrate the shock wave.

PENTRE. This subroutine is used in the internal flow field integration to control the computation of an interior field point when the streamline has penetrated the internal shock wave. If the streamline-shock wave intersection point is sufficiently close to the current solution plane, an interior point unit process on the downstream side of the shock wave is not performed. Instead, in this case, a streamline projection onto the solution plane and subsequent flow property interpolation in this plane is performed. Alternatively, if the streamline-shock wave intersection point is sufficiently far from the solution plane, an interior point unit process is performed on the downstream side of the shock wave.

TRACE. This subroutine is used in conjunction with subroutine INTSCT to compute the intersection point of a streamline with an internal shock wave. With the intersection point coordinates determined, the trivariate interpolation polynomials are evaluated to obtain the flow properties at the intersection point.

SØLINT. This subroutine is used in the internal flow field integration to determine the intersection point coordinates of and the flow properties at an interior field point when the streamline penetrates an internal shock wave with the intersection point being sufficiently close to the current solution plane. SØLINT is called from subroutine PENTRE.

SWITCH. This subroutine is used in the internal flow field integration to perform the post computation interchange of indices when a streamline which initially appeared to intersect the internal shock wave ultimately did not. Consequently, a standard interior point unit process is used for this point instead of a shock-modified interior point unit process performed on the downstream side of the shock wave.

SHKRFL. This subroutine contains the control logic used for calculating an internal shock wave-solid boundary intersection.

INTRFL. This subroutine performs the necessary point reflections when flow symmetry exists for the solution points on the space curve defined by the intersection of the internal shock wave with a solid boundary.

ISHOCK. This subroutine is used in the internal flow field integration to compute the incident shock wave upstream and downstream flow properties at a point where the incident shock wave intersects a solid boundary.
**STRSHK.** This subroutine is used to compute the position of and the flow properties at the intersection point of a body streamline with the space curve defined by the intersection of the incident shock wave with a solid boundary.

**RSHOCK.** This subroutine is used with subroutine BSHOCK to compute the flow properties on the body downstream of an internal reflected shock wave.

12. **ØVERLAY (3,3)**

**LINK33.** This program routine contains the control logic used in the computation of the supersonic internal flow field in which shock waves are not discretely fitted. LINK33 is the main control routine in ØVERLAY (3,3). ØVERLAY (3,3) is a secondary level overlay which is called from routine LINK30.

13. **ØVERLAY (4,0)**

**LINK40.** This program routine is the main control routine in ØVERLAY (4,0). LINK40 controls the boundary layer computation on both the forebody/centerbody and the cowl. LINK40 calls the secondary level overlays, ØVERLAY (4,1), ØVERLAY (4,2), ØVERLAY (4,3), and ØVERLAY (4,4).

**GEØD.** This subroutine computes the metric coefficients and geodesic curvature terms used in the boundary layer computation. The version of GEØD supplied with the program assumes that both the forebody/centerbody and cowl are axisymmetric. More arbitrary geometries can be described by suitably modifying or replacing this subroutine. If GEØD is replaced, the subroutine argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

- **KBØDY**
  - If KBØDY=1, forebody/centerbody geometry is to be specified.
  - If KBØDY=2, cowl geometry is to be supplied.

- **KPLANE**
  - If KPLANE=1, axial location is for current initial-value plane.
  - If KPLANE=2, axial location is for current solution plane.

- **XBASEI**
  - Base axial coordinate of the current initial-value plane.

- **XBASES**
  - Base axial coordinate of the current solution plane.

**XCURV.** This subroutine computes the x curvilinear coordinate given the x base coordinate. The version of XCURV supplied with the program assumes that both the forebody/centerbody and cowl are axisymmetric. More arbitrary geometries can be described by suitably modifying or replacing this subroutine. If XCURV is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.
KBODY

If KBODY=1, forebody/centerbody geometry is to be specified.
If KBODY=2, cowl geometry is to be specified.

XBASEI

Base axial coordinate of the current initial-value plane.

XBASES

Base axial coordinate of the current solution plane.

EINTRP. This subroutine determines the external flow properties for the boundary layer computation by interpolation of the supersonic core flow solution.

WALL. This subroutine calculates the wall condition parameters for computation of the boundary layer.

WTEMP. This subroutine determines the wall temperature boundary condition for use in the boundary layer computation. Both temperature and normal temperature gradient boundary conditions can be specified. Subroutine WTEMP is called from subroutine WALL.

TURB. This subroutine computes the turbulent eddy viscosity and turbulent eddy thermal conductivity for use in the boundary layer computation. The version of TURB supplied with the program employs an isotropic two-layer eddy diffusivity model(7). The turbulent thermal conductivity is expressed in terms of the eddy viscosity by use of the turbulent Prandtl number. Other turbulence models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If TURB is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

DECODE. This subroutine is used to decode the boundary layer transformed variables into physical variables and then to print both the forebody/centerbody and cowl boundary layer solutions.

THERMD. This subroutine is used to compute the spatial gradient of the static enthalpy. The assumed thermodynamic model is that of a thermally and
calorically perfect gas. Other thermodynamic models may be incorporated into the analysis by suitably modifying or replacing this subroutine. If subroutine THERMD is replaced, the argument list must be identical to the existing list. The parameters in the argument list are defined as follows.

T  temperature
P  pressure.
DTDY first partial spatial derivative of temperature
DPDY first partial spatial derivative of pressure
DHDY first partial spatial derivative of static enthalpy.

Thermodynamic property information is supplied to subroutine THERMD through the named common block GAS1.

14. OVERLAY (4,1)

LINK41. This program routine is the main control routine in OVERLAY (4,1) and is used to control the integration of the boundary layer differential equations.

ABLSLN. This subroutine computes the flow properties across the boundary layer at a circumferential station that is on the plane of symmetry. The transformed governing differential equations are solved implicitly using the matrix solution algorithm in subroutine BTRID.

AEXT. This subroutine calculates the edge condition parameters for the computation of a plane of symmetry boundary layer station. Subroutine AEXT is called from subroutine ABLSLN.

ASPEC. This subroutine determines certain parameters which are used in the plane of symmetry boundary layer computation. Subroutine ASPEC is called from subroutine ABLSLN.

GBLSLN. This subroutine computes the properties across the boundary layer at a circumferential station that is not on a plane of flow symmetry. The transformed governing equations are solved implicitly using the matrix solution algorithm in subroutine BTRID.

GEEXT. This subroutine calculates the edge condition parameters for the computation of a boundary layer station that is not on the plane of flow symmetry. Subroutine GEXT is called from subroutine GBLSLN.

GSPEC. This subroutine determines certain parameters which are used in the boundary layer computation for stations not on the plane of flow symmetry. Subroutine GSPEC is called from subroutine GBLSLN.

BTRID. This subroutine solves a system of simultaneous linear equations with a block tridiagonal coefficient matrix. A direct factorization procedure employing triangular decomposition is used to obtain the solution vector.
PRD. This subroutine is used to perform matrix multiplication. Subroutine PRD is called from subroutine BTRID.

15. OVERLAY (4,2)

LINK42. This program routine is the main control routine in OVERLAY (4,2) and is used to determine the boundary layer properties downstream of a shock wave-boundary layer interaction region. An integral formulation is used to obtain the solution.

SBLINT. This subroutine determines the downstream boundary layer thickness and velocity profile exponents in a shock wave-boundary layer interaction analysis.

INTEG. This subroutine is used to numerically evaluate certain integral parameters involved in the shock wave-boundary layer interaction analysis.

16. OVERLAY (4,3)

LINK43. This program routine is the main control routine in OVERLAY (4,3) and is used for mesh alteration in the boundary layer computation to account for boundary layer growth.

17. OVERLAY (4,4)

LINK44. This program routine is the main control routine in OVERLAY (4,4) and is used for the internal generation of the cowl boundary layer initial data.
1. INTRODUCTION

The input data required for execution of the computer program are entered by both namelist input and formatted read statements. In all cases, the eleven namelists LIST1 to LIST11 are entered. For cases in which the user selects to specify the flow property field on the initial-value plane, that information is entered by a formatted read of files ITAP1, ITAP2, and ITAP3.

In general, only those parameters and data pertinent to the particular problem being considered must be entered. Many input parameters have default values and do not need to be specified unless values other than the default values are to be entered.

In this section, each input parameter is defined. Where applicable, both the default value and a typical value of the input parameter are given.

2. TITLE CARD

The first card of each data deck is a title card on which 72 alphanumeric characters (any standard Fortran characters) of identifying information may be specified. This card must be the first card of the data deck even if no information is listed on it. The format of the card is (12A6).

3. NAMELIST LIST1

The parameters entered in namelist LIST1 control the overall execution of the program.

KUNIT
An integer variable denoting whether English absolute units or SI units are to be used in the computation. If KUNIT = 1, English absolute units are employed. If KUNIT = 0, SI units are employed. A default value of 1 is specified for KUNIT.

KCALL
A one-dimensional integer variable array consisting of three elements. Each element of KCALL specifies whether or not a particular supersonic flow field integration option is to be performed. If KCALL(I) = 1 (I=1,2,3), then the corresponding flow field integration option is performed. If KCALL(I) = 0, the integration option is not performed. The elements of KCALL control the flow field integration options and have specified default values as listed below.
<table>
<thead>
<tr>
<th>KCALL(i)</th>
<th>Flow Field Integration Option</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCALL(1)</td>
<td>forebody supersonic flow field</td>
<td>1</td>
</tr>
<tr>
<td>KCALL(2)</td>
<td>internal supersonic flow field with discrete shock wave fitting</td>
<td>1</td>
</tr>
<tr>
<td>KCALL(3)</td>
<td>internal supersonic flow field without discrete shock wave fitting</td>
<td>0</td>
</tr>
</tbody>
</table>

Specifying KCALL(2) = 1 and KCALL(3) = 1 simultaneously will cause an error message to be printed and the program execution to be aborted.

**XEND**

A one-dimensional real variable array consisting of three elements. XFND(I) (I=1,2,3) denotes the x-position, in either feet or meters, at which the supersonic flow field integration specified by the corresponding element of KCALL is to be terminated. Each element of XEND denotes a flow field integration option termination point and has a default value as follows:

<table>
<thead>
<tr>
<th>XEND(i)</th>
<th>Termination Point for</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>XEND(1)</td>
<td>forebody supersonic flow field integration</td>
<td>2.0 ft</td>
</tr>
<tr>
<td>XEND(2)</td>
<td>internal supersonic flow field integration with discrete shock wave fitting</td>
<td>3.5 ft</td>
</tr>
<tr>
<td>XEND(3)</td>
<td>internal supersonic flow field integration without discrete shock wave fitting</td>
<td>3.5 ft</td>
</tr>
</tbody>
</table>

If any element of XEND exceeds the x-position to which the centerbody geometry is specified, or if XEND(2) or XEND(3) exceeds the x-position to which the cowl geometry is specified, appropriate error messages are printed and the program execution is aborted. Each element of XEND must be positive. It should be noted that if KCALL(i) = 0, XEND(i) does not have to be specified.

**KTRANS**

An integer variable denoting whether or not distributed wall bleed effects are to be included in the supersonic core flow computation. If KTRANS = 1, bleed effects are included in the computation. If KTRANS = 0, bleed effects are not included in the computation. The wall bleed distribution is specified by the parameters entered in namelist LIST8. A default value of 1 is specified for KTRANS.

**KBLAY**

An integer variable denoting whether or not the boundary layer computation is to be performed. If KBLAY = 1, the boundary layer computation is performed. If KBLAY = 0, the boundary layer computation is not performed. A default value of 1 is specified for KBLAY.
RCAVG A positive real variable denoting the estimated average radius, in either feet or meters, of the bow shock wave at XEND(1). The specified value of RCAVG is used in estimating the captured mass flow rate at XEND(1). This mass flow rate is used in determining if point addition is to be performed in the forebody flow field integration. RCAVG must be specified only if the supersonic forebody flow field integration option is used \([\text{KCALL}(1) = 1]\). RCAVG must be specified even if the forebody integration option is the only integration option used \([\text{KCALL}(2) = \text{KCALL}(3) = 0]\). The cowl lip radius may be used for RCAVG. A default value of 0.8 ft is specified for RCAVG.

KVISCY An integer variable denoting whether or not the viscous and thermal diffusion terms are to be included in the computation of the forebody supersonic flow field or the internal supersonic flow field in which shock waves are not discretely fitted. If KVISCY = 1, these terms are included in the computation. If KVISCY = 0, these terms are not included in the computation. A default value of 0 is specified for KVISCY.

KSYM An integer variable denoting the flow symmetry option to be employed in the computation. If the boundary layer computation is not employed \((\text{KBLAY} = 0)\), KSYM can have the values 0, 1, 2, and 3 corresponding to:

<table>
<thead>
<tr>
<th>KSYM</th>
<th>Flow Symmetry Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no planes of symmetry - computed sector is the entire solution plane</td>
</tr>
<tr>
<td>1</td>
<td>one plane of symmetry - computed sector is the half-plane bounded by the y-axis and containing the +z-axis</td>
</tr>
<tr>
<td>2</td>
<td>two planes of symmetry - computed sector is the quadrant bounded by the +y-axis and the +z-axis</td>
</tr>
<tr>
<td>3</td>
<td>axisymmetric flow - computed sector is the single circumferential station on the +y-axis</td>
</tr>
</tbody>
</table>

If the boundary layer computation is employed \((\text{KBLAY} = 1)\), then the allowable value of KSYM is 1. The supersonic flow networks for the flow symmetry options are illustrated in Figure 3. A default value of 1 is specified for KSYM.

KSGLØB An integer variable denoting whether or not global correction is to be performed in obtaining the solution for the bow shock wave points. If KSGLØB = 1, global correction is performed. If KSGLØB = 0, global correction is not performed. Global correction can only be performed for the bow shock wave points and not for the internal flow field shock wave points. Hence, KSGLØB must be specified only if \(\text{KCALL}(1) = 1\). A default value of 1 is specified for KSGLØB.
(c) TWO PLANES OF SYMMETRY  
(KSYM=2)

(d) AXISYMMETRIC FLOW  
(KSYM=3)

FIGURE 3. (CONTINUED)
KPRINT An integer variable denoting which of three print options is to be employed in the program execution for the supersonic flow solution. KPRINT can have the following values.

<table>
<thead>
<tr>
<th>KPRINT</th>
<th>Print Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>print body solution points and shock wave solution points only</td>
</tr>
<tr>
<td>1</td>
<td>print all solution points</td>
</tr>
<tr>
<td>2</td>
<td>print all solution points and shock wave parameters (incident normal Mach number and shock wave surface normal unit vector components)</td>
</tr>
</tbody>
</table>

A default value of 1 is specified for KPRINT.

IPRSTP A positive integer variable denoting the plane number at which the program execution is to be terminated. This input parameter is typically employed when the execution is intended to be restarted at plane number (IPRSTP + 1). Specifying IPRSTP < 0 has no effect on the execution of the program. A default value of 0 is specified for IPRSTP.

KSTART An integer variable used in controlling the file operations involved in the restarting of the program (if desired). KSTART controls the storage and retrieval of the restart file as follows.

<table>
<thead>
<tr>
<th>KSTART</th>
<th>Control of Restart File</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no file operations</td>
</tr>
<tr>
<td>1</td>
<td>write restart file on TAPE 9</td>
</tr>
<tr>
<td>2</td>
<td>read information for program restart from TAPE 9, and write ensuing solution planes on this tape</td>
</tr>
</tbody>
</table>

A default value of 0 is specified for KSTART. TAPE 9 is linked to the dummy file RESTRT in the PROGRAM card.

4. NAMELIST LIST2

The parameters entered in namelist LIST2 specify the free-stream conditions, the inlet orientation, and the parameters which control the internal generation of the supersonic flow property field on the initial-value plane.

MFS A positive real variable denoting the free-stream Mach number. The specified value of MFS must be greater than 1.0. A default value of 3.0 is specified for MFS.

PFS A positive real variable denoting the free-stream absolute pressure,
in either \( \text{lb} / \text{ft}^2 \) or \( \text{N/m}^2 \). A default value of 242.2 \( \text{lb} / \text{ft}^2 \) is specified for \( P_{FS} \) (this value is the pressure of the standard atmosphere at an altitude of 50,000 ft).

**R\( \Omega \)FS**

A positive real variable denoting the free-stream density, in either \( \text{slug/ft}^3 \) or \( \text{kg/m}^3 \). A default value of 0.0003622 \( \text{slug/ft}^3 \) is specified for \( R_{FS} \) (this value is the density of the standard atmosphere at an altitude of 50,000 ft).

**PITCH**

A real variable denoting the angle, in degrees, subtended by the free-stream velocity vector and the projection of the free-stream velocity vector on the \( (x,z) \)-plane, as illustrated in Figure 4. A default value of 1.0 degree is specified for \( \text{PITCH} \). If \( \text{KBLAY}=1 \) is specified in namelist \( \text{LIST1} \), then \( \text{PITCH} \neq 0.0 \).

**YAW**

A real variable denoting the angle, in degrees, subtended by the \( x \)-axis and the projection of the free-stream velocity vector on the \( (x,z) \)-plane, as illustrated in Figure 4. A default value of 0.0 degrees is specified for \( \text{YAW} \).

**XI**

A positive real variable denoting the axial \( (x) \) position, in either feet or meters, of the supersonic flow initial-value plane. If the forebody flow field integration option is specified \( [\text{KCALL(1)} = 1] \), \( \text{XI} \) must be specified at the beginning of the forebody flow field computational regime (see Figure 1). If only the internal flow field integration option is specified \( [\text{KCALL(1)} = 0, \text{KCALL(2)} = 1 \) or \( \text{KCALL(3)} = 1] \), \( \text{XI} \) must be specified at the axial station of the cowl lip (see Figure 1). \( \text{XI} \) must not fall outside of the range of axial stations for which the centerbody geometry is specified. Also, \( \text{XI} \) must not be greater than the axial station up to which the cowl geometry is specified. A default value of 1.0 ft is specified for \( \text{XI} \).

**KIVS**

An integer variable denoting whether the supersonic flow field on the initial-value plane is to be generated internally or read in. If \( \text{KIVS} = 1 \), the initial-value plane data are computed internally. If \( \text{KIVS} = 0 \), the initial-value plane data must be supplied by the user through a formatted read of file \( \text{ITAPI} \). The formatted read input is described at the end of this section. The internally generated initial-value plane option is applicable only to cases where the forebody is conical up to the axial station where the initial-value plane is located. Specifying \( \text{KIVS} = 1 \) requires that \( \text{YAW} = 0.0 \). A default value of 1 is specified for \( \text{KIVS} \).

**KC\( \Omega \)N**

An integer variable denoting whether or not the bow shock wave is conical. \( \text{KC\( \Omega \)N} \) must be specified only if the forebody flow field integration option is employed \( [\text{KCALL(1)} = 1] \). If \( \text{KC\( \Omega \)N} = 1 \), the bow shock wave is conical. In this case, the angle at each initial-value plane bow shock wave point that is subtended by the shock wave and the \( x \)-axis in the meridional plane defined by the shock wave point is computed internally. If \( \text{KC\( \Omega \)N} = 0 \), the bow shock wave is not conical, and the shock wave angles must be supplied by the user through a
\[ u_\infty = |\vec{V}_\infty| \cos(\text{PITCH}) \cos(\text{YAW}) \]
\[ v_\infty = |\vec{V}_\infty| \sin(\text{PITCH}) \]
\[ w_\infty = |\vec{V}_\infty| \cos(\text{PITCH}) \sin(\text{YAW}) \]

Figure 4. Pitch and yaw angles.
formatted read of file ITAPI. The formatted read input is described at the end of this section. If the initial-value plane is generated internally (KIVS = 1), a conical bow shock wave is assumed (KC0N = 1). A default value of 1 is specified for KC0N.

KSUPER

An integer variable denoting the method to be used in internally generating the supersonic flow initial data. KSUPER must be specified only if the initial data are to be generated internally (KIVS = 1). If KSUPER = 1, the supersonic flow initial data are computed using the approximate Taylor-Maccoll algorithm described in Section II. If KSUPER = 2, the supersonic flow initial data are computed using the Jones algorithm described in Section II. If KSUPER = 1, KSYM can have the values 1, 2, or 3, where if KSYM = 3 the angle of attack must be 0.0 (PITCH = 0.0). If KSUPER = 2, KSYM must be equal to 1 and PITCH ≠ 0.0. A default value of 2 is specified for KSUPER.

ITAPI

A positive integer variable denoting the tape number from which the user supplied supersonic flow initial data are to be entered by a formatted read. ITAPI must be specified only if the initial-value plane flow property field is to be supplied by the user (KIVS = 0). The default value assigned to ITAPI is 5 (the input file). The user may specify ITAPE = 10, in which case the supersonic initial data are read from TAPE 10. TAPE 10 is linked to the dummy file IVSI in the PR0GRAM card.

5. NAMELIST LIST3

The parameters entered in namelist LIST3 specify the number of circumferential and radial stations used in the supersonic flow computational point network.

IST0P

A positive integer variable denoting the number of circumferential stations used in the supersonic solution computed flow field sector. The value specified for IST0P must correspond to the flow symmetry option specified by KSYM (see namelist LIST1) as follows (see Figure 3).

<table>
<thead>
<tr>
<th>KSYM</th>
<th>Allowable Value(s) of IST0P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5 ≤ IST0P ≤ 30</td>
</tr>
<tr>
<td>1</td>
<td>4 ≤ IST0P ≤ 16</td>
</tr>
<tr>
<td>2</td>
<td>3 ≤ IST0P ≤ 8</td>
</tr>
<tr>
<td>3</td>
<td>IST0P = 1</td>
</tr>
</tbody>
</table>

A default value of 15 is specified for IST0P (this recommended value corresponds to KSYM = 1). If the supersonic initial data are to be generated internally using the Jones algorithm (KIVS = 1, KSUPER = 2), then IST0P must be greater than 1.
JMAXI

A positive integer variable denoting the number of radial stations on the supersonic flow initial-value plane. Note that the initial-value plane input format is the same whether the computation is being started at an axial station upstream of the forebody computational flow regime or at the axial station of the cowl lip. The specified value for JMAXI must be at least 3 and no greater than 15. The default and recommended value for JMAXI is 11.

Whatever the value of JMAXI, the outermost radial station corresponds to the downstream bow shock wave points, and the remaining \((JMAXI - 1)\) radial stations correspond to the streamline points.

JINLET

A positive integer variable denoting the number of radial stations on each solution plane in the supersonic internal flow field integration. JINLET must be specified only if the internal flow field is to be computed. The specified value of JINLET must be at least 4 and no greater than 15. The recommended value and the default value of JINLET is 11. It should be noted that JINLET is independent of JMAXI.

For the internal flow field integration option in which shock waves are not discretely fitted \([\text{KCALL}(2) = 0, \text{KCALL}(3) = 1]\), JINLET specifies the number of streamline points at each circumferential station. For the internal flow field integration option in which shock waves are discretely fitted \([\text{KCALL}(2) = 1, \text{KCALL}(3) = 0]\), the number of streamline points at each circumferential station is equal to \((JINLET - 2)\). The remaining two storage locations are assigned to the upstream and downstream shock wave solution points.

JLIMIT

A one-dimensional integer variable array consisting of two elements. JLIMIT must be specified only if the forebody flow field integration option is employed \([\text{KCALL}(1) = 1]\). The elements of JLIMIT are used in controlling the number of interior field points which are added in the computation of the forebody flow field. The first element of JLIMIT \([\text{JLIMIT}(1)]\) denotes the allowable maximum number of radial stations on a solution plane in the forebody flow field computation when the mass flow rate across that plane is less than a specified fraction \([\text{denoted by CRIT(7) in namelist LIST10}]\) of the estimated mass flow rate at XEND(1), the axial location at which the forebody flow field integration is to be terminated. The second element of JLIMIT \([\text{JLIMIT}(2)]\) denotes the allowable maximum number of radial stations when the mass flow rate exceeds the specified fraction of the estimated mass flow rate at XEND(1). Each element of JLIMIT must be positive, odd, and no less than 5 but no greater than 15. JLIMIT(1) should be less than or equal to JLIMIT(2). A default value of 11 is specified for JLIMIT(1), and a default value of 15 is specified for JLIMIT(2).
6. NAMELIST LIST4

The parameters entered in namelist LIST4 specify the thermodynamic model and the molecular transport properties.

R A positive real variable denoting the gas constant, in either \((\text{ft-lbf})/(\text{slug-R})\) or \((\text{J/kg-K})\). A default value of 1716.15116 \((\text{ft-lbf})/(\text{slug-R})\) is specified for R.

GAMMA A positive real variable denoting the specific heat ratio. A default value of 1.4 is specified for GAMMA.

If the boundary layer computation is not employed \((\text{KBLAY} = 0)\) and if the influence of molecular transport is not to be included in the supersonic flow computation \((\text{KVISCY} = 0)\), then no other parameters need be specified in namelist LIST4. If these options are employed in the computation, then the parameters presented in the following discussion must be specified.

The molecular dynamic viscosity is represented in the computer program by the Sutherland formula (6).

\[
\mu = \nu_0 \left(\frac{T}{T_o}\right)^{1.5} \left(\frac{T_o + B}{T + B}\right)
\]

In equation (1), \(\mu\) is the dynamic viscosity at the absolute temperature \(T\), and \(B\) is a constant. For air, \(B\) has the value of 198.6 R \((110\ K)\). The parameter \(\nu_0\) is the viscosity at the reference temperature \(T_o\). The constants \(\nu_0\), \(T_o\), and \(B\) must be specified in the program input by entering the following three parameters.

VIS\(\theta\) A positive real variable denoting the reference viscosity \(\nu_0\) in equation (1). The units of VIS\(\theta\) are either \((\text{lbf-sec/ft}^2)\) or \((\text{N-s/m}^2)\). A default value of \(3.5 \times 10^{-7}\ (\text{lbf-sec/ft}^2)\) is specified for VIS\(\theta\) (this value is the dynamic viscosity of air at 492.0 R).

T\(\theta\) A positive real variable denoting the reference absolute temperature \(T_o\) in equation (1). The units of T\(\theta\) are either R or K. The specified value of T\(\theta\) must correspond to the specified value of VIS\(\theta\). A default value of 492.0 R is specified for T\(\theta\).

B A positive real variable denoting the constant \(B\) in equation (1). The units for \(B\) are either R or K. A default value of 198.6 R is specified for \(B\).
The molecular thermal conductivity is represented in the computer program by

\[ \kappa = \frac{c_p \mu}{Pr} \]  

(2)

where \( \kappa \) denotes the thermal conductivity, \( c_p \) is the constant pressure specific heat, and \( Pr \) is the laminar Prandtl number which is assumed constant in the analysis. The specific heat \( c_p \) is calculated internally in the program, whereas the Prandtl number \( Pr \) is user specified by entering the following parameter.

PR  
A positive real variable denoting the laminar Prandtl number. A default value of 0.71 is specified for PR.

7. NAMELIST LIST5

The input parameters entered in namelist LIST5 specify the contours of the centerbody and the cowl. It is assumed that both the centerbody and the cowl are axisymmetric. The x-coordinate axis is the longitudinal axis of both the centerbody and the cowl (see Figure 1). The forebody tip must be located at \( x = 0.0 \). The axial station of the cowl lip must be specified at \( x > 0.0 \).

For the purpose of geometry description, the axial (x) domain is divided into a number of intervals, as illustrated in Figure 5. The number of axial stations at which the centerbody geometry is specified is denoted by NCENT. The number of intervals on the centerbody is equal to \( (NCENT - 1) \). The number of axial stations at which the cowl geometry is specified is denoted by NCOWL. The number of intervals on the cowl is equal to \( (NCOWL - 1) \).

In any interval, the centerbody or cowl radius may be specified either by tabular input, or by supplying the coefficients in a cubic polynomial written as a function of x. For the tabular input option, the body radius \( r(x) \) at axial position \( x \) in the \( i \) th interval \( (x_i \leq x < x_{i+1}) \) is found by linear interpolation between point \( (x_i,r_i) \) and point \( (x_{i+1},r_{i+1}) \). The local slope of the body for this interval in a given meridional plane is then given by the slope of the line segment joining these two points. Alternatively, employing the cubic polynomial

\[ r(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \quad (x_i \leq x < x_{i+1}) \]  

(3)

requires that the curve fit coefficients \( a_i, b_i, c_i, \) and \( d_i \) be supplied by the user. Since equation (3) is a cubic, slope and curvature can be matched at the junction point between two adjacent intervals employing this formulation. An option exists to employ the following cubic polynomial instead of equation (3).

\[ r(x) = a_i + b_i x + c_i x^2 + d_i x^3 \quad (x_i \leq x < x_{i+1}) \]  

(4)
FIGURE 5. BOUNDARY CONTOUR DESCRIPTION
When employing equation (3) or equation (4), the coefficients \( a_i, b_i, c_i \) and 
\( d_i \) must be specified for up to at most \((\text{NCENT - 1})\) and/or \((\text{NCWNL - 1})\) intervals.
The axial location \( x_i \) must always be specified for \text{NCENT} and (if the internal 
flow field is to be computed) \text{NCWNL} axial stations, no matter which formulation 
is used.

If the forebody is conical ahead of a certain axial station, the forebody/ 
centerbody geometry in this interval (1st interval) may be specified by enter-
ing the cone half-angle directly rather than by supplying the curve fit coeffi-
cients or entering the body radius by tabular input.

The geometry description option for a given interval is specified by the 
user and does not have to be the same for all intervals. For instance, the 
forebody/centerbody contour may have a conical tip, then a quadratic or cubic 
variation with \( x \), then a linear variation with \( x \), then again a quadratic or 
cubic variation with \( x \). A way to describe this contour would be to input the 
cone half-angle for the first interval, the cubic curve fit coefficients for 
the second interval, the body radii at the ends of the third interval, and the 
cubic curve fit coefficients for the fourth interval. Alternatively, the appro-
riate cubic curve fit coefficients could be supplied for each of the four in-
tervals. It should be noted that in the input of the geometry data, radius, 
slope, and curvature should be made compatible between adjacent intervals. The 
boundary contours are specified by entering the following parameters.

\[ \textbf{KBASE} \]

An integer variable denoting whether equation (3) or equation (4) is 
to be employed when at least one interval of the centerbody or cowl 
geometry is specified by either of these two cubic equations. If 
neither equation (3) nor equation (4) is used in the geometry de-
scription, then \text{KBASE} does not have to be specified. If a cubic 
equation is to be used, then entering \text{KBASE} = 0 specifies that 
equation (3) will be employed. If \text{KBASE} = 1, then equation (4) will 
be used. A default value of 0 is specified for \text{KBASE}. The specified 
value of \text{KBASE} applies to both the forebody/centerbody contour and 
the cowl contour.

\[ \textbf{NCENT} \]

A positive integer variable denoting the number of axial station 
used in specifying the forebody/centerbody geometry. The number 
of intervals for the forebody/centerbody is equal to \((\text{NCENT - 1})\). 
The specified value for \text{NCENT} must be at least 2 and no greater 
than 25. A default value of 2 is specified for \text{NCENT}.

\[ \textbf{KDCENT} \]

A one-dimensional integer variable array (dimensioned at 25) consist-
ing of \((\text{NCENT - 1})\) elements. Each element of \text{KDCENT} specifies the 
forebody/centerbody geometry description option to be used in the 
corresponding interval. Specifying \text{KDCENT}(1) = 1 for the \text{i}th interval 
selects the option in which the forebody/centerbody radius is 
described by equation (3) or equation (4) (depending on the value of 
\text{KBASE}). Specifying \text{KDCENT}(1) = 2 for the \text{i}th interval selects the 
option in which the forebody/centerbody radius is specified by tabu-
lar input. If the forebody tip is conical, the geometry in the first 
forebody/centerbody interval may be described by entering the cone
half-angle directly and specifying KDCENT(1) = 3. The specified value for KDCENT(1) must be 1 or 2, except for the first interval (I = 1) in which case values of 1, 2, or 3 may be specified. Specifying other values than those allowed causes the program execution to be aborted. The default value for KDCENT(1) is 3, while all other elements of KDCENT have no default values specified.

**XCENT**

A one-dimensional real variable array (dimensioned at 25) consisting of NCENT elements. Each element of XCENT denotes the axial (x) position, in either feet or meters, of the beginning of a forebody/centerbody interval [XCENT(NCENT) denotes the axial position of the end of the last interval]. The elements of XCENT must be nonnegative and monotonically increasing. The default values for XCENT(1) and XCENT(2) are 1.0 ft and 3.5 ft, respectively. The remaining elements of XCENT do not have default values specified.

**RCENT**

A one-dimensional real variable array (dimensioned at 25) consisting of up to NCENT elements. Each element of RCENT specifies the forebody/centerbody radius, in either feet or meters, at the axial location specified by the corresponding element of XCENT. If KDCENT(1) = 2, then RCENT(1) and RCENT(I + 1) must be specified. If KDCENT(1) = 1 or 3, then RCENT(1) and RCENT(I + 1) do not have to be specified. Each element of RCENT must be nonnegative. No default values are specified for the elements of RCENT.

**ACENT**, **BCENT**, **CCENT**, and **DCENT**

One-dimensional real variable arrays (each array is dimensioned at 25), where each array consists of up to (NCENT - 1) elements. These arrays are used in conjunction with equation (3) or equation (4) for specification of the forebody/centerbody geometry. The elements of ACENT, BCENT, CCENT, and DCENT specify the coefficients $a_i$, $b_i$, $c_i$, and $d_i$, respectively, in equation (3) or equation (4). If KDCENT(1) = 1, then ACENT(1), BCENT(1), CCENT(1), and DCENT(1) must be specified for the $i$th interval. If KDCENT(1) = 2 or 3, then ACENT(1), BCENT(1), CCENT(1), and DCENT(1) do not have to be specified for that interval. The units for the elements of ACENT, BCENT, CCENT, and DCENT are either feet or meters. The elements of BCENT are dimensionless. The units for the elements of CCENT are either $(\text{feet})^{-1}$ or $(\text{meters})^{-1}$. The units for the elements of DCENT are $(\text{feet})^{-2}$ or $(\text{meters})^{-2}$. No default values are specified for the elements of ACENT, BCENT, CCENT, and DCENT.

**CONE**

A real variable denoting the cone half-angle, in degrees, of the forebody tip if it is conical. If KDCENT(1) = 3, then CONE must be specified. If KDCENT(1) = 1 or 2, then CONE does not have to be specified. A default value of 10.0 degrees is specified for CONE.

If only the external flow field about the forebody is to be computed [KCALL(1) = 1, KCALL(2) = 0, and KCALL(3) = 0], no further parameters must be specified in namelist LIST5. If the flow field in the annulus is to be determined, the following parameters must be entered.
NCWLN: A positive integer variable denoting the number of axial stations used in specifying the cowl geometry. The number of intervals for the cowl is equal to (NCWLN - 1). The specified value for NCWLN must be at least 2 and no greater than 25. No default value is specified for NCWLN.

KDCWLN: A one-dimensional integer variable array (dimensioned at 25) consisting of (NCWLN - 1) elements. Each element of KDCWLN specifies the cowl geometry description option to be used for the corresponding interval. Specifying KDCWLN(I) = 1 for the Ith interval selects the option in which the cowl radius is described by equation (3) or equation (4) (depending on the value of KBASE). Specifying KDCWLN(I) = 2 for the Ith interval selects the option in which the cowl radius is specified by tabular input. The specified value for KDCWLN(I) must be either 1 or 2. Specifying other values than those allowed causes the program execution to be aborted. The elements of KDCWLN do not have default values specified.

XCWLN: A one-dimensional real variable array (dimensioned at 25) consisting of NCWLN elements. Each element of XCWLN specifies the axial (x) position, in either feet or meters, of the beginning of a cowl interval [XCWLN(NCWLN) denotes the axial position of the end of the last interval]. Each element of XCWLN must be nonnegative and monotonically increasing. The elements of XCWLN do not have default values specified.

RCWLN: A one-dimensional real variable array (dimensioned at 25) consisting of NCWLN elements. Each element of RCWLN specifies the cowl radius, in either feet or meters, at the axial location specified by the corresponding element of XCWLN. If KDCWLN(I) = 2, then RCWLN(I) and RCWLN(I + 1) must be specified. If KDCWLN(I) = 1, then RCWLN(I) and RCWLN(I + 1) do not have to be specified. Each element of RCWLN must be nonnegative. The elements of RCWLN do not have default values specified.

ACWLN, BCWLN, CCWLN, DCWLN: One-dimensional real variable arrays (each array is dimensioned at 25), where each array consists of up to (NCWLN - 1) elements. These arrays are used in conjunction with equation (3) or equation (4) for specification of the cowl geometry. The elements of ACWLN, BCWLN, CCWLN, and DCWLN specify the coefficients a_i, b_i, c_i, and d_i, respectively, in equation (3) or equation (4). If KDCWLN(I) = 1, then ACWLN(I), BCWLN(I), CCWLN(I), and DCWLN(I) must be specified for the Ith interval. If KDCWLN(I) = 2, then ACWLN(I), BCWLN(I), CCWLN(I), and DCWLN(I) do not have to be specified for that interval. The units of the elements of ACWLN are either feet or meters. The elements of BCWLN are dimensionless. The units for the elements of CCWLN are either (feet)^{-1} or (meters)^{-1}. The units for the elements of DCWLN are either (feet)^{-2} or (meters)^{-2}. No default values are specified for the elements of ACWLN, BCWLN, CCWLN, and DCWLN.

DXTRAN: A real variable denoting the centerbody translation from the design point position, or, equivalently, the amount the cowl has been trans-
lated with respect to the centerbody. The units of DXTRAN are either feet or meters. Translation occurs solely in the x-direction. Moreover, the origin of the coordinate system is maintained at the forebody tip when translation occurs. A positive value for DXTRAN corresponds to a forward centerbody translation or a rearward cowl translation. A default value of 0.0 is specified for DXTRAN.

8. NAMELIST LIST6

The parameters entered in namelist LIST6 control the internal generation of the boundary layer initial data and specify the boundary layer computational mesh. The parameters entered in this namelist need only be specified if the boundary layer computation is to be performed [KBLAY = 1 specified in namelist LIST1].

The following six parameters are used for specification of the forebody/centerbody boundary layer initial data.

KBLIDA An integer variable denoting whether or not the forebody/centerbody boundary layer initial data are to be internally generated by the Adams finite difference algorithm described in Section II. The Adams algorithm is applicable only to cases in which the forebody is conical ahead of the station where the boundary layer data are to be generated. If KBLIDA = 1, the initial data are internally generated. If KBLIDA = 0, the initial data are entered by a formatted read of file ITAP2. The formatted read is described at the end of this section. A default value of 1 is specified for KBLIDA.

If KBLIDA = 1, the following four parameters must be entered.

KTURB An integer variable denoting if the Adams algorithm is to generate laminar flow or turbulent flow initial data for the forebody/centerbody boundary layer. If KTURB = 0, laminar flow initial data are generated. If KTURB = 1, turbulent flow initial data are generated. A default value of 0 is specified for KTURB.

CLENGH A positive real variable denoting the length of the conical section of the forebody in either feet or meters. A default value of 4.0 ft is specified for CLENGH.

The following two parameters define the computational mesh used in the Adams algorithm solution [see Reference (5) for further discussion]. In general, the program is executed by retaining these input parameters at their default values.

ADY A positive real variable denoting the first transformed mesh length in the surface normal direction that is used in the Adams algorithm solution. The default and recommended value of ADY is 0.010.

ARATIO A positive real variable denoting the ratio of successive normal
mesh steps used in the Adams algorithm solution. The default and recommended value of ARATIΩ is 1.0630.

If KBLIDA = 0 is specified in this namelist, then the following parameters must be entered.

**ITAP2** A positive integer variable denoting the tape number from which the forebody/centerbody boundary layer initial data are to be entered by a formatted read. The default value assigned to ITAP2 is 5 (the input file). The user may specify ITAP2 = 11, in which case the forebody/centerbody boundary layer initial data are read from TAPE11. TAPE11 is linked to the dummy file IVS2 in the PROGRAM card.

The following five parameters are used for specification of the cowl boundary layer initial data and must be entered only if the cowl boundary layer is to be calculated [KCALL(2) = 1 or KCALL(3) = 1 and KBLAY = 1 specified in namelist LIST1].

**KBLIDB** An integer variable denoting whether or not the cowl boundary layer initial data are to be internally generated by an approximate technique described in this section. If KBLIDB = 1, the initial data are internally generated. If KBLIDB = 0, the initial data are entered by a formatted read of file ITAP3. The formatted read is described at the end of this section. A default value of 1 is specified for KBLIDB.

The internally generated cowl boundary layer initial data are obtained using an approximate analysis briefly described below and presented in greater detail in Reference (1). The initial step in the analysis is to define the boundary layer thickness at each circumferential station in the computed sector. For laminar flow, the local boundary layer thickness \( \delta \) is approximated by

\[
\delta = 5.0 \left( \frac{\nu_e \tilde{u}_e}{\rho_e U_e} \right)^{1/2}
\]

whereas for turbulent flow, \( \delta \) is approximated by

\[
\delta = 0.37\bar{X} \left( \frac{\rho_e \tilde{u}_e}{\nu_e} \right)^{-1/5}
\]

where \( \rho_e, \tilde{u}_e, \) and \( \nu_e \) denote the local boundary layer edge density, streamwise velocity, and laminar dynamic viscosity, respectively, and \( \bar{X} \) is the streamwise curvilinear coordinate on the cowl (see Figure 5). With the boundary layer thickness determined, the streamwise and cross-flow velocity profiles for laminar...
flow are defined by

\[ \frac{\tilde{u}}{\tilde{u}_e} = 2.0 \left( \frac{\tilde{y}}{\delta} \right) - \left( \frac{\tilde{y}}{\delta} \right)^2 \]

(7)

\[ \frac{\tilde{w}}{\tilde{w}_e} = 2.0 \left( \frac{\tilde{y}}{\delta} \right) - \left( \frac{\tilde{y}}{\delta} \right)^2 \]

(8)

whereas for turbulent flow, the following power laws are employed

\[ \frac{\tilde{u}}{\tilde{u}_e} = \left( \frac{\tilde{y}}{\delta} \right)^\alpha \]

(9)

\[ \frac{\tilde{w}}{\tilde{w}_e} = \left( \frac{\tilde{y}}{\delta} \right)^\beta \]

(10)

In the above equations, \( \tilde{u} \) and \( \tilde{w} \) denote the velocity components in the streamwise \( \tilde{x} \) and cross-flow \( \tilde{z} \) directions, respectively, \( \tilde{y} \) is the distance measured normal to the wall, \( \alpha \) and \( \beta \) are constants, and the subscript \( e \) denotes boundary layer edge conditions. The total enthalpy \( H \) distribution is given by assuming a quadratic variation with distance across the boundary layer and then imposing the appropriate boundary conditions. This yields

\[ H = H_w + 2(H_e - H_w)\left( \frac{\tilde{y}}{\delta} \right) + (H_w - H_e)\left( \frac{\tilde{y}}{\delta} \right)^2 \]

(11)

for cases in which the wall temperature is specified, and

\[ H = (H_e - \frac{1}{2} \delta H_w') + \delta H_w' \left( \frac{\tilde{y}}{\delta} \right) - \frac{1}{2} \delta H_w' \left( \frac{\tilde{y}}{\delta} \right)^2 \]

(12)

for cases in which the temperature derivative at the wall is specified. In equations (11) and (12), \( H_w \) and \( H_w' \) denote the total enthalpy and total enthalpy normal derivative at the wall, respectively, and \( H_e \) denotes the total enthalpy at the boundary layer edge. Specification of the total enthalpy and velocity.
profiles allow the density distribution to be determined if the pressure is assumed to be constant along a given boundary layer normal.

The following three parameters must be entered if KBLIDB = 1 and are used for specification of the cowl boundary layer initial data.

**KTURBB**
An integer variable denoting whether laminar flow or turbulent flow cowl boundary layer initial data are to be generated internally by the approximate analysis presented above. If KTURBB = 0, laminar flow initial data are generated. If KTURBB = 1, turbulent flow initial data are generated. A default value of 0 is specified for KTURBB.

**ALPCWL**
A positive real variable denoting the exponent α in the turbulent power law streamwise velocity profile given by equation (9). ALPCWL must be entered only if KTURBB = 1 is specified in this namelist. A default value of 1.0/7.0 = 0.142857 is specified for ALPCWL. This value of ALPCWL corresponds to the assumptions made in deriving equation (6).

**BETCWL**
A positive real variable denoting the exponent β in the turbulent power law cross-flow velocity profile given by equation (10). BETCWL must be entered only if KTURBB = 1 is specified in this namelist. A default value of 1.0/7.0 = 0.142857 is specified for BETCWL. This value of BETCWL corresponds to the assumptions made in deriving equation (6).

If KBLIDB = 0 is specified in this namelist, then the following parameter must be entered.

**ITAP3**
A positive integer variable denoting the tape number from which the cowl boundary layer initial data are to be entered by a formatted read. The default value assigned to ITAP3 is 5 (the input file). The user may specify ITAP3 = 12, in which case the cowl boundary layer initial data are read from TAPE12. TAPE12 is linked to the dummy file IVS3 in the PROGRAM card.

The following two parameters designate the values of the streamwise curvilinear coordinate $x$ at which the boundary layer initial data are specified. See Figure 5 for definition of the $x$ coordinates for both the forebody/centerbody and cowl. Note that for the forebody/centerbody, $x = 0.0$ is located at the forebody tip, while for the cowl, $x = 0.0$, is located at the cowl lip.

**XASTRT**
A positive real variable denoting the value of the streamwise curvilinear coordinate $x$ (see Figure 5) at which the forebody/centerbody boundary layer initial data are specified. XASTRT must be entered only if KBLIDA = 0 is specified in this namelist. XASTRT must correspond to the value of XI specified in namelist LIST2. No default value is specified for XASTRT.
A positive real variable denoting the value of the streamwise curvilinear coordinate $x$ (see Figure 5) at which the cowl boundary layer initial data are specified. XBSTRT must be entered only if KBLIDB = 0 is specified in this namelist. XBSTRT must correspond to the axial location of the first solution plane inside the annulus. No default value is specified for XBSTRT.

The following six parameters are used to specify the boundary layer computational mesh. The boundary layer computational point networks are illustrated in Figure 6.

A positive integer variable denoting the number of circumferential stations to be used in the computation of both the forebody/centerbody and cowl boundary layers (see Figure 6). MBLAY must be at least 5 but no greater than 16. The default value and recommended value for MBLAY for KSYM = 1 is 15.

If the boundary layer initial data are specified by the user, then the following two parameters are entered to designate the number of radial points in the supplied data.

A positive integer variable denoting the number of radial points in the user-supplied forebody/centerbody boundary layer initial data. NINA must be entered only if KBLIDA = 0 is specified in this namelist. NINA must be at least 5 but no greater than 20. A default value of 20 is specified for NINA.

A positive integer variable denoting the number of radial points in the user-supplied cowl boundary layer initial data. NINB must be entered only if the cowl boundary layer is to be computed and if KBLIDB = 0 is specified in this namelist. NINB must be at least 5 but no greater than 20. A default of 20 is specified for NINB.

The following two parameters designate the number of radial points used in the boundary layer computation. The following parameters may be different from NINA and NINB since the user-supplied data will be interpolated.

A positive integer variable denoting the number of radial stations employed in the forebody/centerbody boundary layer computation. NA must be at least 5 but no greater than 20. A default value of 20 is specified for NA.

A positive integer variable denoting the number of radial stations employed in the cowl boundary layer computation. NB must be specified only if the cowl boundary layer is to be computed. NB must be at least 5 but no greater than 20. A default value of 20 is specified for NB.
(a) CIRCUMFERENTIAL NETWORK

(b) RADIAL NETWORK

FIGURE 6. BOUNDARY LAYER COMPUTATIONAL POINT NETWORKS
The following parameter specifies the mesh distortion in the boundary layer normal direction.

**FACTΩR**  
A one-dimensional real variable array consisting of two elements. The elements of FACTΩR denote the ratio of two successive step sizes in the boundary layer normal direction, the normal step size being expressed in terms of transformed variables [see Reference (1)]. FACTΩR (1) and FACTΩR (2) denote the successive normal step size ratios for the forebody/centerbody and cowl boundary layers, respectively. FACTΩR (2) must be entered only if the cowl boundary layer is to be calculated. Specifying FACTΩR(1) = 1.0 produces a mesh that is uniform in the boundary layer normal direction, whereas specifying FACTΩR(1) > 1.0 produces a mesh which is more closely spaced near the wall. Default values of 1.0 are specified for both elements of FACTΩR.

9. **NAMELIST LIST7**

The parameters entered in namelist LIST7 specify the wall temperature boundary condition to be used in the boundary layer computation. The parameters entered in this namelist need only be specified if the boundary layer computation is to be performed (KBLAY = 1 specified in namelist LIST1).

**KTYPE**  
An integer parameter denoting whether the wall temperature or wall temperature normal derivative is to be used as a boundary condition in both the forebody/centerbody and cowl boundary layer solutions. If KTYPE = 1, the wall temperature is used as a boundary condition. If KTYPE = 2, the normal derivative of the temperature at the wall is used as a boundary condition. If the forebody/centerbody boundary layer initial data are generated internally (KBLIDA = 1 specified in namelist LIST6), then the wall temperature boundary condition option must be specified (KTYPE = 1). A default value of 1 is specified for KTYPE.

The wall temperature or its normal derivative may be specified as being either a constant or as having functional dependence upon axial position. For the case of axial position dependency, the wall temperature or its derivative is specified by tabular input. The temperature boundary condition on the forebody/centerbody is specified by entering the following parameters.

**KWLTΔ**  
An integer variable denoting whether a constant or variable temperature or temperature derivative boundary condition is to be used for the forebody/centerbody boundary layer computation. If KWLTΔ = 1, a constant boundary condition is specified. If KWLTΔ = 2, a variable boundary condition is specified. A default value of 1 is specified for KWLTΔ.

If a constant temperature or temperature derivative boundary condition is to be specified, then one of the two following parameters is entered.
TC\(\text{CONST}\)TA A positive real variable denoting the constant wall temperature, in either \(R\) or \(K\), for the forebody/centerbody. \(TC\text{CONST}\)TA must be entered only if \(K\text{TYPE} = 1\) and \(K\text{WLTA} = 1\) are specified in this namelist. The free-stream stagnation temperature is recommended for \(TC\text{CONST}\)TA. A default value of 500.0 \(R\) is specified for \(TC\text{CONST}\)TA.

DTDYCA A real variable denoting the constant wall temperature-normal derivative, in either \((R/ft)\) or \((K/m)\), for the forebody/centerbody. DTDYCA must be entered only if \(K\text{TYPE} = 2\) and \(K\text{WLTA} = 1\) are specified in this namelist. A default value of 0.0 is specified for DTDYCA.

If a variable temperature or temperature derivative boundary condition is to be specified, then the following parameters are entered.

NTABA A positive integer variable denoting the number of tabular data points used in the temperature boundary condition specification on the forebody/centerbody. NTABA must be entered only if \(K\text{WLTA} = 2\) is specified in this namelist. NTABA must be at least 3 but no greater than 25. No default value is specified for NTABA.

XWLA A one-dimensional real variable array (dimensioned at 25) consisting of NTABA elements. The XWLA array must be entered only if \(K\text{WLTA} = 2\) is specified in this namelist. Each element of XWLA specifies the axial (x) position, in either feet or meters, at which the wall temperature or its normal derivative is to be specified for the forebody/centerbody. Each element of XWLA must be nonnegative, monotonically increasing, and within bounds of the specified geometry. No default values are specified for the elements of XWLA.

TWLA A one-dimensional real variable array (dimensioned at 25) consisting of NTABA elements. The TWLA array must be entered only if \(K\text{TYPE} = 1\) and \(K\text{WLTA} = 2\) are specified in this namelist. Each element of TWLA specifies the forebody/centerbody wall temperature, in either \(R\) or \(K\), at the axial position specified by the corresponding element XWLA. Each element of TWLA must be positive. No default values are specified for the elements of TWLA.

DTDYWA A one-dimensional real variable array (dimensioned at 25) consisting of NTABA elements. The DTDYWA array must be entered only if \(K\text{TYPE} = 2\) and \(K\text{WLTA} = 2\) are specified in this namelist. Each element of DTDYWA specifies the forebody/centerbody wall temperature normal derivative, in either \((R/ft)\) or \((K/m)\), at the axial position specified by the corresponding element of XWLA. No default values are specified for the elements of DTDYWA.

If only the forebody flow field and boundary layer are to be calculated [\(K\text{CALL}(1) = 1\), \(K\text{CALL}(2) = K\text{CALL}(3) = 0\), and \(K\text{BLAY} = 1\) specified in namelist L\(\text{IST1}\)], then no other input parameters have to be specified in this namelist. If the internal flow field and boundary layers have to be computed [\(K\text{CALL}(2) = 1\) or \(K\text{CALL}(3) = 1\), and \(K\text{BLAY} = 1\) specified in namelist L\(\text{IST1}\)], then the follow-
ing parameters must be entered to specify the wall temperature boundary condition for the cowl boundary layer solution.

**KWL TB**

An integer variable denoting whether a constant or variable temperature or temperature derivative boundary condition is to be used for the cowl boundary layer computation. If KWL TB = 1, a constant boundary condition is specified. If KWL TB = 2, a variable boundary condition is specified. A default value of 1 is specified for KWL TB.

If a constant temperature or temperature derivative boundary condition is to be specified, then one of the two following parameters is entered.

**TCN STB**

A positive real variable denoting the constant wall temperature, in either R or K, for the cowl. TCN STB must be entered only if KTYPE = 1 and KWL TB = 1 are specified in this namelist. The free-stream stagnation temperature is recommended for TCN STB. A default value of 500.0 R is specified for TCN STB.

**TDY CB**

A real variable denoting the constant wall temperature normal derivative, in either (R/ft) or (K/m), for the cowl. DTDY CB must be entered only if KTYPE = 2 and KWL TB = 1 are specified in this namelist. A default value of 0.0 is specified for DTDY CB.

If a variable temperature or temperature derivative boundary condition is specified, then the following parameters are entered.

**NT ABB**

A positive integer variable denoting the number of tabular data points used in the temperature boundary condition specification on the cowl. NT ABB must be entered only if KWL TB = 2 is specified in this namelist. NT ABB must be at least 3 but no greater than 25. No default value is specified for NT ABB.

**XW LB**

A one-dimensional real variable array (dimensioned at 25) consisting of NT ABB elements. The XW LB array must be entered only if KWL TB = 2 is specified in this namelist. Each element of XW LB specifies the axial (x) position, in either feet or meters, at which the wall temperature or its normal derivative is to be specified for the cowl. Each element of XW LB must be nonnegative, monotonically increasing, and within bounds of the specified geometry. No default values are specified for the elements of XW LB.

**TW LB**

A one-dimensional real variable array (dimensioned at 25) consisting of NT ABB elements. The TW LB array must be entered only if KTYPE = 1 and KWL TB = 2 are specified in this namelist. Each element of TW LB specifies the wall temperature, in either R or K, at the axial position specified by the corresponding element of XW LB. Each element of TW LB must be positive. No default values are specified for the elements of TW LB.

**TDY WB**

A one-dimensional real variable array (dimensioned at 25) consisting of NT ABB elements. The DTDY WB array must be entered only if KTYPE =
2 and KWLTB = 2 are specified in this namelist. Each element of DTDYWB specifies the cowl wall temperature normal derivative, in either \((R/ft)\) or \((K/m)\), at the axial position specified by the corresponding element of XWLB. No default values are specified for the elements of DTDYWB.

10. NAMELIST LIST8

The parameters entered in namelist LIST8 specify the wall mass bleed distribution. If the case being considered requires no mass bleed, then the parameters entered in this namelist do not have to be specified. For those cases which require mass removal at the wall, the bleed distribution is specified by tabular input. The tabular input requires the specification of the axial location and extent of the bleed zones and specification of the bleed mass flux \([\text{mass flow rate}/\text{area}]\) within each zone (see Figure 7). Options exist to specify a zero bleed rate for either the forebody/centerbody or cowl.

The bleed distribution for the forebody/centerbody is specified by entering the following parameters.

**KDFA**

An integer variable denoting whether or not mass transfer occurs at the forebody/centerbody wall. If KDFA = 0, a case with no mass transfer (bleed) is specified. If KDFA = 1, a case with mass transfer is specified. A default value of 0 is specified for KDFA.

If KDFA = 1 is specified, the following four parameters must be entered.

**NRA**

A positive integer variable denoting the number of bleed zones on the forebody/centerbody (see Figure 7). NRA must be at least 1 but no greater than 25. No default value is specified for NRA.

**XSA**

A one-dimensional real variable array (dimensioned at 25) consisting of NRA elements. Each element of XSA denotes the axial \((x)\) position, in either feet or meters, of the beginning of a mass bleed zone on the forebody/centerbody (see Figure 7). The elements of XSA must be positive, monotonically increasing, and within bounds of the specified geometry. No default values are specified for the elements of XSA.

**XEA**

A one-dimensional real variable array (dimensioned at 25) consisting of NRA elements. Each element of XEA denotes the axial \((x)\) position, in either feet or meters, of the end of a mass bleed zone on the forebody/centerbody (see Figure 7). The elements of XEA must be positive, monotonically increasing, and within bounds of the specified geometry. Moreover, for the \(i\)th element, \(XEA(i) \geq XSA(i)\). No default values are specified for the elements of XEA.

**RVOA**

A one-dimensional real variable array (dimensioned at 25) consisting of NRA elements. Each element of RVOA denotes the mass flux \((\text{density} \times \text{velocity})\), in units of \((\text{Slug}/(ft \times \text{sec}))\) or \((\text{kg}/(m^2 \times \text{sec}))\), for the bleed zone defined by the corresponding elements of XSA and XEA. For mass bleed, the elements of RVOA must be specified as positive.
FIGURE 7. BLEED DISTRIBUTION SPECIFICATION
No default values are specified for the elements of \( \text{R}_\text{VB} \).

If only the forebody flow field is to be calculated [\( \text{KCALL}(1) = 1, \text{KCALL}(2) = \text{KCALL}(3) = 0 \) specified in namelist \text{LIST1}], then no other parameters need be specified in this namelist. If the internal flow is to be calculated [\( \text{KCALL}(2) = 1 \) or \( \text{KCALL}(3) = 1 \) specified in namelist \text{LIST1}] and mass transfer occurs at the inlet walls, then the following parameters must be entered to specify the cowl bleed distribution.

**KDFB**

An integer variable denoting whether or not mass transfer occurs at the cowl wall. If \( \text{KDFB} = 0 \), a case with no mass transfer is specified. If \( \text{KDFB} = 1 \), a case with mass transfer (bleed) is specified. A default value of 0 is specified for \( \text{KDFB} \).

If \( \text{KDFB} = 1 \) is specified, the following four parameters must be entered.

**NRB**

A positive integer variable denoting the number of bleed zones on the cowl (see Figure 7). \( \text{NRB} \) must be at least 1 but no greater than 25. No default value is specified for \( \text{NRB} \).

**XSB**

A one-dimensional real variable array (dimensioned at 25) consisting of \( \text{NRB} \) elements. Each element of \( \text{XSB} \) denotes the axial \((x)\) position, in either feet or meters, of the beginning of a mass bleed zone on the cowl (see Figure 7). The elements of \( \text{XSB} \) must be positive, monotonically increasing, and within bounds of the specified geometry. No default values are specified for the elements of \( \text{XSB} \).

**XEB**

A one-dimensional real variable array (dimensioned at 25) consisting of \( \text{NRB} \) elements. Each element of \( \text{XEB} \) denotes the axial \((x)\) position, in either feet or meters, of the end of a mass bleed zone on the cowl (see Figure 7). The elements of \( \text{XEB} \) must be positive, monotonically increasing, and within bounds of the specified geometry. Moreover, for the \( i \)th element, \( \text{XEB}(i) > \text{XSB}(i) \). No default values are specified for the elements of \( \text{XEB} \).

**R\_VB**

A one-dimensional real variable array (dimensioned at 25) consisting of \( \text{NRB} \) elements. Each element of \( \text{R\_VB} \) denotes the mass flux \((\text{density} \times \text{velocity})\), in units of \((\text{slug} / \text{ft}^2 \cdot \text{sec})\) or \((\text{kg} / \text{m}^2 \cdot \text{sec})\), for the bleed zone defined by the corresponding elements of \( \text{XSB} \) and \( \text{XEB} \). For mass bleed, the elements of \( \text{R\_VB} \) must be specified as positive. No default values are specified for the elements of \( \text{R\_VB} \).

11. NAMELIST \text{LIST9}

The parameters entered in namelist \text{LIST9} specify the turbulence model and the transition model used in the boundary layer computation. The parameters entered in this namelist need only be specified if the boundary layer computation is to be performed (\( \text{KBLAY} = 1 \) specified in namelist \text{LIST1}).

The three-dimensional turbulence model incorporated into the program is
based on a two-layer formulation with [see Reference (1)]

\[ \varepsilon_x = \varepsilon_{xI} \quad (0 \leq \tilde{y} \leq \tilde{y}_T) \]  
\[ \varepsilon_x = \varepsilon_{xO} \quad (\tilde{y}_T \leq \tilde{y} \leq \delta) \]  

where \( \varepsilon_x \) denotes the eddy viscosity in the streamwise momentum equation, \( \varepsilon_{xI} \) is the inner region eddy viscosity, \( \varepsilon_{xO} \) is the outer region eddy viscosity; \( \tilde{y} \) is the distance measured normal to the wall, \( \tilde{y}_T \) is defined by the point where \( \varepsilon_{xI} = \varepsilon_{xO} \), and \( \delta \) is the local boundary layer thickness.

The inner layer eddy viscosity is given by

\[ \varepsilon_{xI} = \delta_{TR}^2 \left[ \left( \frac{\hat{u}}{\hat{y}} \right)^2 + \left( \frac{\hat{w}}{\hat{y}} \right)^2 \right]^{1/2} \]  

where \( \hat{u} \) and \( \hat{w} \) denote the velocity components in the boundary layer streamwise (\( \hat{x} \)) and cross-flow (\( \hat{z} \)) directions, respectively, \( L \) is the mixing length, and \( \delta_{TR} \) is an appropriate factor accounting for the transition from laminar to turbulent flow. The mixing length \( L \) is given by

\[ L = \kappa \tilde{y} \left[ 1 - \exp \left( -\frac{\tilde{y}}{A} \right) \right] \]  

where \( \kappa \) is the von Karman parameter taken to be a constant with a recommended value of

\[ \kappa = 0.40 \]  

and \( A \) is defined by

\[ A = A^+ \cdot f \]  

In equation (18), \( f \) is a function of the flow gradients and local properties.
and is presented in Reference (1). The parameter $A^+$ is the van Driest damping factor which is taken to be a constant with a recommended value of

$$A^+ = 26.0$$  \hfill (19)

The outer region eddy viscosity is given by the velocity defect relation

$$\epsilon_{xo} = \delta_{TR} \int_0^\infty \left[ \left( \tilde{u}_e^2 + \tilde{w}_e^2 \right)^{1/2} - \left( \tilde{u}^2 + \tilde{w}^2 \right)^{1/2} \right] dy$$ \hfill (20)

where the subscript $e$ denotes the boundary layer edge conditions, and $\alpha$ is taken to be a constant with a recommended value of

$$\alpha = 0.0168$$ \hfill (21)

With the streamwise momentum equation eddy viscosity $\epsilon_x$ defined by the above relations, the cross-flow momentum equation eddy viscosity $\epsilon_z$ is defined by

$$\epsilon_z = \lambda \epsilon_x$$ \hfill (22)

where $\lambda$ is a constant. For isotropic turbulence, $\lambda$ takes the value

$$\lambda = 1.0$$ \hfill (23)

The turbulent eddy thermal conductivity $\epsilon_0$ is given by

$$\epsilon_0 = \frac{\epsilon}{Pr_t}$$ \hfill (24)
where $Pr_t$ is the turbulent Prandtl number which is assumed to be a constant in the analysis, and $\varepsilon$ is defined by

$$
\varepsilon = \left[ e_x^2 + e_z^2 \right]^{1/2}.
$$

(25)

The three-dimensional turbulence model is defined by entering the following parameters.

**APLUS**  
A positive real variable denoting the van Driest damping factor in equation (18). The default and recommended value of APLUS is 26.0.

**XKAPPA**  
A positive real variable denoting the von Karman parameter in equation (16). The default and recommended value of XKAPPA is 0.40.

**XALPHA**  
A positive real variable denoting the constant $\alpha$ in equation (20). The default and recommended value of XALPHA is 0.0168.

**PRT**  
A positive real variable denoting the turbulent Prandtl number in equation (24). The default and recommended value of PRT is 0.90.

**TFACTR**  
A positive real variable denoting the constant $\lambda$ in equation (22). The default and recommended value of TFACTR is 1.0.

In addition to the above parameters, two other input parameters are employed in the turbulence model of the Adams algorithm which is used to internally generate the forebody/centerbody boundary layer initial data (KBLIDA = 1 specified in namelist LIST6). The user should consult Reference (5) for further discussion of these parameters. In general, the program is executed by retaining the following two parameters at their default values.

**AKLM**  
A positive real variable used in the Adams algorithm turbulence model [see Reference (5) for discussion]. The default and recommended value for AKLM is 0.435.

**ALAM**  
A positive real variable used in the Adams algorithm turbulence model [see Reference (5) for discussion]. The default and recommended value for ALAM is 0.09.

A number of models have been incorporated into the computer program for determining the transition parameter $\delta_{TR}$ in equations (15) and (20). The transition models include:

Model No. 1: An instantaneous transition model with fully turbulent flow being specified as occurring at a particular value $x_T$ of the boundary layer streamwise curvilinear coordinate $x$ (see Figure 5). The transition parameter $\delta_{TR}$ is calculated from
Model No. 2: An instantaneous transition model with fully turbulent flow being specified as occurring at a critical Reynolds number $Re_T$ where the Reynolds number $Re$ is given by

\[
Re = \frac{\rho e \hat{u} \hat{x}}{\nu_e} \quad (28)
\]

with $\rho_e$, $\hat{u}_e$, and $\nu_e$ being the boundary layer edge density, streamwise velocity, and dynamic laminar viscosity, respectively. The transition parameter $\delta_{TR}$ is calculated from

\[
\delta_{TR} = 0.0 \quad (Re < Re_T) \quad (29)
\]

\[
\delta_{TR} = 1.0 \quad (Re \geq Re_T) \quad (30)
\]

Model No. 3: A progressive transition model with the onset of transitional flow occurring at $\tilde{x}_{T1}$ and with the onset of fully turbulent flow occurring at $\tilde{x}_{T2}$. The transition parameter $\delta_{TR}$ is calculated from

\[
\delta_{TR} = 0.0 \quad (\tilde{x} < \tilde{x}_{T1}) \quad (31)
\]

\[
\delta_{TR} = 1.0 \quad (\tilde{x} \geq \tilde{x}_{T2}) \quad (32)
\]

\[
\delta_{TR} = \frac{\tilde{x} - \tilde{x}_{T1}}{\tilde{x}_{T2} - \tilde{x}_{T1}} \quad (\tilde{x}_{T1} \leq \tilde{x} \leq \tilde{x}_{T2}) \quad (33)
\]
where $\bar{x}$ is the local value of the boundary layer streamwise curvilinear coordinate.

Model No. 4: A progressive transition model with the onset of transitional flow occurring at the Reynolds number $Re_{T1}$ and with the onset of fully turbulent flow occurring at $Re_{T2}$. The transitional parameter $\delta_{TR}$ is calculated from

$$\delta_{TR} = 0.0 \quad (Re < Re_{T1}) \quad (34)$$

$$\delta_{TR} = 1.0 \quad (Re > Re_{T2}) \quad (35)$$

$$\delta_{TR} = \frac{Re - Re_{T1}}{Re_{T2} - Re_{T1}} \quad (Re_{T1} \leq Re \leq Re_{T2}) \quad (36)$$

where $Re$ is defined by equation (28).

Model No. 5: A progressive transition model using the Dhawan and Narasimha formulation (8). In this model the onset of transitional flow is specified as occurring at $x_{T1}$ and it is assumed that fully turbulent flow occurs at $x = 2x_{T1}$. The transition parameter $\delta_{TR}$ is calculated from

$$\delta_{TR} = 0.0 \quad (\tilde{x} < \tilde{x}_{T1}) \quad (37)$$

$$\delta_{TR} = 1.0 - \exp \left[ -3.6097 \left( \frac{\bar{x}}{\bar{x}_{T1}} - 1.0 \right)^2 \right] \quad (\tilde{x} \geq \tilde{x}_{T1}) \quad (38)$$

The transition models are specified by entering the following one-dimensional and two-dimensional arrays. For each array, $K = 1$ and $K = 2$ denote the forebody/centerbody and cowl boundary layers, respectively. For the two-dimensional arrays, the index $IB$ denotes the $IB$th circumferential station (see Figure 6).

$\text{ITRANM}$ A one-dimensional integer variable array consisting of two elements. $\text{ITRANM}(1)$ and $\text{ITRANM}(2)$ denote the transition models to be used in the forebody/centerbody and cowl boundary layer computations, respectively. $\text{ITRANM}(K)$ can have values of 1, 2, 3, 4, and 5 corresponding to the aforementioned transition models. Default values of 5 are specified for both elements of $\text{ITRANM}$.
**XT**
A two-dimensional real variable array dimensioned at \((16, 2)\). 
\(XT( IB, K) ( IB = 1, \ldots, MBLAY)\) denotes the transition distance \(\xi_T\) for the \(IB\)th circumferential station as described in Model No. 1 and must be entered only if \(ITRANM(K) = 1\). No default values are specified for the elements of \(XT\).

**RET**
A one-dimensional real variable array consisting of two elements. 
The \(RET\) array must be entered only if \(ITRANM(K) = 2\) is specified in this namelist. The elements of \(RET\) specify the Reynolds number [defined by equation (28)] at which the flow transitions instantaneously from laminar to turbulent. \(RET(1)\) and \(RET(2)\) designate the transition Reynolds numbers for the forebody/centerbody and cowl, respectively. \(RET(2)\) must be entered only if the cowl boundary layer is to be calculated. No default values are specified for the elements of \(RET\).

**XT1**
A two-dimensional real variable array dimensioned at \((16, 2)\). 
\(XT1( IB, K) ( IB = 1, \ldots, MBLAY)\) denotes the transition distance \(\xi_T\) for the \(IB\)th circumferential station as described in Model Nos. 3 and 5, and must be entered only if \(ITRANM(K) = 3\) or 5. No default values are specified for the elements of \(XT1\).

**XT2**
A two-dimensional real variable array dimensioned at \((16, 2)\). 
\(XT2( IB, K) ( IB = 1, \ldots, MBLAY)\) denotes the transition distance \(\xi_T\) for the \(IB\)th circumferential station as described in Model No. 3, and must be entered only if \(ITRANM(K) = 3\). No default values are specified for the elements of \(XT2\).

**RETI**
A one-dimensional real variable array consisting of two elements. The \(RETI\) array must be entered only if \(ITRANM(K) = 4\) is specified in this namelist. The elements of \(RETI\) specify the Reynolds number [defined by equation (28)] at which the onset of transitional flow occurs. \(RETI(1)\) and \(RETI(2)\) specify the transitional flow onset Reynolds number for the forebody/centerbody and cowl, respectively. \(RETI(2)\) must be specified only if the cowl boundary layer is to be calculated. No default values are specified for the elements of \(RETI\).

**RET2**
A one-dimensional real variable array consisting of two elements. The \(RET2\) array must be entered only if \(ITRANM(K) = 4\) is specified in this namelist. The elements of \(RET2\) specify the Reynolds number [defined by equation (28)] at which the onset of fully turbulent flow occurs. \(RET2(1)\) and \(RET2(2)\) specify the fully turbulent flow onset Reynolds number for the forebody/centerbody and cowl, respectively. \(RET2(2)\) must be specified only if the cowl boundary layer is to be calculated. No default values are specified for the elements of \(RET2\).
12. NAMELIST LIST10

The parameters entered in namelist LIST10 specify the various convergence
tolerances and iteration limits used in the numerical integration. All para-
meters in this namelist have specified default values. In general, the program
is executed without changing the values of any of the parameters in this name-
list.

SAFEIN
A positive real variable denoting the ratio of the axial marching
step taken to the axial marching step allowed by the Courant-
Friedrichs-Lewy (CFL) stability criterion. This variable is used
to determine the axial position of both the first solution plane in
the forebody flow field integration \([\text{KCALL}(1) = 1]\) and the first
solution plane in the internal flow field integration in which
shock waves are not discretely fitted \([\text{KCALL}(3) = 1]\). Ensuing solu-
tion planes for these integration options have their axial locations
adjusted in accord with an internally computed value of SAFEIN.
For the internal flow field integration option in which shock waves
are discretely fitted \([\text{KCALL}(2) = 1]\), the axial position of each
solution plane (except in the vicinity of a shock wave reflection)
is controlled by the input value of SAFEIN. The specified value of
SAFEIN must be positive, and must be less than 1.0 to satisfy the
CFL stability criterion. The default and recommended value of
SAFEIN is 0.975.

CRIT
A one-dimensional real variable array consisting of 18 elements.
Each element of CRIT specifies a convergence tolerance or other
parameter. The elements of CRIT have the following definitions
and default values.

CRIT(1)
A positive real variable denoting the tolerance, in either feet or
meters, used to determine if a user supplied initial-value plane
data point is sufficiently close to a plane of symmetry when the
data point is supposed to lie on the plane of symmetry. CRIT(1) is
also used to determine if a user supplied initial-value plane data
point is sufficiently close to the solid boundary when that point
is supposed to lie on the solid boundary. A default value of 0.1
ft (or 0.1m) is specified for CRIT(1).

CRIT(2)
A positive real variable denoting the relative tolerance used in
testing for a loss of significance in IBM library subroutine GELG
(GELG is used to solve a system of simultaneous linear equations).
A default value of \(10^{-7}\) is specified for CRIT(2).
CRIT(3) A positive real variable denoting the relative tolerance used in testing for convergence in the internal generation of the initial-value plane flow property field. A default value of $10^{-4}$ is specified for CRIT(3).

CRIT(4) A positive real variable denoting the relative tolerance used in testing for convergence of all three coordinates in the iterative scheme employed in computing a streamline-surface intersection or a bicharacteristic-surface intersection. A default value of $10^{-5}$ is specified for CRIT(4).

CRIT(5) A positive real variable denoting the relative tolerance used in testing for the convergence of the five flow properties $u$, $v$, $w$, $P$, and $p$ in subroutine SÖLVE. A default value of $10^{-4}$ is specified for CRIT(5).

CRIT(6) A positive real variable denoting the relative tolerance used in testing for the convergence of the static pressure in subroutine SHÔCK. Convergence is attained in the local iteration loop if

$$\frac{|P(2)-P^*(2)|}{P(2)} \leq \text{CRIT}(6)$$

where $P(2)$ is the solution point pressure obtained from the local Hugoniot relations, and $P^*(2)$ is the pressure obtained from the wave surface compatibility relation. A default value of $10^{-4}$ is specified for CRIT(6).

CRIT(7) A positive real variable denoting the mass flow rate ratio at which the maximum number of radial stations allowed in the forebody flow field computation is changed from JLIMIT(1) to JLIMIT(2). The mass flow rate ratio is the mass flow rate at a given forebody flow field solution plane divided by the estimated mass flow rate at the axial station corresponding to XEND(1). A default value of 0.5 is specified for CRIT(7).

CRIT(8) A positive real variable used as a multiplier of the mass flow ratio which is employed in determining whether or not point addition is to be performed on a solution plane in the forebody flow field integration. The mass flow rate ratio is the mass flow rate at the solution plane just computed divided by that at the last solution plane where point addition or deletion was performed. A default value of 1.0 is specified for CRIT(8).

CRIT(9) A positive real variable denoting the relative tolerance used in routine LINK31 for determining when the angle $\alpha$ calculated in the global correction for the bow shock wave points has converged. A default value of $10^{-4}$ is specified for CRIT(9).
CRIT(10) A positive real variable used in routine LINK31 for determining if
a sufficient number of shock wave solution points have converged in
global correction. Convergence is attained when

\[
\frac{M}{\text{IST}\kappa P} \geq \text{CRIT}(10)
\]

where \( M \) is the number of shock wave solution points which have
converged in global correction, and \( \text{IST}\kappa P \) is the number of cir-
cumferential stations in the computed sector. A default value
of 0.8 is specified for CRIT(10).

CRIT(11) A positive real variable denoting the relative tolerance used in
subroutine BSHOCK for determining if the velocity component down-
stream of the shock wave and normal to the surface of the solid
boundary has converged to a specified value. A default value of
\( 10^{-2} \) is specified for CRIT(11).

CRIT(12) A positive real variable used in routine LINK32 for determining if
another solution plane is to be inserted between the last solution
plane and the intersection of the incident internal shock wave with
the solid boundary. Another solution plane is inserted if

\[
\frac{\Delta x}{\Delta x_{\text{CFL}}} \geq \text{CRIT}(12)
\]

where \( \Delta x \) is the axial \((x)\) distance between the last computed plane
and the nearest point on the space curve defined by the intersec-
tion of the incident internal shock wave with solid boundary, and
\( \Delta x_{\text{CFL}} \) is the axial step allowed by the Courant-Friedrichs-Lewy (CFL)
stability criterion. A default value of 0.2 is specified for CRIT(12).

CRIT(13) Not presently employed.

CRIT(14) A positive real variable used in subroutine PENTRE for determining
if a streamline-shock wave intersection point is sufficiently close
to the current solution plane, so that an interior point unit process
on the downstream side of the shock wave is not performed. Instead,
a streamline projection onto the solution plane and subsequent flow
property interpolation in this plane is performed. The application
of the interior point unit process is not performed if

\[
\left( \frac{x_s - x_{\text{int}}}{\Delta x_{\text{CFL}}} \right) < \text{CRIT}(14)
\]
where \( x_s \) is the axial position of the solution plane, \( x_{int} \) is the axial location of the streamline-shock wave intersection point, and \( \Delta x_{CFL} \) is the axial marching step allowed by the Courant-Friedrichs-Lewy stability criterion. A default value of 0.4 is specified for CRIT(14).

**CRIT(15)**

A positive real variable used in subroutine STRSHK for determining if convergence has been obtained in calculating the intersection point of a body streamline with the space curve defined by the intersection of the incident internal shock wave with a solid boundary. Convergence is attained when

\[
|\theta_{i+1} - \theta_i| \leq \text{CRIT}(15)
\]

where \( \theta_i \) is the polar angle of the intersection point on the \( i \)th iteration, and \( \theta_{i+1} \) is the polar angle on the \((i+1)\)th iteration. A default value of 10\(^{-4}\) radians is specified for CRIT(15).

**CRIT(16)**

A positive real variable used in subroutine INTSCT for determining if convergence has been obtained in calculating the intersection point of a bicharacteristic with either a solid boundary or a shock wave, or the intersection point of a streamline with a shock wave. Convergence is attained when

\[
|R_1 - R_S| \leq \text{CRIT}(16)
\]

where \( R_1 \) is the radius of the intersection point obtained by integrating the equation for a streamline or bicharacteristic, and \( R_S \) is the intersection point radius obtained from the shock wave or boundary surface formulations. A default value of 10\(^{-4}\) ft (or 10\(^{-4}\) m) is specified for CRIT(16).

**CRIT(17)**

A positive real variable denoting the relative tolerance used in subroutines ABLSLN and GBLSLN to test for convergence of the wall boundary streamwise velocity normal derivative in the boundary layer implicit finite difference algorithm. A default value of 10\(^{-2}\) is specified for CRIT(17).

**CRIT(18)**

A positive real variable denoting the tolerance used in subroutine SBLINT to test for convergence of the continuity, streamwise momentum, and cross-flow momentum equations in the shock wave-boundary layer integral interaction analysis. A default value of 10\(^{-5}\) is specified for CRIT(18).
ITEND A one-dimensional integer variable array consisting of 8 elements. Each element of ITEND specifies a limit to the number of iterations permissible in a given iteration loop. The elements of ITEND have the following definitions and default values.

ITEND(1) A positive integer variable denoting the maximum number of inner iterations permissible in determining the intersection coordinates of either a streamline with a surface, or a bicharacteristic with a surface. ITEND(1) is used in conjunction with CRIT(4). A default value of 10 is specified for ITEND(1).

ITEND(2) A positive integer variable denoting the maximum number of outer iterations permissible in obtaining the five flow properties $u$, $v$, $w$, $P$, and $p$ in all unit processes except the shock wave-solid boundary point unit process. A default value of 10 is specified for ITEND(2).

ITEND(3) Not presently employed.

ITEND(4) A positive integer variable denoting the maximum number of iterations permissible in the relaxation of the velocity component normal to the solid boundary and downstream of the reflected (cowl lip) shock wave in the shock wave-solid boundary point unit process (subroutine BSHOCK). A default value of 20 is specified for ITEND(4).

ITEND(5) Not presently employed.

ITEND(6) A positive integer variable denoting the maximum number of permissible subiterations in determining the intersection point of a line segment with a given three-dimensional surface (subroutine INTSCT). A default value of 10 is specified for ITEND(6).

ITEND(7) A positive integer variable denoting the maximum number of iterations permissible in obtaining convergence for the wall boundary normal derivative of the streamwise velocity in the boundary layer implicit finite difference algorithm. ITEND(7) is used in conjunction with CRIT(17). A default value of 10 is specified for ITEND(7).

ITEND(8) A positive integer variable denoting the maximum number of iterations permissible in obtaining convergence for the continuity, streamwise momentum, and cross-flow momentum equations in the integral shock wave-boundary layer interaction analysis. ITEND(8) is used in conjunction with CRIT(18). A default value of 15 is specified for ITEND(8).

13. NAMELIST LISTII

The parameters entered in namelist LISTII specify if debug output is to be printed.

KDUMP A one-dimensional integer variable array consisting of 9 elements.
Each element of KDUMP specifies whether or not a particular computational process is to have debug output printed. Specifying KDUMP(I) = 1 (I=1 to 9) activates the debug output option for the corresponding process. Specifying KDUMP(I) = 0 causes no debug output to be printed for the corresponding process. The elements of KDUMP activate the debug output option for the following processes and have the following default values.

<table>
<thead>
<tr>
<th>KDUMP(I)</th>
<th>Activates Debug Output for</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KDUMP(1)</td>
<td>supersonic flow interior point scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(2)</td>
<td>supersonic flow solid body point scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(3)</td>
<td>supersonic flow field-shock wave point scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(4)</td>
<td>supersonic flow solid body-shock wave point scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(5)</td>
<td>boundary layer initial data generation schemes</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(6)</td>
<td>interpolation scheme for boundary layer edge conditions</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(7)</td>
<td>plane of symmetry finite difference-boundary layer scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(8)</td>
<td>three-dimensional finite difference boundary layer scheme</td>
<td>0</td>
</tr>
<tr>
<td>KDUMP(9)</td>
<td>shock wave-boundary layer interaction region scheme</td>
<td>0</td>
</tr>
</tbody>
</table>

ISTART A positive integer variable denoting the solution plane number at which debug output is to be initiated. A default value of 1 is specified for ISTART.

14. FORMATTED READ OF THE INITIAL-VALUE FLOW PROPERTY FIELDS

The user supplied supersonic flow initial data are entered by a formatted read of file ITAPI after all eleven namelists have been input. To enter the supersonic flow initial data by tabular input, KIVS = 0 must be specified in namelist LIST2. The default value for ITAPI is 5 (the input file). The supersonic flow initial-value plane may be read from TAPE10 by specifying ITAPI = 10 in namelist LIST2. TAPE10 is linked to the dummy file IVSI in the PROGRAM card.

The index limits for the supersonic flow initial-value plane, ISTOP and JMAXI, are entered in namelist LIST3. The initial-value plane point networks for the four flow symmetry options are illustrated in Figure 3.
The supersonic flow initial data are entered by the formatted read statement

```
READ (ITAPI,III) ((Y(I,J),Z(I,J),U(I,J),V(I,J),W(I,J),P(I,J),R0(I,J),
                   J=1,JMAXI),I=1,ISTP)
```

with the format (4E20.13/3E20.13). The parameters in the formatted read statement have the following definitions (see Figure 3).

- **I**: An integer denoting the circumferential index of the data point.
- **J**: An integer denoting the radial index of the data point.
- **Y**: A two-dimensional real variable array, each element of which denotes the y-position, in either feet or meters, of point (I,J). The Y array is dimensioned at (30,15). No default values are specified for the elements of Y.
- **Z**: A two-dimensional real variable array, each element of which denotes the z-position, in either feet or meters, of point (I,J). The Z array is dimensioned at (30,15). No default values are specified for the elements of Z.
- **U**: A two-dimensional real variable array, each element of which denotes the x-component of velocity, in either (ft/sec) or (m/s), at point (I,J). The U array is dimensioned at (30,15). No default values are specified for the elements of U.
- **V**: A two-dimensional real variable array, each element of which denotes the y-component of velocity, in either (ft/sec) or (m/s), at point (I,J). The V array is dimensioned at (30,15). No default values are specified for the elements of V.
- **W**: A two-dimensional real variable array, each element of which denotes the z-component of the velocity, in either (ft/sec) or (m/s), at point (I,J). The W array is dimensioned at (30,15). No default values are specified for the elements of W.
- **P**: A two-dimensional real variable array, each element of which denotes the pressure, in either (lbf/ft²) or (N/m²), at point (I,J). The P array is dimensioned at (30,15). No default values are specified for the elements of P.
- **R0**: A two-dimensional real variable array, each element of which denotes the density, in either (slug/ft³) or (kg/m³), at point (I,J). The R0 array is dimensioned at (30,15). No default values are specified for the elements of R0.

In all cases, the supersonic flow initial-value plane data points with J = 1 must lie (to a close approximation) on the surface of the forebody/centerbody. The supersonic flow initial-value plane data points with J = JMAXI correspond to the downstream bow shock wave points. If only the internal flow is to be computed, the initial-value plane is located at the cowl lip axial station. It is sufficient to specify the flow property field, in this case, to a point just outside of the cowl lip. If the bow shock wave radius is less than that of the cowl.
For the case of no planes of flow symmetry \((KSYM = 0)\), the computed sector is the entire solution plane corresponding to \(IST\) circumferential stations and \(JMAXI\) radial stations \([\text{see Figure 3(a)}]\). For the case of one plane of flow symmetry \((KSYM = 1)\), the computed sector is the half-plane bounded by the \(y\)-axis and containing the \(\pm z\)-axis \([\text{see Figure 3(b)}]\). In this case, the data points with \(I = 1\) must lie on the \(+y\)-axis, and the data points with \(I = IST\) must lie on the \(-y\)-axis. For the case of two planes of flow symmetry \((KSYM = 2)\), the computed sector is the quadrant bounded by the \(y\)-axis and the \(+z\)-axis \([\text{see Figure 3(c)}]\). In this case, the data points with \(I = 1\) must lie on the \(+y\)-axis, and the data points with \(I = IST\) must lie on the \(+z\)-axis. For the axisymmetric flow case \((KSYM = 3)\), the computed sector is limited to the single circumferential station lying on the \(+y\)-axis \([\text{see Figure 3(d)}]\). In this case, the data points with \(I = 1\) must lie on the \(+y\)-axis.

If the forebody supersonic flow field is not being calculated \([\text{KCALL}(1) = 0]\), or if it is being computed and the bow shock wave is conical \([\text{KC\_N} = 1]\), then the following shock wave angle input parameters do not have to be entered. If, however, the forebody flow field is to be calculated \([\text{KCALL}(1) = 1]\) and the bow shock wave is not conical \([\text{KC\_N} = 0]\), then the angle subtended by the bow shock wave and the \(x\)-axis in the meridional plane defined by the shock wave point for each shock wave point in the computed sector must be entered by the formatted read statement.

\[
\text{READ (ITAP1,II2) (BETA(1),I=1,ISTP) }
\]

with the format \((E20.13)\). The parameters in the formatted read statement have the following definitions (see Figure 3).

- \(I\): An integer denoting the circumferential index of the initial-value plane shock wave point.
- \(BETA\): A one-dimensional real variable array (dimensioned at 30), each element of which denotes the angle, in radians, subtended by the bow shock wave and the \(x\)-axis in the meridional plane defined by the corresponding initial-value plane downstream shock wave point. Each element of \(BETA\) must be positive. No default values are specified for the elements of \(BETA\).

The following parameters must be entered only if the boundary layer computation is to be performed \([\text{KBLAY} = 1\] specified in namelist \text{LIST1})\).

The user-supplied forebody/centerbody boundary layer initial data are entered by a formatted read of file \text{ITAP2} after all eleven namelists have been input and after the supersonic flow initial data have been input if that data was externally generated. To enter the forebody/centerbody boundary layer initial data by tabular
input, $KBLIDA = 0$ must be specified in namelist LIST6. The default value for ITAP2 is 5 (the input file). The forebody/centerbody boundary layer initial data may be read from TAPE11 by specifying ITAP2 = 11 in namelist LIST6. TAPE11 is linked to the dummy file IVS2 in the PROGRAM card.

The index limits for the forebody/centerbody boundary layer initial data, $MBLAY$ and $NINA$, are entered in namelist LIST6. The boundary layer point networks are illustrated in Figure 6.

The forebody/centerbody boundary layer initial data are entered by the formatted read statements

\[
\text{READ (ITAP2,II3) ((ZZ(IB),FA(IB,JB),UA(IB,JB),WA(IB,JB),XLAMDA(IB,JB),}
\]
\[
\text{JB=1,NINA),IB=1,MBLAY)}
\]
\[
\text{READ (ITAP2,II4) (UEA(IB),WEA(IB),PEA(IB),R\_E\_A(IB),DUDXA(IB),DWDXA(IB),}
\]
\[
\text{DPDXA(IB),DRDXA(IB),IB=1,MBLAY)}
\]

with the formats (4E20.13/4E20.13) and (4E20.13/4E20.13), respectively. The parameters in the formatted read statements have the following definitions (see Figure 6).

- **IB**: An integer denoting the circumferential index of the data point.
- **JB**: An integer denoting the radial (or boundary layer normal) index of the solution point.
- **ZZ**: A one-dimensional real variable array, each element of which denotes the circumferential angle, in radians, of the IBth circumferential station. The ZZ array is dimensioned at (16). No default values are specified for the elements of ZZ.
- **FA**: A two-dimensional real variable array, each element of which denotes the distance, in either feet or meters, between point (IB,JB) and the surface as measured along the surface normal passing through point (IB,JB). The FA array is dimensioned at (16,20). No default values are specified for the elements of FA.
- **UA**: A two-dimensional real variable array, each element of which denotes the boundary layer streamwise (x) component of velocity, in either \((\text{ft/s})\) or \((\text{m/s})\), at point (IB,JB). The UA array is dimensioned at (16,20). No default values are specified for the elements of UA.
- **WA**: A two-dimensional real variable array, each element of which denotes the boundary layer cross flow (z) component of velocity, in either \((\text{ft/s})\) or \((\text{m/s})\), at point (IB,JB). The WA is dimensioned at (16,20). No default values are specified for the elements of WA.
- **XLAMDA**: A two-dimensional real variable array, each element of which denotes the density, in either \((\text{slug/ft}^3)\) or \((\text{kg/m}^3)\), at point (IB,JB). The XLAMDA array is dimensioned at (16,20). No default values are specified for the elements of XLAMDA.
- **UEA**: A one-dimensional real variable array, each element of which denotes
the boundary layer edge streamwise ($\bar{u}$) component of velocity, in either (ft/sec) or (m/sec), at the 16th circumferential station. The UEA array is dimensioned at (16). No default values are specified for the elements of UEA.

**WEA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge cross flow (z) component of velocity, in either (ft/sec) or (m/sec), at the 16th circumferential station. The WEA array is dimensioned at (16). No default values are specified for the elements of WEA.

**PEA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge pressure, in either (lbf/ft$^2$) or (N/m$^2$), at the 16th circumferential station. The PEA array is dimensioned at (16). No default values are specified for the elements of PEA.

**R$\theta$EA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge density, in either (slug/ft$^3$) or (kg/m$^3$), at the 16th circumferential station. The R$\theta$EA array is dimensioned at (16). No default values are specified for the elements of R$\theta$EA.

**DUDXA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge derivative of the streamwise velocity component ($\bar{u}$) with respect to the streamwise curvilinear coordinate ($\bar{x}$) at the 16th circumferential station. The units for DUDXA are (sec$^{-1}$). The DUDXA array is dimensioned at (16). No default values are specified for the elements of DUDXA.

**DWDXA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge derivative of the cross flow velocity component ($\bar{w}$) with respect to the streamwise curvilinear coordinate ($\bar{x}$) at the 16th circumferential station. The units for DWDXA are (sec$^{-1}$). The DWDXA array is dimensioned at (16). No default values are specified for the elements of DWDXA.

**DPDXA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge derivative of the static pressure ($\bar{p}$) with respect to the streamwise curvilinear coordinate ($\bar{x}$) at the 16th circumferential station. The units for DPDXA are either (lbf/ft$^2$) or (N/m$^2$). The DPDXA array is dimensioned at (16). No default values are specified for the elements of DPDXA.

**DRDXA**
A one-dimensional real variable array, each element of which denotes the boundary layer edge derivative of the density ($\bar{\rho}$) with respect to the streamwise curvilinear coordinate ($\bar{x}$) at the 16th circumferential station. The units for DRDXA are either (slug/ft$^2$) or (kg/m$^2$). The DRDXA array is dimensioned at (16). No default values are specified for the elements of DRDXA.

The user-supplied cowl boundary layer initial data are entered by a formatted read of file ITAP3 after all eleven namelists have been input and after the supersonic flow and forebody/centerbody boundary layer flow initial data have been input if they are externally generated. To enter the cowl boundary layer initial data by tabular input, KBLIBD = 0 must be specified in namelist LIST6. The default value for ITAP3 is 5 (the input file). The cowl boundary layer initial data may
be read from TAPE12 by specifying ITAP3 = 12 in namelist LIST6. TAPE12 is
linked to the dummy file IVS3 in the PROGRAM card.

The index limits for the cowl boundary layer initial data, MBLAY and NINB,
are entered in namelist LIST6. The boundary layer point networks are illustrated
in Figure 6.

The cowl boundary layer initial data are entered by the formatted read state-
ments

```
READ (ITAP3,113) ((ZZ(IB),FA(IB,JB),UA(IB,JB),WA(IB,JB),XLAMDA(IB,JB),
                   JB=1,NINB),IB=1,MBLAY)
READ (ITAP3,114) (UEA(IB),WEA(IB),PEA(IB),RUEA(IB),DUDXA(IB),DWDXA(IB),
                    DPDXA(IB),DRDXA(IB),IB=1,MBLAY)
```

with the same formats and parameter definitions as presented before for the
forebody/centerbody boundary layer initial data formatted read.

In all cases, the boundary layer initial data points with JB = 1 must lie
(to a close approximation) on the appropriate body surface. For the case of
one plane of flow symmetry (KSYM = 1), the initial data points with IB = 1 must
lie on the -y-axis, and the points with IB = MBLAY must lie on the +y-axis.
SECTION V.

OUTPUT INTERPRETATION

1. INTRODUCTION

The initial portion of the computer output comprises preliminary information. This preliminary output consists of information identifying the problem being considered, the specified computation options, the flow symmetry option, the thermodynamic model and the molecular transport properties, the vehicle orientation and the free-stream conditions, certain index parameters, the contours of the centerbody and the cowl, and the convergence tolerances and the iteration limits. The initial-value plane is then printed. Alternatively, if a program restart is specified, the last solution plane written on the restart file is printed. Each solution plane is then printed in a format similar to the initial-value plane printout. The supersonic core flow solution is printed first, followed by the forebody/centerbody and cowl boundary layer solutions. Additionally, the redistributed data plane at the cowl lip axial station is printed if the internal flow integration option is specified. Moreover, for the internal flow field computation, the solution points are printed which lie along the space curves defined by the intersection of the internal shock wave with the solid boundaries.

2. SUPersonic CORE FLOW SOLUTION OUTPUT

The supersonic core flow solution output parameters listed on the computer printout are defined below.

- \( I \) circumferential index of the solution point
- \( J \) radial index of the solution point
- \( X \) axial position of the solution plane or the solution point, \((\text{ft})\) or \((\text{m})\)
- \( Y \) \( y \)-position, \((\text{ft})\) or \((\text{m})\)
- \( Z \) \( z \)-position, \((\text{ft})\) or \((\text{m})\)
- \( M \) Mach number
- \( Q \) velocity magnitude, \((\text{ft/sec})\) or \((\text{m/sec})\)
- \( P \) pressure, \((\text{lbf/ft}^2)\) or \((\text{N/m}^2)\)
\( \rho \) density, \((\text{slug/ft}^3) \) or \((\text{kg/m}^3) \)

\( T \) absolute temperature, \((R)\) or \((K)\)

\( U \) x-component of velocity, \((\text{ft/sec})\) or \((\text{m/sec})\)

\( V \) y-component of velocity, \((\text{ft/sec})\) or \((\text{m/sec})\)

\( W \) z-component of velocity, \((\text{ft/sec})\) or \((\text{m/sec})\)

\( P_T \) stagnation pressure, \((\text{lbf/ft}^2)\) or \((\text{N/m}^2)\)

\( T_T \) stagnation temperature, \((R)\) or \((K)\)

\( \text{ITG} \) number of global corrector applications

\( \text{ITL} \) number of local iterations

Streamline solution points have both \( I \) and \( J \) indices which are numbers. An upstream shock wave solution point is denoted by a numerical \( I \) index and the \( J \) index is \( U \). A downstream shock wave solution point is denoted by a numerical \( I \) index and the \( J \) index is \( D \).

For the external flow field about the forebody, the body streamline solution points are denoted by \( J = 1 \). The outer bound to the computational flow regime is defined by the locus of downstream shock wave solution points, points with \( J = D \). Since periodic point addition and deletion are performed in the external flow field integration, continuous streamlines throughout the computational flow regime are not available. Inserted solution points are noted by \( \text{ITG} = \text{ITL} = 0 \).

For the continuous internal flow field integration option, the body streamline points on the surface of the centerbody are denoted by \( J = -1 \), and the body streamline points on the surface of the cowl are denoted \( J = \text{JINLET} \). The solution is found on the continuous streamlines which pass through the redistributed points on the solution plane at the cowl lip axial station.

For the internal flow field integration option in which shock waves are discretely fitted, the body streamline points on the surface of the centerbody are denoted by \( J = 1 \). The body streamline points on the surface of the cowl are denoted by \( J = (\text{JINLET} - 2) \). The shock wave solution points float in the storage arrays as the internal shock wave travels between the centerbody and the cowl on successive solution planes. The streamline points between the upstream side solid boundary (either centerbody or cowl) and the upstream shock wave points on a given solution plane lie in the upstream flow field sector on that solution plane. In a like manner, streamline points which lie between the other solid boundary and the downstream shock wave points on a given solution plane lie in the downstream flow field sector on that solution plane. A reversal of the upstream and downstream sectors occurs at an internal shock wave-solid boundary intersection. It should be noted that continuous streamlines are followed in the internal flow field integration.
The intersection of the incident internal shock wave with a solid boundary at a shock wave-solid boundary intersection defines a space curve. The solution is found on both the upstream and downstream sides of both the incident and reflected shock waves at points on this space curve.

At the end of a solution plane printout, the Courant number and the x-step regulation parameters are printed. The Courant number is the ratio of the axial step taken to the axial step allowed by the Courant-Friedrichs-Lewy stability criterion (based on immediate neighbors in the interpolation fit point stencils). The Courant number listed is that used in obtaining the solution plane that was just printed. Likewise, the x-step regulation parameters refer to the solution plane that was just printed.

3. BOUNDARY LAYER FLOW SOLUTION OUTPUT

The boundary layer flow solution output parameters listed on the computer printout are defined below.

I. circumferential index of the solution point
J. radial index of the solution point
X. axial position of the corresponding supersonic core flow solution plane for the current boundary layer solution surface, (ft) or (m)
XC. streamwise curvilinear coordinate (\(\tilde{x}\)) of the boundary layer solution surface (for the forebody/centerbody, \(XC=0.0\) corresponds to the forebody tip; for the cowl, \(XC=0.0\) corresponds to the cowl lip), (ft) or (m)
Y. distance measured normal to the wall, (ft) or (m)
Z. polar angle (see Figure 6), \(Z=0.0^\circ\) corresponds to the windward meridian; \(Z=180.0^\circ\) corresponds to the leeward meridian), (degrees)
M. Mach number
Q. velocity magnitude, (ft/sec) or (m/sec)
P. pressure, (lbf/ft\(^2\)) or (N/m\(^2\))
\(\rho\). density, (slug/ft\(^3\)) or (kg/m\(^3\))
T. absolute temperature, (R) or (K)
U streamwise (\(\hat{x}\)) component of velocity, (ft/sec) or (m/sec)
V normal (\(\hat{y}\)) component of velocity, (ft/sec) or (m/sec)
W cross-flow (\(\hat{z}\)) component of velocity, (ft/sec) or (m/sec)
PT stagnation pressure, (lbf/ft\(^2\)) or (N/m\(^2\))
TT stagnation temperature, (R) or (K)
UE streamwise (\(\hat{x}\)) component of velocity at the boundary layer edge, (ft/sec) or (m/sec)
WE cross-flow (\(\hat{z}\)) component of velocity at the boundary layer edge, (ft/sec) or (m/sec)
PE pressure at the boundary layer edge, (lbf/ft\(^2\)) or (N/m\(^2\))
R\(\Omega\)E density at the boundary layer edge, (slug/ft\(^3\)) or (kg/m\(^3\))
TE absolute temperature at the boundary layer edge, (R) or (K)
HTE total enthalpy at the boundary layer edge, (ft\(^2\)/sec\(^2\)) or (m\(^2\)/sec\(^2\))
D\(\partial\)ED\(\partial\)X first partial derivative of the boundary layer edge streamwise velocity component (UE) with respect to the streamwise curvilinear coordinate (\(\hat{x}\)), (sec\(^{-1}\))
D\(\partial\)ED\(\partial\)X first partial derivative of the boundary layer edge cross-flow velocity component (WE) with respect to the streamwise curvilinear coordinate (\(\hat{x}\)), (sec\(^{-1}\))
D\(\partial\)ED\(\partial\)X first partial derivative of the boundary layer edge pressure (PE) with respect to the streamwise curvilinear coordinate (\(\hat{x}\)), (lbf/ft\(^3\)) or (N/m\(^3\))
D\(\partial\)ED\(\partial\)X first partial derivative of the boundary layer edge density (R\(\Omega\)E) with respect to the streamwise curvilinear coordinate (\(\hat{x}\)), (slug/ft\(^4\)) or (kg/m\(^4\))
D\(\partial\)ED\(\partial\)Z first partial derivative of the boundary layer edge streamwise velocity component (UE) with respect to polar angle, (ft/sec/radian) or (m/sec/radian)
DWEDZ first partial derivative of the boundary layer edge cross-flow velocity component (WE) with respect to polar angle, (ft/sec/radian) or (m/sec/radian).

DPEDZ first partial derivative of the boundary layer edge pressure (PE) with respect to polar angle, (1bfsq/ft²/radian) or (N/m²/radian).

DRQEDZ first partial derivative of the boundary layer edge density (RBE) with respect to polar angle, (slug/ft³/radian) or (kg/m³/radian).

DTX streamwise boundary layer displacement thickness (δtx), (ft) or (m)

DTZ cross-flow boundary layer displacement thickness (δtz), (ft) or (m)

MTX streamwise boundary layer momentum thickness (δmx), (ft) or (m)

MTZ cross-flow boundary layer momentum thickness (δmz), (ft) or (m)

TWX streamwise wall shear stress component (τwx), (1bf/sq.ft) or (N/m²)

TWZ cross-flow wall shear stress component (τwz), (1bf/sq.ft) or (N/m²)

TWT total wall shear stress (τwt), (1bf/sq.ft) or (N/m²)

RQVB mass bleed flux (RQVB<0 denotes mass bleed), (slug/(sq.ft-sec)) or (kg/(m²-sec))

The respective displacement and momentum thicknesses are defined by:

\[ \delta_{tx} = \int_0^\infty \left( 1 - \frac{\rho w}{\rho_e u_e} \right) \, dy \]  

\[ \delta_{tz} = \int_0^\infty \left( 1 - \frac{\rho w}{\rho_e u_e} \right) r \, \gamma \, dy \]  

\[ \delta_{mx} = \int_0^\infty \frac{\rho w}{\rho_e u_e} \left( 1 - \frac{\rho w}{\rho_e u_e} \right) \, dy \]
\[ \delta_{niz} = \left( \int_0^\infty \frac{\rho \dot{w}}{\rho_{e e}} \left( 1 - \frac{\dot{w}}{\dot{w}_e} \right) \, dy \right)^{1/2} \]  

where \( \dot{u} \) and \( \dot{w} \) denote the velocity components in the boundary layer streamwise (x) and cross-flow (z) directions, respectively, \( \rho \) denotes density, \( \bar{y} \) denotes the normal coordinate, and the subscript \( e \) denotes boundary layer edge conditions.

In all cases, solution points with \( J = 1 \) correspond to the wall surface, and solution points with \( J = NA \) or \( J = NB \) correspond to the boundary layer edge. For the points on planes of flow symmetry, the cross-flow displacement and momentum thicknesses are output as 0.0 as is the cross-flow wall shear stress. For the initial-data surfaces and solution surfaces immediately downstream of a shock wave-wall reflection, the normal component of velocity is not computed and is output as 0.0.
SECTION VI
SAMPLE CASES

1. INTRODUCTION

Four sample cases are presented in this section to illustrate the application of the computer program for calculating the flow field in supersonic mixed-compression aircraft inlets. For each of the four sample cases, a discussion of the problem is given, the required input data are presented, and selected portions of the computer output are listed. The input parameter discussions follow the order in which the input parameters are presented in Section IV.

Sample Case No. 1 considers the computation of the supersonic external flow about the forebody of a typical mixed-compression inlet at angle of attack. Sample Case No. 2 is concerned with the computation of both the supersonic external flow and the boundary layer flow for the forebody geometry considered in Sample Case No. 1. Sample Case No. 3 is concerned with the computation of the internal supersonic core flow for the Mach 3.5 inlet documented in Reference (9) at angle of attack. Sample Case No. 4 considers the computation of both the internal supersonic core flow and the boundary layer flow for the mixed-compression inlet considered in Sample Case No. 3.

It should be noted that additional sample cases may be found in Reference (3). Although Reference (3) does not discuss the boundary layer computational procedures, the discussion concerning the computation of the supersonic core flow is similar to that presented herein.

2. SAMPLE CASE NO. 1

This sample case is concerned with the computation of the supersonic external flow field about the axisymmetric forebody of a typical mixed-compression inlet at incidence. The supersonic initial-value plane is generated internally in the program using the Jones algorithm described in Section II.

The data deck for Sample Case No. 1 is presented in Figure 8. The first card of the data deck is the title card. English units are used, so KUNIT retains its default value of 1 in namelist LIST1. Since only the forebody flow field is to be computed, KCALL(2)=0 is specified in namelist LIST1, while KCALL(1) and KCALL(3) retain their default values of 1 and 0, respectively. The forebody flow integration termination point, denoted by XEND(1), is 2.0 ft, the default value. Since one plane of flow symmetry exists, KSYM is retained at its default value of 1. The molecular transport terms are not to be included in the computation, and global correction is to be performed on the bow shock wave solution points; hence, KVISCY and KSGLB are retained at their default.
values of 0 and 1, respectively. Mass transfer effects are not to be included in the computation, hence KTRANS=O is specified in namelist LIST1. For this sample case, the boundary layer computation will not be performed, thus KBLAY=O is specified. The default value of RCAVG=0.8 ft is used for estimating the mass flow rate downstream of the bow shock wave at the cowl lip axial station. KPRINT retains its default value of 1, consequently all solution points are printed. IPRSTP and KSTART are both kept at their default values of 0, thus the execution is not terminated at a specified solution plane, nor are any restart file operations performed.

All input parameters in namelist LIST2 except for the free stream Mach number, MFS, retain their default values. Consequently, the free-stream pressure PFS and the free-stream density RFS have values of 242.2 (lbf/ft²) and 0.0003622 (slug/ft³), respectively. The free-stream Mach number for this case is 2.5; hence MFS=2.5. PITCH and YAW retain their default values of 1.0 and 0.0 degrees, respectively. Thus, the specified angle of attack is 1.0 degree. The axial position of the initial-value plane, specified by the default value of XI, is 1.0 ft. Since KIVS and KCEN are both 1, the initial-value plane is internally generated and the bow shock wave is assumed to be conical (the forebody is conical). Since KSUPER retains its default value of 2, the supersonic flow initial data are generated using the Jones algorithm described in Section II. The parameter ITAPI is not employed since the initial-value plane is generated internally (KIVS=1).

All input parameters in namelist LIST3 retain their default values. Consequently, ISTP and JMAXT have values of 15 and 11, respectively, so that 15 circumferential stations are employed, and 11 radial stations on the initial-value plane are specified. JLIMIT(1) and JLIMIT(2) retain their default values of 11 and 15 radial stations, respectively.

All input parameters in namelist LIST4 retain their default values. Thus, the specific heat ratio and gas constant, specified by GAMMA and R, respectively, have values of 1.4 and 1716.16116 (ft·lbf)/(slug·R), respectively. Since the molecular transport terms are not included in the computation (KVISCY=0), the input parameters VIS, T0, B and PR are not employed.

All input parameters in namelist LIST5 retain their default values. The default inlet geometry has a conical forebody/centerbody with a cone half-angle of 10.0 degrees. The forebody tip is located at x=0.0 ft, and the centerbody geometry is specified to x=3.5 ft. Thus, NCENT=2, KCENT(1)=3, XCENT(1)=1.0, XCENT(2)=3.5, and CÔNE=10.0. The remaining input parameters in namelist LIST5 are not employed.

Since the boundary layer computation is not invoked and mass transfer effects are not to be considered (KBLAY=0 and KTRANS=0 specified in namelist LIST1), the input parameters in namelists LIST6, LIST7, LIST8, and LIST9 do not have to be entered.

All convergence tolerances and iteration limits retain their default values in namelist LIST10.
No debug output is to be printed, hence all input parameters in namelist LIST11 retain their default values.

Selected portions of the computer output for this sample case are presented in Figure 9. The first portion of the program output presents the job title, the specified computation options, the flow symmetry option, the thermodynamic model, the vehicle orientation and free-stream data, the type of initial-value plane, certain index parameters, the centerbody and the cowl contours, and the various convergence tolerances and iteration limits. The next portion presents the internally generated initial-value plane flow property field. The final portion of the program output presents selected supersonic flow solution planes.
CASE NO. 1
LIST1 KCALL(2)=0, KTRANS=0, KELAY=0 &END
LIST2 MFS=2.5 &END
LIST3 &END
LIST4 &END
LIST5 &END
LIST6 &END
LIST7 &END
LIST8 &END
LIST9 &END
LIST10 &END
LIST11 &END

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OF POOR QUALITY.

Figure 8. Data deck for Sample Case No. 1.
The analysis of steady three-dimensional flow in supersonic mixed-compression aircraft inlets

Abstract

The flow field in a supersonic mixed-compression aircraft inlet is computed using a local algorithm. The supersonic core flow is computed by a Riemann solvability algorithm with discrete shock wave fitting. The boundary layer flow is computed using an implicit finite difference method. Flow in a shock wave-boundary layer interaction region is computed using an integral analysis.

This program was developed by the Purdue University Thermal Sciences and Propulsion Center by J. Yadav under sponsorship from the NASA Lewis Research Center. J.J. Hoffnagel and J.R. Bishop served as the principal investigator and technical monitor, respectively.

Job Title

Case No. 1

Specified Computation Options

1.) Forebody Flow Field
   Boundary layer computation is not invoked.

Flow Symmetry

One plane of symmetry - Computed sector is the half-plane bounded by the y-axis and containing the +x-axis

Global Correction

Global correction is performed on the bow shock wave points

Thermodynamic Model

A thermally and calorically perfect gas is specified with

Specific Heat Ratio = 1.6666666676444444
Gas Constant = 0.1716466404(FT/PSI/SLUG/DEG R)

Molecular Transport Terms for Supersonic Core Flow Solution

Viscous and thermal diffusion terms are not included in the computation - Inviscid and adiabatic flow is assumed.

Orientation and Free Stream Data

Orientation = Pitch = 1.000000 (degrees)
Free Stream Data = Mach No. = 2.50000

Figure 9. Selected output for Sample Case No. 1.
SUPERSONIC CODE FLOW INITIAL-VALUE SURFACE

AN INTERNALLY GENERATED INITIAL VALUE SURFACE IS SPECIFIED AS BEING LOCATED AT X=6,1000000+01(FT)
A CONICAL SHOCK WAVE IS SPECIFIED - THE INTERNALLY GENERATED SHOCK WAVE ANGLES ARE

\[ \beta_{11} = 0.6461464 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{12} = 0.6462123 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{13} = 0.6462467 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{14} = 0.6462917 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{15} = 0.6463555 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{16} = 0.6468476 \text{ DEG}(\text{RADIANs}) \]
\[ \beta_{17} = 0.6468476 \text{ DEG}(\text{RADIANs}) \]

INDEX PARAMETERS

ISPAN=15 INSPAN=JNAXI=11
JLINIT(1)=11 JLINIT(2)=15

INTEGRATION TERMINATION POINTS

FOREBODY FLOW FIELD INTEGRATION TERMINATES AT X=0,2000000+01(FT)
FOR FOREBODY FLOW - RCAY=0,000000+00(FT)

FOREBODY/CLUTTER/GEOmetry

CODE HALF ANGLE=10,00000(DEGREES)

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<th>ACAY (FT)</th>
<th>DCAY (FT)</th>
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PASS TRANSFER BOUNDARY CONDITIONS

Figure 9. Continued.
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Figure 9. Continued.
3. SAMPLE CASE NO. 2

This sample-case is concerned with the computation of both the supersonic external flow and the boundary layer flow for the forebody geometry considered in Sample Case No. 1. Both the supersonic flow initial data and the boundary layer flow initial data are generated internally in the program.

The data deck for Sample Case No. 2 is presented in Figure 10. Again, the first card of the data deck is the title card.

Namelist LIST1 for Sample Case No. 2 is identical to that for Sample Case No. 1 except for the value of KBLAY. Since in the present case, the boundary layer is to be computed, KBLAY is retained at its default value of 1.

Namelists LIST2, LIST3, LIST4, and LIST5 for Sample Case No. 2 are identical to those specified in Sample Case No. 1.

All input parameters in namelist LIST6 retain their default values except for FACTOR and CLENGH. As a consequence, KBLIDA and KTURB retain their default values of 1 and 0, respectively. Thereby, the forebody boundary layer initial data are generated internally and laminar flow is specified. CLENGH is specified as 3.5 ft, the value to which the forebody geometry is specified. The Adams program input parameters ADY and ARATI0 are retained at their default values of 0.010 and 1.0630, respectively. Since the boundary layer initial data are being internally generated, the input parameter XASTRT, which denotes the position of the initial data surface, does not have to be entered but rather is computed internally. Likewise, the input parameter ITAP2 is not specified. MBLAY and NA are retained at their default values of 15 and 20, respectively. Hence, 15 circumferential and 20 radial stations are used in the forebody boundary layer calculation. The boundary layer normal coordinate stretching factor is selected as 1.10; hence, FACTOR(1)=1.10 is specified in namelist LIST6. Note that since the cowl boundary layer computation is not invoked, the cowl boundary layer input parameters do not have to be specified.

All input parameters in namelist LIST7 retain their default values except for TC0NSTA. Consequently, KTYPE retains its default value of 1, which specifies that a wall temperature rather than temperature derivative boundary condition will be used in the boundary layer computation. The input parameter, KWLTA retains its default of 1, hence a constant wall temperature boundary condition will be employed. Since KWLTA is specified, the wall temperature is specified by entering TC0NSTA, which has been selected as 876.7 R, the free-stream stagnation temperature. The other input parameters for the forebody boundary layer computation (DTDYCA, NTABA, XWLA, TWLA, and DTDYWA) are not used and hence are not specified. The input parameters in namelist LIST7 used for the cowl boundary layer computation are not entered.

All input parameters in namelist LIST8 retain their default values, thereby specifying a case with no wall mass bleed. The input parameter KDFA is left at its default value of 0, which specifies an impermeable forebody/centerbody wall. The other input parameters in namelist LIST8 used for specification of the forebody/centerbody mass bleed distribution (NRA, XSA, XEA, and R0VA) do not have
to be entered. Since the cowl boundary layer computation is not invoked, the mass bleed input parameters used for the cowl boundary layer need not be entered.

All input parameters in namelist LIST9 retain their default values except for XTI. Consequently, the turbulence model parameters APLUS, XKAPPA, XALPHA, PRT, TFACTR, AKLM, and ALAM are left at their default values. The default transition model, denoted by ITRANM(1)=5, is retrained. This transition model requires that the input parameter array XTI be entered. For this sample case, laminar flow has been specified as existing over the entire length of the forebody. This is accomplished by specifying the onset transition location for each circumferential station as being equal to 20.0 ft, hence XTI(1,1)=20.0. The other input parameters in namelist LIST9 do not have to be entered.

All convergence tolerances and iteration limits retain their default values in namelist LIST10.

No debug output is to be printed, hence all input parameters in namelist LIST11 retain their default values.

Selected portions of the computed output for Sample Case No. 2 are presented in Figure II.
CASE NO. 2

&LIST1 KCALL(2)=0, KTRANS=0 &END

&LIST2 MF=2.5 &END

&LIST3 &END

&LIST4 &END

&LIST5 &END

&LIST6 FACTOR(1)=1.10, CLENGH=3.5 &END

&LIST7 TCONSTA=876.7 &END

&LIST8 &END

&LIST9 XT1(1,1)=16*20.0 &END

&LIST10 &END

&LIST11 &END

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Figure 10. Data deck for Sample Case No. 2.
THE ANALYSIS OF STEADY THREE-DIMENSIONAL FLOW IN SUPERSONIC MIXED-COMPRESSION AIRCRAFT INLETS

ABSTRACT

The flow field in a supersonic mixed-compression aircraft inlet is computed using a Zonal Algorithm. The supersonic core flow is computed by a characteristic algorithm with discrete shock wave fitting. The boundary layer flow is computed using an implicit finite difference method. The flow in a shock wave-boundary layer interaction region is computed using an integral analysis.

This program was developed at the Purdue University Thermal Sciences and Propulsion Center by J. Yadav under sponsorship from the NASA Lewis Research Center. J.D. Hoffman and A.R. Bishop served as the principal investigator and technical monitor, respectively.

JOB TITLE

case no. 2

SPECIFIED COMPUTATION OPTIONS

1.) forebody flow field

boundary layer computation is invoked

FLOW SYMMETRY

one plane of symmetry = computed sector is the half-plane bounded by the y-axis and containing the z-axis

GLOBAL CORRECTION

global correction is performed on the bow shock wave points

THERMODYNAMIC MODEL

a thermally and calorically perfect gas is specified with

specific heat ratio = 1.40000

gas constant = 0.171684e+04 (ft-lbf/lb-mol deg)

MOLECULAR TRANSPORT TERMS FOR SUPERSONIC CORE FLOW SOLUTION

viscous and thermal diffusion terms are not included in the computation = inviscid and adiabatic flow is assumed

MOLECULAR TRANSPORT PARAMETERS

viscosity is represented by sutherland's law with

Figure 11. Selected output for Sample Case No. 2.
SUPERSONIC CORE FLOW INITIAL-VALUE SURFACE

AN INTERNALLY GENERATED INITIAL VALUE SURFACE IS SPECIFIED AS BEING LOCATED AT X = 0.100000E+00(FT)

A CONICAL BOW SHOCK WAVE IS SPECIFIED - THE INTERNALLY GENERATED SHOCK WAVE ANGLES ARE

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FOREBODY/CONVERGING BOUNDARY LAYER INITIAL DATA

THE INITIAL DATA ARE INTERNALLY GENERATED WITH

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INDEX PARAMETERS

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Figure 11. Continued.
INTEGRATION TERMINATION POINTS
FOREBODY FLOW FIELD INTEGRATION TERMINATED AT X = 0.200000E+01 (FT)
FOR FOREBODY FLOW - SCVAV = 0.800000E+00 (FT)

FOREBODY/CENTERBODY GEOMETRY

CONE HALF ANGLE = 0.000000 (DEGREES)

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FOREBODY/CENTERBODY TEMPERATURE BOUNDARY CONDITIONS
A CONSTANT WALL TEMPERATURE IS SPECIFIED AT 0.476700E+03 (R) ON (K)

MASS TRANSFER BOUNDARY CONDITIONS
AN INPERMABLE FOREBODY/CENTERBODY WALL IS SPECIFIED

TURBULENCE MODEL PARAMETERS
APLUS = 2.000000E+00 KAPPAM = 0.400000 RALPHM = 0.001600 PRI = 0.900000 TVAC = 1.000000
ALRM = 0.135000 AILRM = 0.098000
TRANSITION MODEL NO. 3 IS USED FOR FOREBODY/CENTERBODY BOUNDARY LAYER COMPUTATION

CONVERGENCE TOLERANCES, ITERATION LIMITS, AND OTHER PARAMETERS

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Figure 11. Continued.
4. SAMPLE CASE NO. 3

Sample Case No. 3 is concerned with the computation of the internal supersonic core flow for the Boeing Mach 3.5 mixed-compression inlet described in Reference (9). The internal supersonic flow field is computed for the off-design conditions of a free-stream Mach number of 2.5, a centerbody forward translation of 0.855 ft, and an angle of incidence of 1.0 degree.

The data deck for Sample Case No. 3 is presented in Figure 12. Again, the first card of the data deck is the title card. All input parameters in namelist LIST1 retain their default values except for KCALL, XEND, KBLAY, and KTRANS. Since only the internal flow field is to be computed, KCALL(1) = 0 is specified to bypass the forebody flow field computation. The integration termination point for the internal flow computation is x=5.05 ft, hence XEND(2)=5.05 is entered. For this sample case, neither the boundary layer computation is to be performed nor are bleed effects to be accounted for in the computation of the supersonic flow; hence, KBLAY=0 and KTRANS=0 are specified in namelist LIST1.

All input parameters in namelist LIST2 retain their default values except for MFS, XI, and KSUPER. Since the free-stream Mach number for this sample case is 2.5; MFS=2.5 is specified in namelist LIST2. With the prescribed centerbody translation of 0.855 ft, the axial location of the cowl lip, and thereby of the initial-value plane, is x=3.715 ft. Note that the origin of the coordinate system remains at the forebody tip, hence a forward centerbody translation corresponds to a rearward cowl translation. Consequently, XI=3.715 is specified in namelist LIST2. For this execution, the results of the approximate analysis described in Section II are used for the initial data since the forebody is conical. Hence, the initial-value plane flow property field is internally specified by entering KSUPER=1.

All input parameters in namelist LIST3, which specifies the supersonic flow computational mesh, are retained at their default values.

All parameters in namelist LIST4, which specifies the thermodynamic and molecular transport property models, retain their default values.

The contours of the centerbody and the cowl are specified in namelist LIST5. For this inlet, the centerbody contour and the cowl contour are described by equation (3) applied to a number of intervals on each contour. Consequently, KBASE retains its default value of 0. The number of axial stations used for the geometry description of the centerbody and the cowl are 11 and 14, respectively; hence NCENT=11 and NCOWL=14. Thus, the number of intervals on the centerbody and the cowl are 10 and 13, respectively. Since equation (3) is used to specify the body radius for all intervals, KDCENT(I)=1 (I=1 to 11) and KDCOWL(I)=1 (I=1 to 14). Note that except for XCENT(11) and XCOWL(14), the specifications for the other input parameters for the last station on either the centerbody or the cowl are immaterial. That is, only the XCENT and XCOWL arrays must be specified for NCENT and NCOWL elements, respectively. The other arrays require that only (NCENT-1) or (NCOWL-1) elements be entered. The 11 elements of the XCENT array are thus entered. Although not used in the computation, the 11 elements of the RCENT array are entered, each element being 0.0. The arrays ACENT, BCENT, CCENT, and DCENT are then entered. For each of these
arrays, the last (11th) element is arbitrarily specified as 0.0. In a like manner, the arrays XCOWL, RCOWL, ACOWL, BCOWL, CCOWL, and DCOWL are entered. For this case, the centerbody has been translated forward by 0.855 ft, or, alternatively, the cowl has been translated backward by 0.855 ft. Hence, DXTRAN=0.855 is specified in namelist LIST5.

Since in this sample case the boundary layer computation is not invoked, the input parameters for namelists LIST6 and LIST7 need not be entered.

Mass transfer effects are not considered for this execution, thereby all input parameters in namelist LIST8 are retained at their default values. Thereby, impermeable forebody/centerbody and cowl contours are specified.

The input parameters for namelist LIST9, which is used for specification of the turbulence model, need not be entered for this sample case.

All convergence tolerances and iteration limits specified in namelist LIST10 retain their default values.

No debug output is to be printed, thereby all input parameters in namelist LIST11 retain their default values.

Selected portions of the computer printout for Sample Case No. 3 are presented in Figure 13.
CASE NO. 3

&LIST1 KCALL(1)=0, XEND(2)=5.05, KBIAY=0, KTRANS=0 &END
&LIST2 MFS=2.5, XI=3.715, KSUPER=1 &END
&LIST3 &END
&LIST4 &END
&LIST5 NCEAT=11, NCWUL=14, KDCENT(1)=11*1, KDCWUL(1)=14*1,
 XCENT(1)= 0.0, 2.798794, 4.0, 4.2, 4.4, 4.55, 4.7, 4.9, 5.5, 6.28, 6.9,
 NCEAT(1)=11*0.0,
 XCENT(1)= 0.0, .499511, .70532, .7367, .759, .763, .785, .7391, .6525, .4, 0.0,
 BCENT(1)= .17633, .17633, .17633, .144, .052, 0.0, 0.0, -.0646, -.1295, -.153,
 0.0, 0.0,
 CCENT(1)= 0.0, 0.0, .0202035, -.1774997, -.1600005, -.1693327,
 -.1615001, -.03499995, .1651873, 0.0, 0.0,
 DCEAT(1)= 0.0, 0.0, -.3367512, -.1750011, -.05925696, -.2044475,
 -.2499656E-03, .01712957, -.4923802, 0.0, 0.0,
 XCOUL(1)= 2.86, 3.1, 3.4, 4.0, 4.2, 4.3, 4.5, 4.6, 4.7, 5.1, 5.6, 6.1, 6.5, 6.9,
 KCOUL(1)=14*0.0,
 ACOUL(1)=1.0, 1.004188, 1.0051, .9681, .9364, .9154, .8768, .864, .8572, .85,
 .85, .8839, .9227, 0.0,
 HCOUL(1)= .01745001, .01745, -.011, -.124, -.1942, -.213, -.163, -.093, -.0485,
 0.0, 0.0, .107, .0729, 0.0,
 CCWUL(1)= 0.0, -.04926635, -.06500001, -.1664999, -.2859976, .05000008,
 .3500018, .3049997, .1075002, 0.0, .1928, .01025012, -.01512487, 0.0,
 DCWUL(1)= 0.0, 4.110418E-03, -.03240740, -.0300005, 1.279984, .2499996,
 .1251464E-03, -.5499974, -.07812535, 0.0, -.1144, -.08812521,
 .74978E-03, 0.0,
 DXTHAN=0.055 &END
&LIST6 &END
&LIST7 &END
&LIST8 &END
&LIST9 &END
&LIST10 &END
&LIST11 &END

Figure 12. Data deck for Sample Case No. 3.
THE ANALYSIS OF STEADY THREE-DIMENSIONAL FLOW IN SUPERSONIC MIXED-COMPRESSION AIRCRAFT INLETS

ABSTRACT

THE FLOW FIELD IN A SUPERSONIC MIXED-COMPRESSION AIRCRAFT INLET IS COMPUTED USING A ZONAL ALGORITHM. THE SUPERSONIC CORE FLOW IS COMPUTED BY A RICHARACTERISTIC ALGORITHM WITH DISCRETE SHOCK WAVE FITTING. THE BOUNDARY LAYER FLOW IS COMPUTED USING AN IMPLICIT FINITE DIFFERENCE METHOD. THE FLOW IN A SHOCK WAVE-BOUNDARY LAYER INTERACTION REGION IS COMPUTED USING AN INTEGRAL ANALYSIS.

THIS PROGRAM WAS DEVELOPED AT THE PURDUE UNIVERSITY AERONAUTICAL SCIENCES AND PROPULSION CENTER BY J. VADIN UNDER SPONSORSHIP FROM THE NASA LEWIS RESEARCH CENTER. J.D. NUFFY AND A.R. BISHOP SERVED AS THE PRINCIPAL INVESTIGATOR AND TECHNICAL MONITOR, RESPECTIVELY.

JOB TITLE

CASE NO. 1

SPECIFIED COMPUTATION OPTIONS

1.) INTERNAL FLOW FIELD WITH SHOCK WAVE SYSTEM
BOUNDARY LAYER COMPUTATION IS NOT INVOKED

FLOW SYMMETRY

ONE PLANE OF SYMMETRY - COMPUTED REGION IS THE HALF-PLANE BOUNDED BY THE Y-AXIS AND CONTAINING THE +X-AXIS

THERMODYNAMIC MODEL

A THERMALLY AND CALORICALLY PERFECT GAS IS SPECIFIED WITH
SPECIFIC HEAT RATIO=1.4,00000
GAS CONSTANT=0.171618E+04(FT-LBF/SLUG-DEG R)

MOLECULAR TRANSPORT TERMS FOR SUPERSONIC CORE FLOW SOLUTION

VISCOSITY AND THERMAL DIFFUSION TERMS ARE NOT INCLUDED IN THE COMPUTATION - INVISCID AND ADIABATIC FLOW IS ASSUMED

ORIENTATION AND FREE STREAM DATA

ORIENTATION = PITCH=1.00000(DEGREES) YAW=0.00000(DEGREES)
FREE STREAM DATA = MACH NO.=2.50000 PRESSURE=0.262200E+03(LBF/FT**2)
TEMPERATURE=0.269664E+03(DEG R)
SONIC SPEED=0.967590E+03(FT/SEC)
X-VELOCITY=0.241853E+04(FT/SEC) T-VELOCITY=0.422159E+02(FT/SEC)
X-VELOCITY=0.000000E+00(FT/SEC)

Figure 13. Selected output for Sample Case No. 3.
### Superbisonic Core Flow Initial-Value Surface

An internally generated initial value surface is specified as being located at \( x = 0, \theta = 0 \) (ft).

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#### Integration Termination Points

Internal flow field integration terminates at \( x = 0.35 \) (ft).

#### Forebody/Centerside Geometry

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**Figure 13.** Continued.
### Core Flow Initial Data Plane

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### Forebody Flow Field

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**Figure 13. Continued.**
**Figure 13. Continued.**
5. SAMPLE CASE NO. 4

This sample case is concerned with the computation of both the supersonic core flow and forebody/centerbody and cowl boundary layer flows for the Mach 3.5 mixed-compression inlet considered in Sample Case No. 3. The internal flow field is again computed for the off-design conditions of a free-stream Mach number of 2.5, a centerbody forward translation of 0.855 ft, and an angle of attack of 1.0 degree. The computation for this sample case includes the effects of distributed mass bleed. Independent turbulent transition models are specified for the forebody/centerbody and cowl boundary layer calculations.

The data deck for Sample Case No. 4 is presented in Figure 14. The first card of the data deck is again the title card. Namelist LIST1 for this sample case is identical to that in Sample Case No. 3 except for the input parameter KBLAY. Since the boundary layer computation is to be invoked for this sample case, KBLAY retains its default value of 1. Mass transfer effects will not be considered in the computation of the supersonic core flow, hence KTRANS is retained at the value of 0.

Namelists LIST2, LIST3, LIST4, and LIST5 for this sample are identical to those in Sample Case No. 3.

All input parameters in namelist LIST6 retain their default values except for the coordinate stretching parameter FACTOR. Hence, the laminar forebody/centerbody boundary layer initial data will be generated internally using the Adams algorithm (KBLIDA=1 and KTURB=0). Since CLENCH=4.0, the length of the conical forebody section is specified as 4.0 ft. The Adams algorithm mesh parameters ADY and ARAT10 retain their default values of 0.010 and 1.0630. The laminar cowl boundary layer initial data are internally generated (KBLIDB=1 and KTURBB=0). Since MBLAY, NA, and NB retain their default values of 15, 20, and 20 respectively, both the forebody/centerbody and cowl boundary layer computations employ 15 circumferential stations and 20 radial stations. For this sample case, the boundary layer normal coordinate stretching factor is specified as 1.175 for both boundary layers; hence, both elements of FACTOR are specified as 1.175.

All input parameters in namelist LIST7 are retained at their default values except for TCNSTA and TCNSTB. Consequently, constant wall temperature boundary conditions are specified for both the forebody/centerbody and cowl boundary layer computations (KTYPE=1, KWLTAG=1, and KWLTB=1). TCNSTA and TCNSTB are both specified as 876.698, which is the free-stream stagnation temperature of 876.698 R.

Distributed mass bleed is specified on both the forebody/centerbody contour and the cowl contour for this computation, hence KDFA=1 and KDFB=1 are entered in namelist LIST8. Two bleed zones on the forebody/centerbody contour and one bleed zone on the cowl contour are employed, thus NRA=2 and NRB=1. The bleed zones for the forebody/centerbody contour extend from x=4.2 ft to x=4.4 ft for the first zone, and from x=4.9 ft to x=5.1 ft for the second zone. Hence, XSA(1)=4.2, XEA(1)=4.4, XSA(2)=4.9, and XEA(2)=5.1 are entered in namelist LIST8. For the cowl, the bleed zone extends from x=3.75 ft to x=3.8 ft; hence,
XSB(1) = 3.75 and XEB(1) = 3.85 are specified. The bleed mass flux for each zone is 0.000001 (slug/ft²·sec). Consequently, RΩVA(1), RΩVA(2), and RΩVB(1) are each entered as 0.000001.

The turbulence model parameters are specified in namelist LIST9. For this computation, transition models No. 5 and No. 3 will be used for the forebody/centerbody and cowl boundary layer computations, respectively. Hence, ITRANM(1) = 5 and ITRANM(2) = 3 are entered. Both models require specification of the transition onset location array XT1. Although a different transition onset distance for each circumferential station can be specified, a constant distance is used in the present computation. For the forebody/centerbody, a transition onset location of R = 4.0 ft is arbitrarily selected; whereas for the cowl, a transition onset location of R = 0.3 ft is selected. Consequently, XT1(1, 1) = 16 * 4.0 and XT1(1, 2) = 16 * 0.3 are entered. The transition model used for the cowl boundary layer computation requires that the XT2 array be entered to denote the onset location of fully turbulent flow. For the present case, all circumferential stations on the cowl have R = 1.8 ft selected as this fully turbulent onset location; hence, XT2(1, 2) = 16 * 1.8 is entered in namelist LIST9.

All convergence tolerances and iteration limits retain their default values in namelist LIST10.

No debug output is to be printed for this sample case, so all input parameters in namelist LIST11 retain their default values.

Selected portions of the computer output for Sample Case No. 4 are presented in Figure 15.
Figure 14. Data deck for Sample Case No. 4.
THE ANALYSIS OF STEADY THREE-DIMENSIONAL FLOW IN SUPERSONIC MIXED-COMPRESSION AIRCRAFT INLETS

ABSTRACT

The flow field in a supersonic mixed-compression aircraft inlet is computed using a RONAL algorithm. The supersonic core flow is computed by a RICKA characteristic algorithm with discrete shock wave fitting. The boundary layer flow is computed using an implicit finite difference method. The flow in a shock wave-boundary layer interaction region is computed using an integral analysis.

This program was developed at the Purdue University Thermal Sciences and Propulsion Center by J. WADSM under sponsorship from the NASA Lewis Research Center. J. D. HOFFMAN and A.J. BISHOP SERVE AS THE PRINCIPAL INVESTIGATOR AND TECHNICAL MONITOR, RESPECTIVELY.

JOB TITLE

CASE NO. 4

SPECIFIED COMPUTATION OPTIONS

1. INTERNAL FLOW FIELD WITH SHOCK WAVE SYSTEM
2. BOUNDARY LAYER COMPUTATION IS INVOKED

FLOW SYMMETRY

ONE PLANE OF SYMMETRY = COMPUTED SECTOR IS THE HALF-PLANE BOUNDED BY THE Y-AXIS AND CONTAINING THE X-AXIS

THERMODYNAMIC MODEL

A THERMALLY AND CALORICALLY PERFECT GAS IS SPECIFIED WITH

SPECIFIC HEAT RATIO=1.400000
GAS CONSTANT=0.171616E+04(FT-LBF/SLUG-DEG)

MOLECULAR TRANSPORT TERMS FOR SUPERSONIC CORE FLOW SOLUTION

VISCOSITY AND THERMAL DIFFUSION TERMS ARE NOT INCLUDED IN THE COMPUTATION — INVISCID AND ADIABATIC FLOW IS ASSUMED

MOLECULAR TRANSPORT PARAMETERS

VISCOITY IS REPRESENTED BY RUTHERFORD'S LAW WITH

REFERENCE VISCOITY=0.350000E-06(LBF-SEC/FT²)
REFERENCE TEMPERATURE=0.492000E+03(DEG)
BASE TEMPERATURE=0.158600E+03(DEG)
LAMINAR FRICTION NUMBER=0.710

Figure 15. Selected output for Sample Case No. 4.
Figure 15. Continued.
### Cowl Geometry

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<th>3</th>
<th>4</th>
<th>5</th>
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</table>

**FOREBODY/CENTREBODY TEMPERATURE BOUNDARY CONDITIONS**

A constant wall temperature is specified at 0.8764982E+00 (R) on (k).

**COWL TEMPERATURE BOUNDARY CONDITIONS**

A constant wall temperature is specified at 0.8764982E+00 (R) on (k).

**Mass Transfer Boundary Conditions**

A permeable forebody/centrebody wall is specified with

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A permeable cowl wall is specified with

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</tr>
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</table>

**Figure 15. Continued.**
(P* or P) (P* or P) (P* or P)

1 3.7500 3.4500 0.160000E+05

TURBULENCE MODEL PARAMETERS

APLUS = 26.0000  XLAPMA = 0.4000  XALPHA = 0.01680  PRHY = 0.5000  TFACTOR = 1.0000

ALPHA = 0.420000  ALPHM = 0.090000

TRANSITION MODEL NO. 5 IS USED FOR FOREBODY/CENTERBODY BOUNDARY LAYER COMPUTATION

TRANSITION MODEL NO. 3 IS USED FOR CWL BOUNDARY LAYER COMPUTATION

CONVERGENCE TOLERANCES, ITERATION LIMITS, AND OTHER PARAMETERS

CONVERGENCE TOLERANCES AND OTHER PARAMETERS

CRIT: 1 = 0.100000E+00
CRIT: 2 = 0.100000E+00
CRIT: 3 = 0.100000E+00
CRIT: 4 = 0.100000E+00
CRIT: 5 = 0.100000E+00
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CRIT:14 = 0.100000E+00
CRIT:15 = 0.100000E+00
CRIT:16 = 0.100000E+00
CRIT:17 = 0.100000E+00
CRIT:18 = 0.100000E+00

ITERATION LIMITS

ITEM(1)=10
ITEM(2)=10
ITEM(3)=10
ITEM(4)=10
ITEM(5)=10
ITEM(6)=10
ITEM(7)=10
ITEM(8)=10

INPUT SAFETY FACTOR = 0.975000E+00

Figure 15. Continued.
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**Figure 15. Continued.**
### CENTERBOUNDS LINEAR SOLUTION FOR PLANE NO. 9

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<tr>
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<td>$T$</td>
<td>$H$</td>
<td>$N$</td>
<td>$P$</td>
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<td>$\Delta D$</td>
<td>$L$</td>
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#### Figure 15. Continued.
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Figure 15. Continued.
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<th>Y</th>
<th>EFD</th>
<th>a</th>
<th>b</th>
<th>( \frac{a}{b} )</th>
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**Figure 15. Continued.**
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<th>Y (FT)</th>
<th>T (DEG)</th>
<th>T (FT/SEC)</th>
<th>T (LBF/FT2)</th>
<th>T (SLUG/FT3)</th>
<th>T (DEG R)</th>
<th>T (FT/SEC)</th>
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Figure 15. Continued.
REFERENCES


