ZEUS USER MANUAL
"REAL GAS" EFFECTS

BY F. J. PRIOLO AND A. B. WARDLAW, JR
RESEARCH AND TECHNOLOGY DEPARTMENT

6 MAY 1991

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NAVAL SURFACE WARFARE CENTER
Dahlgren, Virginia 22448-5000 • Silver Spring, Maryland 20903-5000
FOREWORD

The extension and application of the ZEUS code to high, hypersonic Mach numbers by incorporating high-temperature equilibrium air effects is described. The ZEUS code is a space-marching Euler solver. It uses an automatic multiple zone grid generation technique and a finite volume, second-order Godunov scheme for steady supersonic flow. High-temperature effects are achieved by using curve fits of the thermodynamic properties of equilibrium air. Sample calculations for a sharp cone and a blunt nosed cylinder are provided.

This work was supported by the Naval Weapons Center at China Lake.

CARL W. LARSON, Head
Physics & Technology Division
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CHAPTER 1

INTRODUCTION

This report describes the extension and application of the ZEUS code to high, hypersonic Mach numbers by incorporating high-temperature equilibrium air or "real gas" effects. This approach is important for accurate aerodynamic predictions in support of atmospheric reentry vehicles with high maneuverability and future hypersonic weapons. The program employs an automatic multiple zone grid generation technique which is particularly suited to describing missile-type geometries in supersonic flight. The ZEUS code,\textsuperscript{1-9} whose numerical algorithm is well described in References 1–2 and applications in References 2–9, is a supersonic/hypersonic space-marching Euler solver which is capable of computing internal as well as external flows. The present report provides recent modifications to the program (described in Reference 2) for real gas effects and user instructions for its application.

The ZEUS code uses a zonal, finite volume, second order Godunov scheme to integrate the Euler equations. The computation proceeds for an initial data plane on which the flow field is specified, as shown in Figure 1, and marches in a streamwise direction until the end of the region of interest is encountered. In the case of a missile, the initial data plane is taken near the nose of the missile, and the flow field on this plane can be defined using conical flow, a blunt body solution, or uniform flow. The calculation is marched down the axis of the missile until the base of the missile is encountered. Throughout the computation, the flow field must remain supersonic everywhere.

At high flight Mach numbers and altitudes, computation of the flow field in local chemical and thermodynamic equilibrium is necessary to account for the high-temperature or real gas effects. These high temperature effects are taken into account by using the curve fits of Scrinivansan et. al.\textsuperscript{10} to compute the thermodynamic properties of equilibrium air as well as modifying parts of the ZEUS code.
CHAPTER 2
HIGH-TEMPERATURE EQUILIBRIUM AIR

The computation of missiles or atmospheric reentry bodies at high hypersonic Mach numbers and high altitudes requires the flow field to be calculated in local thermodynamic and chemical equilibrium. To solve an equilibrium flow field, two thermodynamic state variables (such as T and p) need to be expressed in terms of two other state variables (such as \( p \) and \( h \)).\(^{11}\) The high-temperature thermodynamic properties of equilibrium chemically reacting air are obtained from statistical thermodynamics as discussed in Reference 11. To simplify matters, tables of thermodynamic properties of high-temperature air have been constructed (see Hilsenrath and Klein\(^ {12}\)) which can be used in numerical flow field calculations via a "table look-up" procedure which interpolates between discrete entries from the tables. Furthermore, polynomial curve fits of the tabulated thermodynamic data for equilibrium air as discussed in Reference 10 have been correlated for computational convenience and efficiency. This latter method is the approach implemented in the ZEUS code.

2.1 COMPUTED THERMODYNAMIC PROPERTIES

The tabulated thermodynamic properties of equilibrium air are curve fit as discussed in Reference 10 and are implemented in ZEUS through the equilibrium air subroutines used in NASA Langley's CFL3DE program,\(^ {13}\) a time-dependent Navier-Stokes program. Each subroutine correlates different properties. For instance, subroutine:

- TGAS1 — computes \( p, a, T \) as a function of \( e \) and \( \rho \).
- TGAS2 — computes \( s \) as a function of \( e \) and \( \rho \).
- TGAS4 — computes \( h \) as a function of \( p \) and \( \rho \).
- TGAS5 — computes \( \rho \) as a function of \( p \) and \( s \).
- TGAS7 — computes \( a \) as a function of \( p \) and \( s \).

where, \( p \) = pressure, \( \rho \) = density, \( T \) = temperature, \( e \) = internal energy, \( h \) = enthalpy, \( s \) = entropy, and \( a \) = sound speed.
2.2 EFFECTIVE GAMMA

It is convenient to define an "effective gamma" as follows:

\[ \Gamma = \frac{1}{1 - \frac{p}{\rho h}} \]  

(1)

This is used in decoding the flow variables as discussed in Section 3.2.
CHAPTER 3
NUMERICAL PROCEDURE

3.1 GOVERNING EQUATIONS

Using the notation and coordinates of Figure 2, control volume mass and momentum conservation equations are given by:

$$\bar{U}_{i,j}^{n+1} = \bar{U}_{i,j}^{n} - \bar{F}_{i+\frac{1}{2},j} + \bar{F}_{i-\frac{1}{2},j} - \bar{F}_{i,j+\frac{1}{2}} + \bar{F}_{i,j-\frac{1}{2}}$$

(2)

where:

$$\bar{U}_{i,j}^{n} = A_{i,j}^{n} \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ \rho u v \\ \rho u V \\ \rho u V + n_z p \\ \rho u V + n_x p \\ \rho u V + n_y p \end{bmatrix}_{i,j} = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix}_{i,j}$$

(3)

$$\bar{F}_{i+\frac{1}{2},j} = \begin{bmatrix} \rho v \\ \rho u v + n_z p \\ \rho v V + n_x p \\ \rho v V + n_y p \end{bmatrix}_{i+\frac{1}{2},j}$$

(4)

$$V = \bar{n}_{i+\frac{1}{2},j} \cdot (u, v, w)_{i+\frac{1}{2},j}$$

(5)

Here, $\bar{U}$ is the flux in the $z$-direction which passes through the shaded cell ends while the $\bar{F}$'s are the fluxes associated with the remaining cell edges. The $A$'s are the cell edge areas, $\bar{n}$ is the vector normal to the cell, and $u, v, w$ are the cartesian velocity components. Equations (2) – (5) are closed using the constant total enthalpy condition

$$H_0 = h + \frac{1}{2}(u^2 + v^2 + w^2)$$

(6)

where $h = h(p, \rho)$. 
3.2 DECODING

After the corrector step, the flow variables $\rho$, $p$, $u$, $v$, $w$ must be determined or decoded from the computed conservative variables $U_1$, $U_2$, $U_3$, $U_4$, as displayed in Equation (3). This is done using an iterative procedure similar to that used by Solomon et. al.\textsuperscript{14}

By definition, we have

\begin{align*}
    u &= U_3/U_1 \\
    v &= U_4/U_1 \\
    p &= (U_2 - U_1w)/A \\
    \rho &= U_1/w/A
\end{align*}

Substitute Equations (7) – (10) into Equation (6) which yields:

\[ h = \frac{1}{2}[H' - w^2] \]  

where:

\[ H' = 2H_0 - \frac{U_3^2 + U_4^2}{U_1^2} \]

Substitute Equations (9-11) into Equation (1) to get a quadratic for $w$. The root of this equation corresponding to $w^2 > \Gamma p/\rho$ is

\[ w = \frac{U_2[\Gamma + \sqrt{1 - \Phi}]}{U_1[\Gamma + 1]} \]  

where:

\[ \Phi = (\Gamma^2 - 1) \left[ H' \left( \frac{U_1}{U_2} \right)^2 - 1 \right] \]

In the case of a perfect gas, $\Gamma = \gamma$, which is known, and Equations (7) – (10), and (13) provide the desired decoding formulas. For a more general gas (such as equilibrium air) where $h=h(p,\rho)$ is curve fit to thermodynamic data, $\Gamma$ is not known a-priori, and the decoding cannot be done in closed form. In this case, the decoding is done by solving the nonlinear equation

\[ h(p, \rho) - \frac{1}{2} [H' - w^2] = 0 \]

for $w$. In the code, Equation (15) is solved iteratively using the Secant Method. This is done in the following manner:

(a.) Guess a value of $\Gamma_1$ from $p$, $\rho$, $h$ computed in the predictor step and substitute $\Gamma_1$ into Equation (13) to get $w$. 

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(b.) Decode values of $u, v$ and compute new values of $p, \rho$ with the value of $w$ computed in Step (a.)

(c.) Solve Equation (15) by using the equilibrium air subroutine, TGAS4, for $h(p, \rho)$. This gives the first error estimate, $f(\Gamma_1)$.

(d.) Use the values of $p, \rho, h$ from Step (b.) to compute second guess value of $\Gamma_2$ using Equation (1).

(e.) Use $\Gamma_2$ to compute new values of $w$ from Equation (13) and $p, \rho$ from Equations (9) and (10) which gives a new value of $h(p, \rho)$ using subroutine TGAS4.

(f.) Solve Equation (15) using the new values of $w, p, \rho, h$ to get second error estimate, $f(\Gamma_2)$.

(g.) Compute new value of $\Gamma_3$ by

$$\Gamma_3 = \frac{\Gamma_1 f(\Gamma_2) - \Gamma_2 f(\Gamma_1)}{f(\Gamma_2) - f(\Gamma_1)}$$

(h.) Use $\Gamma_3$ to compute new values of $w, p, \rho, h$ as in Step (e.) and solve Equation (15) to get $f(\Gamma_3)$.

(i.) If $\left| \frac{f(\Gamma_2)}{h(p, \rho)} \right| < 10^{-3}$ is true, then the solution for $w$ is converged. If it is false, then go to Step (e.) and continue until converged.

3.3 NEW DENSITY

The predictor step uses Euler's equations in non-conservation form to predict the properties of $u, v, w, \rho$. For a perfect gas computation, the known total enthalpy constraint is used to determine $\rho$. For equilibrium air, the density must be obtained by numerically solving the differential equation for $\rho$.

To construct the differential equation, $d\rho$, the equation for total enthalpy is written as

$$H_0 = h(p, \rho) + \frac{q^2}{2}$$

where $q$ is the velocity. Rearranging Equation (17) for $h(p, \rho)$ gives

$$h(p, \rho) = H_0 - \frac{q^2}{2}$$

Casting Equation (18) in terms of differentials which gives

$$\left( \frac{\partial h}{\partial \rho} \right)_p dp + \left( \frac{\partial h}{\partial p} \right)_\rho d\rho = -qdq$$

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and rearranging Equation (19) for \( dp \) yields

\[
dp = \frac{-qdq - \left( \frac{\partial h}{\partial \rho} \right)_\rho dp}{\left( \frac{\partial h}{\partial \rho} \right)_\rho}
\]  
(20)

Using the following finite difference expressions for the differentials, Equation (20) can be computed in closed form:

\[
\left( \frac{\partial h}{\partial \rho} \right)_\rho = \frac{h(p, \rho) - h(p, \rho + \Delta \rho)}{\Delta \rho}
\]  
(21)

\[
\left( \frac{\partial h}{\partial \rho} \right)_\rho = \frac{h(p, \rho) - h(p + \Delta \rho, \rho)}{\Delta \rho}
\]  
(22)

\[
dp = p_2 - p_1
\]  
(23)

\[
dp = \rho_2 - \rho_1
\]  
(24)

\[
dq = q_2 - q_1
\]  
(25)

\[
\Delta p = .001p_1
\]  
(26)

\[
\Delta \rho = .001\rho_1
\]  
(27)

Equations (21) – (27) are substituted into Equation (20) and solved for the new density, \( \rho_2 \) with \( p_1, \rho_1, q_1, p_2, q_2, h \) given. Here the values of \( h \) are determined using the equilibrium air subroutine, TGAS4. This yields the following expression for \( \rho_2 \):

\[
\rho_2 = \rho_1 - \left\{ \frac{q_1(q_2 - q_1) + \left[ \frac{h(p_1, \rho_1) - h(p_1, 1.001 \rho_1)}{0.001 \rho_1} \right](p_2 - p_1)}{\left[ \frac{h(p_1, \rho_1) - h(p_1, 1.001 \rho_1)}{0.001 \rho_1} \right]} \right\}
\]  
(28)

where

\[
q_1 = \sqrt{u_1^2 + v_1^2 + w_1^2}
\]  
(29)

\[
q_2 = \sqrt{u_2^2 + v_2^2 + w_2^2}
\]
3.4 OBLIQUE SHOCKS

The inviscid boundary conditions at a surface require that the flow be tangent to the surface. ZEUS requires that the velocity vector be turned through either a shock or an expansion wave to align the velocity with the surface as illustrated in Figure 3. To solve for flow properties across an oblique shock wave in equilibrium air, a closed form solution does not exist. Refering to Figure 3(a), the following energy equation is solved iteratively:

\[ u_-^2 + 2h_-(p_-, \rho_-) = u_+^2 + 2h_+(p_+, \rho_+) \] (30)

where for an oblique shock,

\[ u_- = V_- \sin \beta \]

\[ u_+ = V_- \cos \beta \frac{(1 - \tan \theta \cot \beta)}{(\tan \theta + \cot \beta)} \]

\[ \rho_+ = \rho_- \frac{u_-}{u_+} \] (31)

\[ p_+ = \rho_- (u_- - u_+) + p_- \]

\[ \theta = \cos^{-1} \left( \frac{\vec{n}_+ \cdot \vec{n}_-}{|\vec{n}_+||\vec{n}_-|} \right) \]

and \( \beta \) is the shock wave angle to be determined. Here the \(-\) and \(+\) subscripts denote the upstream and downstream conditions, respectively. \( V_- \) is the upstream velocity component tangent to the surface, \( u_- \) and \( u_+ \) are the velocity components normal to the shock, \( \vec{n}_- \), \( \vec{n}_+ \) are the surface normal vectors, \( p_- \), \( p_+ \) are the pressures, and \( \rho_- \), \( \rho_+ \) are the densities, and \( \theta \) is the deflection angle.

To solve Equations (30) – (31), the Secant Method iterative procedure is implemented in a similar fashion as in Section 3.2 for decoding. Computations proceed by initializing

\[ \sin \beta > \max \{\sin \theta, \sin \left(1/M_-\right)\} \] (32)

where \( M_- \) is the upstream Mach number. The error is estimated using Equation (30) as follows:

\[ f(\sin \beta) = u_-^2 + 2h_-(p_-, \rho_-) - u_+^2 - 2h_+(p_+, \rho_+) \] (33)

The value of \( \sin \beta \) is increased until the relative error is less than \( 10^{-3} \) or
$$\left| \frac{f(\sin \beta)}{h_+(p_+, \rho_+)} \right| < 10^{-3} \quad (34)$$

This results in the final properties behind the shock, $p_+, \rho_+, V_+$ for which the velocity is tangent to the surface.

### 3.5 EXPANSION WAVES

To satisfy the inviscid boundary condition at a surface, often the velocity vector must be turned through a Prandtl-Meyer expansion to align the flow tangent to the surface. As in the case for oblique shock turns, a closed form solution does not exists for equilibrium air conditions; therefore, the expansion must be computed iteratively.

Referring to Figure 3(b), the equation for a centered expansion can be written in differential form:

$$\frac{dp}{d\phi} = \frac{-\rho q^2}{\sqrt{q^2/a^2 - 1}} \quad \text{for } 0 \leq \phi \leq \theta \quad (35)$$

where

\begin{align*}
q^2 &= 2H_0 - 2h(p, \rho) \\
s_- &= s(p_-, \rho_-) \\
\rho &= \rho(s_-, p) \\
a^2 &= a^2(p, \rho) \\
\theta &= \cos^{-1} \left( \frac{\bar{n}_+ \cdot \bar{n}_-}{|\bar{n}_+||\bar{n}_-|} \right) = \text{turn angle}
\end{align*}

The $-$ and $+$ subscripts represent upstream and downstream conditions, respectively. The unsubscripted variables are integrated values. Computations proceed by integrating Equations (35) – (36) on the interval $0 \leq \phi \leq \theta$ subject to the initial conditions $p = p_-$ and $q = V_-$ at $\phi=0$ using the second-order Improved Euler method. Subdivisions are every $.377^\circ$. The final results at $\phi=\theta$ give $p_+ = p_\phi=\theta, \rho_+ = \rho_\phi=\theta, V_+ = q_\phi=\theta$.

### 3.6 SHOCK ANGLE

The computation of the bow shock angle is determined using information along the positive characteristic at the cell adjacent to the bow shock. The shock angle is

$$\beta_+ = \tan^{-1} \left[ \theta + \frac{1}{\sqrt{M^2 - 1}} \right] \quad (37)$$
or in terms of velocities

\[ \beta_+ = \tan^{-1} \left[ \frac{V_n}{w} + \frac{1}{\sqrt{\frac{V_n^2 + w^2}{a^2} - 1}} \right] \]

(38)

Here, the variables are Roe averaged in the following manner:

\[ V_{nav} = \frac{\left( \frac{1}{2} \rho_+ V_{n+} + \frac{1}{2} \rho_- V_{n-} \right)}{\rho_+ + \rho_-} \]

\[ w_{av} = \frac{\left( \frac{1}{2} \rho_+ w_+ + \frac{1}{2} \rho_- w_- \right)}{\rho_+ + \rho_-} \]

\[ a_{av}^2 = (\Gamma_{av} - 1) \left[ H_{0av} - \frac{1}{2} (V_{nav}^2 + w_{av}^2) \right] \]

(39)

\[ H_{0av} = \frac{\left( \frac{1}{2} \rho_+ H_{0+} + \frac{1}{2} \rho_- H_{0-} \right)}{\rho_+ + \rho_-} \]

\[ \Gamma_{av} = \frac{\left( \rho_+ \Gamma_+ + \rho_- \Gamma_- \right)}{\rho_+ + \rho_-} \]

The + and − subscripts represent properties in the free stream and at the cell adjacent to the shock, respectively. \( V_n \) is the velocity component normal to the cell edge; \( w \) is the velocity component in the streamwise direction; \( a \) is the speed of sound; \( H_0 \) is the total enthalpy; and \( \Gamma \) is the effective gamma.
CHAPTER 4
ZEUS INPUT FILE (TAPE 5)

The ZEUS input file, as described in Reference 2, allows the user to:

1. Control the manner in which ZEUS integrates the Euler equations;
2. Select boundary condition options;
3. Specify the amount of output generated;
4. Choose the separation model;
5. Select the type of initial data to be used;
6. Specify mesh size and clustering.

The set up commands and options for the current version of ZEUS include the items outlined above from Reference 2. However, two more options are included which are inserted between items 4 and 5 above in the input file. They are:

- Selection of the gas type;
- Specification of the dimensional units.

Moreover, two input parameters are added to item 1 and one parameter to item 3 above. The complete input file is listed in Appendix A. The following sections give a description of the input variables, in order of their occurrence in file zeuse.da.

4.1 INTEGRATION CONTROL

**ZETAEND** — Terminate the calculation when ZETA ≥ ZETAEND. The last step size is adjusted to place the final integration plane at ZETAEND.

**KEND** — Terminate the calculation after executing KEND steps. If the initial step number is STEPI, the termination step number is STEPI+KEND.

**FCFL** — Step size safety factor. The step size is determined by multiplying the allowed step size, based on the CFL condition, by FCFL. For values of FCFL > 1, the calculation should be unstable. A value of .9 is typically used. Program abort can sometimes be rectified by using a smaller value. Also, oscillations in surface properties may be reduced by decreasing FCFL.
XKI — Limiting constant for cells not adjacent to a surface. The recommend value for this quantity is 1, however, XKI may be assigned any value between 2 and 0. Increasing XKI promotes increased accuracy and sharper shock capturing but may lead to oscillations in the solution. If XKI = 0, the scheme reduces to the first order Godunov method.

IAPR — The Davis approximate Riemann problem is applied if IAPR = 0, while the complete Riemann problem is solved if IAPR = 1. On most computing systems IAPR = 0 is faster, more robust and gives nearly the same results as IAPR = 1. However, IAPR = 0 is more dissipative, and differences between these solvers can be noted in solutions featuring strong crossflow shocks. For equilibrium air (IGAS = 1), IAPR must be set to 0.

ISHFLUX — The flux at the cell edge next to the bow shock is determined using the full Riemann problem if ISHFLUX = 0 or the free stream conditions if ISHFLUX = 1. For most cases, a value of 0 can be used; however, use 1 if wiggles occur at the shock.

ISHANG — The bow shock angle is determined using information from the full Riemann problem if ISHANG = 0 or determined from Roe averaged variables as described in Section 3.6 if ISHANG = 1. In general, a value of 0 can be used; however, for equilibrium air a value of 1 is recommended.

4.2 BOUNDARY CONDITIONS

NXKE — Number of edges at which the default limiter setting will not be applied. Cells adjacent to a surface use different limiter values than the interior point setting of XKI. Increasing the limiter values improve the solution accuracy in smooth flow regions, but can lead to surface pressure oscillations near shocks and fin edges. Different limiter values can be selected for each edge of each zone. If NXKE = 0, default limiter values will be applied at all edges. These are 2 on edges 1 and 3 and 0 on edges 2 and 4. The presumption here is that a smooth flow, such as that generated by a tangent ogive body, will occur near edges 1 or 3. However, shocks or expansions may occur near edges 2 and 4 as a consequence of surface slope discontinuities and fin edges. If these default values do not fit the case under consideration, set NXKE to the number of edges at which default values are to be changed. List the zone number, edge number, and limiter value for each edge which is to be changed at the indicated position in the input file.

NSUR — Number of edges which do not feature the default surface type. The user has the latitude of specifying the type of surface which occurs on each zone edge. The possibilities are:

0 — interior; do not apply boundary conditions;
1 — solid surface; apply tangent flow boundary conditions;
2 — free stream boundary; cell value fixed at free stream conditions;
3 — fitted shock or expansion.

If NSUR = 0, edge 1 will be type 1 and edge 3 will be type 1 unless a shock is being fitted (i.e., ISHOCK = 1). In this case edge 3 will automatically be set to 3. If edge 3 is defined outside the bow shock in the free stream, set to 2. Edges 2 and 4 will be set to 0, however, a surface will be assumed to occur for ω < s < Ω. To change these options, set NSUR to the number of
edges to be altered and for each edge list zone number, edge number and option number. Insert this list at the indicated position in the input file. 

**DFAC** — At locations where local Mach number is too small to allow the flow to be turned parallel to the wall, the turn angle is diminished. This is accomplished by computing the maximum turn angle associated with this Mach number. The turn angle to be used in the calculation is calculated by multiplying this maximum Mach angle by DFAC. DFAC should be set between 0 and 1 and is typically taken to be .9.

### 4.3 OUTPUT CONTROL

Tape 6 (output file) The first and last crossflow planes are always written to tape 6.

**IPRINT** — Print the crossflow plane if the step number is evenly divisible by IPRINT. If IPRINT = 100, the crossflow plane will be printed at step 100, 200, etc. The crossflow plane at the first and last step of the calculation will also be printed.

**NSKIP** — The crossflow plane output only contains those N planes which are evenly divisible by NSKIP. Set NSKIP to 1 if all n planes are to be printed.

**MSKIP** — The crossflow plane output only contains those M planes which are evenly divisible by MSKIP. Set MSKIP to 1 if all m planes are to be printed.

**ISKIP** — Print the step size if the step number is evenly divisible by ISKIP. Set ISKIP to 1 if the step size is to be printed after every step.

**PLOTZA** (Force and Surface Pressure Summary)

**JSPPR** — Following the completion of the final computational step, PLOTZA, which contains a list of forces and pressures at zone edges for each step, is read, and surface pressures along each edge may be printed. The default option is to list pressures only along edge 1 of each zone. JSPPR is the number of edges at which this output convention is to be changed. For each altered edge, list the zone number, edge number and the print option; 1 print, 0 don’t print this edge. Insert this list at the indicated position in the input file.

**JSPDIS** — Print the location of each grid point on the edges specified by JSPPR in addition to the surface pressures if JSPDIS is 1 (does not appear on PLOTZA). Do not print if JSPDIS is 0.

**KSKIP** — Write the surface pressures, forces and moments to PLOTZA at steps with numbers which are evenly divisible by KSKIP.

**NPRT** — On edges 2 and 4, only list the surface pressures for n planes less than NPRT.

**DELZA** — Write surface pressures, forces and moments to PLOTZA at step zeta intervals of DELZA.

**PLOTZC** (Plot tape) Crossflow plane at first and last step is always written to PLOTZC
IPLOT — Write the crossflow plane to PLOTZC at step numbers which are evenly divisible by IPLOT.
DELZC — Write the crossflow plane to DELZC at zeta intervals of DELZC.
IPLOTN — Number of target zeta stations at which crossflow plane will be written to PLOTZC. If IPLOTN > 0, a list of these stations, in ascending order should be included as indicated in the input file.

4.4 AERODYNAMIC DATA

AREF — Reference area to be used in the force and moment calculations.
XLREF — Reference length to be used in the force and moment calculations.
IEFORCE — Controls the output of forces on individual edges. Application of this option allows forces on individual fins to be determined. Set IEFORCE = 1 to invoke this option. Otherwise let IEFORCE = 0.

4.5 SEPARATION MODELING

IVIS — Type of separation model:
0 — no separation modeling;
1 — clipping;
2 — forced separation.

If options 0 or 1 are selected, the remainder of the information in this section is unnecessary. Note that option 2 can only be used with cylindrical coordinates. If option 2 is used, the information listed below is needed:
1 NSEP — The number of separation lines. Use of more than one separation line is necessary if separation on a body without pitch plane symmetry is to be modeled. Additional separation lines can also be used to model secondary separation.
2. For each separation line specify:
• ISSIDE — the side of the body on which separation occurs; 0 – 0° ≤ φ ≤ 180°, 1 – 180° ≤ φ ≤ 360°, where φ is the location of the separation line;
• ISEP — number of points used to define the separation line;
• ZSSEP — Zeta value at which separation is started;
• ZESEP — Zeta value at which separation is terminated;
• PHICD, PHIAD, BETACD, BETAAD — Flow direction in degrees. Typical values are 20°, 20°, 20°, 5°, respectively.
• A list of ISEP pairs of separation line coordinates (ZEPZ, ZEPP), where ZEPZ and ZEPP are the z and φ coordinates for each point.
4.6 GAS TYPE

IGAS — Type of gas

0 — Air is treated as a perfect gas;
1 — Air is treated in chemical equilibrium. Thermodynamic properties are determined using the subroutines for equilibrium air. IAPR must equal 0. Use of CONES is not recommended, and the flowfield must be initialized from uniform conditions (IMOD = 0) or using the blunt body program, BLUNT2.

4.7 UNITS

IUNITS — Dimensional units of problem. All input units must be consistent. Output units are the same.

0 — English units are used for input and output.
    (p = lbf / ft**2; \( \rho = \text{slug} / \text{ft}^3 \); \( T = ^\circ\text{R} \); x,y,z = ft);

1 — Metric units are used for input and output.
    (p = N / m**2; \( \rho = \text{kg} / \text{m}^3 \); \( T = ^\circ\text{K} \); x,y,z = m).

4.8 INITIAL PLANE DATA

IMOD

0 — Use a uniform initial flow field to start the calculation.
1 — Read the initial flow field from file START. This flow field can be generated by:

- The RESTART file from another ZEUS run;
- Program CONVERT which rezones RESTART files;
- Program CONES which generates an approximate conical flow field;
- Program NOSETIP or BLUNT2 which generates the starting data plane from a blunt body solution for flow over a sphere.

If IMOD = 1, the remainder of the data in this section is unnecessary. Instructions for applying CONVERT, CONES and NOSETIP are given in Reference 2. For IMOD = 0, the initial flow field and mesh size are defined using the following information:

IZN — Number of zones;
NA — Number of cells in the \( \xi \) direction;
MA — Number of cells in the $\eta$ direction summed over all zones. This information is followed by a list of the number of cells in the $\eta$ direction in each zone; 
ZETA — $z$ coordinate of initial data plane; 
ALPHA — Angle of attack in degrees (see Figure 1); 
BETA — Yaw angle in degrees (see Figure 1); 
XMINF — Free stream Mach number; 
PINF — Free stream pressure. The magnitude of the free stream pressure scales out of solution. For example, if the free stream pressure is doubled, all solution pressures are doubled. Setting $\text{PINF} = 1$ insures that solution pressures are scaled by $\text{PINF}$. However, for $\text{IGAS} = 1$, $\text{PINF}$ must be dimensional; 
DINF — Free stream density. The magnitude of the free stream density also scales out of the solution. However, for $\text{IGAS} = 1$, $\text{DINF}$ must be dimensional; 
ICORD — 0,1,2 for cartesian, cylindrical or elliptical coordinates. 
IASYM — 0 — flow is not symmetric about pitch plane; 1 — flow is symmetric about pitch plane symmetry; 
ISHOCK — Set to 1 if edge 3 is to be fitted as a shock or expansion; otherwise set to zero.

4.9 MESH CLUSTERING

IMESHF — 0 if the mesh is to be uniform in the $\xi$ direction, 1 for a clustered mesh. If clustering in this direction is used, a list of the $f$ clustering function values at cell centers must be inserted into the input file as indicated. Start the list at the cell center adjacent to edge 1. 
IMESHG — 0 if the mesh is to be uniform in the $\eta$ direction, 1 for a clustered mesh. If clustering in this direction is used, a different clustering function may be used in each zone. Hence it is necessary to specify $g$ values at cell centers in each zone. Insert cell center $g$ values into the input file as indicated, starting at zone 1 and ending at the final zone. Start the list at the cell center adjacent to edge 4.
CHAPTER 5
PRE-PROCESSING PROGRAMS

This section describes the programs used to generate the START file for a ZEUS. Programs CONES, NOSETIP, GEOTEST, and CONVERT are described in Reference 2 and will not be further discussed here.

5.1 BLUNT2

The BLUNT2 program generates the START tape for flow over a sphere for air as both a perfect gas and in chemical equilibrium. The program in turn creates the ZEUS START file. BLUNT2 can be applied for Mach numbers greater than 1.5; however, the freestream Mach number must be large enough to insure that the axial component of the flow is supersonic at the sphere-afterbody junction so that the ZEUS code is marchable.

The BLUNT2 INPUT file is prepared by editing the following file:

The following file describes the required input for BLUNT2. To execute BLUNT2, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the lines containing the >>>>> and <<<<< symbols. Do not eliminate any lines from this file.

```

-------------------
VALUE VARIABLE DESCRIPTION
-------------------

<<<<TITLE;;;;;; Read in the title of computation using A-format with a maximum of 72 characters.

>>>>>start title

<<<<end title

<<<<FREESTREAM CONDITIONS<<<<

() AMINF  Mach number
() PINF   Pressure used if IATMP=0; otherwise, set PINF=1. For English units (IUNITS=0) use lbf/ft**2, and for metric units (IUNITS=1) use N/m**2.
() TINF   Temperature used if IATMP=0; otherwise set TINF=1. For English units (IUNITS=0) use Rankine, and for metric units (IUNITS=1) use Kelvin.
() IATMP  0-use input values of PINF and TINF; 59-use 1959 ARDC Tables; or 62-use 1962 U.S. Standard Tables to compute PINF and TINF.

-------------------

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ALT
Altitude used if IATMP=59 or 62 to compute PINF and TINF; otherwise, if IATMP=0, set ALT=0. For English units (IUNITS=0) use feet, and for metric units (IUNITS=1) use meters.

*****GAS AND UNITS OPTIONS*****

IRG 0, 1 - air is a perfect gas or in chemical equilibrium.
IUNITS 0, 1 - dimensions are in English or metric units.

*****SPHERE DATA*****

RN Nose radius of the sphere in ft for IUNITS=0 or m for IUNITS=1.
YMAX Maximum angle (in degrees) over the sphere for which the flow field will be computed. The 0 deg line corresponds to the stagnation streamline. (Typically 120.)
NMAX Number of mesh points between the body and the shock. (Typically 18.)
MMAX Number of mesh points in the streamwise direction. (Typically 18)
IMAX Number of time steps. Generally at least 500 steps is needed to converge the solution.

*****ZEUS DATA*****

ZSTART Axial distance from the nosetip to the starting plane in ft for IUNITS=0 or m for IUNITS=1.
Z0 Axial distance from the nosetip to the center of the sphere in ft for IUNITS=0 or m for IUNITS=1.
IASYM 0, 1 - non symmetric or symmetric flowfield computation. If BETANOT NOT equal to 0, then set IASYM=0.
NA Number of mesh points between the body and shock for the ZEUS starting crossflow plane.
MA Number of mesh points in the circumferential direction for the ZEUS starting crossflow plane.
ALPHA Angle of attack (in degrees).
BETA Angle of yaw (in degrees).
CHAPTER 6
SAMPLE CASES

This section discusses the computation of sample cases using ZEUS for equilibrium chemically reacting air.

6.1 HYPERSONIC SHARP CONE

This case compares perfect gas and equilibrium air computations for a sharp cone at 0° incidence and an altitude of 100,000 ft. Solutions were computed for three different hypersonic similarity parameters, \( K_c = M_\infty \sin \theta_c = 5.18, 8.45, 14.79 \). Calculations were performed using the geometry described in cylindrical coordinates on a one zone 18 x 18 mesh. The solution was initiated using uniform flow conditions at ZETA = .1 and terminated at ZETA = 50. In addition, results are provided, as well as output found in Appendix B, for the sharp cone at the same altitude for \( M_\infty = 20 \) and 20° incidence on a 18 x 36 single zone mesh.

6.1.1 Geometry

A description of the edges of the zone are as follows:

EDGE 1: \( b = \zeta \tan \theta_c, b_z = \tan \theta_c, b_\phi = 0 \).
EDGE 2: \( \psi = \pi, \psi_z = \nu_r = 0 \).
EDGE 3: not needed (shock fitted)
EDGE 4: \( \sigma = 0, \sigma_z = \sigma_r = 0 \).

The required geometry routines are as follows:

```
SUBROUTINE BCONST(ZETA, BOFZ, BZOFZ)
  C  ..  THIS SUBROUTINE CALCULATES THE MAJOR AXIS OF AN ELLIPSE
  C  (BOFZ) AND ITS Z DERIVATIVE (BZOFZ)
RETURN
```

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SUBROUTINE EDGE1(IN, ZETA, YY, BT, BZT, BYT)
C......THIS SUBROUTINE DEFINES EDGE1
C......USER DEFINES BT, BZT AND BYT AS A FUNCTION OF ZETA (ZETA)
C Y OR PHI (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: BT - X OR R LOCATION OF EDGE 1
C BZT - Z DERIVATIVE OF BT.
C BYT - DERIVATIVE OF BT.
C.....CHOOSE CONE ANGLE, THETAC=15,20,25,ETC.
THETAC=25.
PI=4.*ATAN(1.)
RAD=PI/180.
THETAR=THETAC*RAD
BT=ZETA*TAN(THETAR)
BZT=Iqn(THETAR)
BYT=0.
RETURN
END
SUBROUTINE EDGE2(IN, ZETA, XX, THT, THZT, THXT)
C......THIS SUBROUTINE DEFINES EDGE2
C......USER DEFINES THT, THZT AND THXT AS A FUNCTION OF ZETA (ZETA)
C X OR R (XX) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: THT - Y OR PHI LOCATION OF F' ??
C THZT - Z DERIVATIVE OF THT
C THXT - X DERIVATIVE OF THT.
C THT=4.*ATAN(1.)
THZT=0.
THXT=0.
RETURN
END
SUBROUTINE EDGE3(IN, ZETA, PHI, CT, CZT, CYT)
C......USER DEFINES CT, CZT, CYT IF BOW SHOCK IS NOT BEING TRACKED.
C Y OR PHI (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: CT - X OR R LOCATION OF EDGE 3
C CZT - Z DERIVATIVE OF CT.
C CYT - Y DERIVATIVE OF CT.
C RETURN
END
SUBROUTINE EDGE4(IN, ZETA, XX, SGT, SGZT, SGXT)
C......THIS SUBROUTINE DEFINES EDGE4
C......THE USER MUST PROVIDE A DEFINITION OF SGT, SGZT, SGXT, AS A FUNCTION
C OF ZETA (ZETA), X OR R (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: SGT - Y OR PHI LOCATION OF EDGE 4
The following ZEUS input file is used for the sharp cone with a 25° half-angle at Mach 35 and 0° incidence (note that the flowfield is initiated with uniform conditions and the START file is not needed):

The following file describes the required input for ZEUS. To execute ZEUS, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the lines containing the >>>>> and <<<<< symbols. Variables enclosed by [] should be placed by themselves on a line. Do not eliminate any lines from this file.

VALUE VARIABLE DESCRIPTION

*****INTEGRATION CONTROL*****

50. ZETAEND Terminate calculation if ZETA > ZETAEND.
5000. KEND Terminate calculation if STEP NUMBER > KEND.
.9 FCFL Step size safety factor (1. > FCFL > 0.) Typically use .9.
1. XKI Interior point limiting constant (2. > XKI > 0.) Typically use 1.
0 JAPR 0,1 for approximate or complete Riemann Problem. Typically use 0. Must use 0 for equilibrium air.
0 ISHFLUX 0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock. Typically use 0.
1 ISHANG 0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use 0. For equilibrium air, a value of 1 is preferred.

*****BOUNDARY CONDITIONS*****
0  NXKE  Number of edges at which default limiter setting won't be used. Default settings are 2 on edges 1 or 3 and 0 on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE).

0  NSUR  Number of edges not featuring default surface types. Default values are 1 on edges 1 and 3 and 0 on edge 2 and 4. Program will automatically account a fitted shock on edge 3 or fin surfaces on edges 2 or 4. For each edge at which the surface type is not of default, add a line that specifies the zone number (KSURZ), edge number (KSURE) and surface type (KSUR).

0  DFAC  In case of a local wall Mach number which is to small to allow the flow to be turned parallel to the wall, the turn angle is multiplied by the constant DFAC (1. > DFAC > 0.).

---Printer---

250  IPRINT  Print crossflow plane if step number is evenly divided by IPRINT.

3  NSKIP  Print n planes which are evenly divisible by NSKIP.

6  MSKIP  Print n planes which are evenly divisible by MSKIP.

10  ISKIP  Print step size if step number is evenly divided by ISKIP.

---PLOTZA/Force-Pressure Summary---

0  JSPPR  In default mode, only edge 1 of each zone will be written to PLOTZA. JSPPR is the number of additional edges which are not to be written in the default manner. For each edge added or deleted from this print list, include a line which specifies zone number (JSPZ), edge number (JSPE) and print code (JSP). JSP = 1 will write this zone edge to PLOTZA, 0 will not.

0  JSPDIS  1 - print grid point locations for the edges specified by JSPPR. 0 - do not print.

50  KSKIP  Write surface properties on selected edges to PLCTZA if if STEP NUMBER is evenly divisible by KSKIP.

100  NPRT  On summary sheet, print surface pressures of edges 2 or 4 if n < NPRT.

10000  DELZA  Write to PLCTZA if (ZETA - ZETA at last write) > DELZA.

---PLOTZC (Plot file)---

10000  IPOINT  Write to PLOTZC if STEP NUMBER is evenly divisible by IPOINT.

10000  DELZC  Write to PLOTZC if (ZETA - ZETA at last write) > DELZC.

0  IPOINTN  Number of target Z stations (ZTARGET) at which PLOTZC will be written. If IPOINTN > 0, Include a list of these stations on the next line (maximum of 20). Stations must be listed in ascending order.

---AERODYNAMIC DATA---

1.  AREF  Reference area used in calculating force and moment coefficients.

1.  XLREF  Reference length used in calculating moment coefficients and center-of-pressure.
**SEPARATION MODELING**

0 IVIS 0,1,2 for no modeling, clipping, and forced separation. Clipping and forced separation can only be used in conjunction with cylindrical coordinates. If IVIS = 2, specify the number of separation lines (NSEP).

> >>>> NSEP

For each separation line specify:

ISSIDE - 0 separation line located between 0 and 180 degrees,
1 separation line located between 180 and 360 degrees.

ISEP - number of points used to define the separation line.

ZSEP - Zeta value at which separation is started
ZESEP - Zeta value at which separation is terminated

PHICD - separation angle phiC (degrees)
PHIAD - separation angle phiA (degrees)
BETACD - separation angle BetaC (degrees)
BETAAD - separation angle BetaA (degrees)

> >>>> [ISSIDE,ISEP,ZSEP,ZESEP,PHICD,PHIAD,BETACD,BETAAD]

A list of ISEP pairs of points (ZEPZ,ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list for each separation line on a separate line and list in same order as used in the above data.

> >>>> start list of ZEPZ,ZEPP

---

**GAS TYPE**

1 IGAS 0-perfect gas; 1-equilibrium air

---

**UNITS**

1 IUNITS 0-english (p=lbf/ft**2, rho=slug/ft**3, t=rankine, xyz=ft);
1-metric (p=n/m**2, rho=kg/m**3, t=kelvin, xyz=m).

All input units must be consistent. Output units are the same.

---

**INITIAL DATA**

0 IMOD 0,1 for new start or restart respectively. For a restart, the initial flow field is read from TAPE3. Additional information is not needed and the remaining entries in this section should be disregarded. A new start assumes a uniform flow field which is described in the following section.

---Mesh Size---

1 IZN Number of zones.
18 NA Number of cells in xi direction (i.e., between edges 1 and 3)
18 MA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

> >>>>Start list of MA for each zone

<<<<end list

---Flow Properties---

.01 ZETA Zeta coordinate of initial data plane

---
---Problem Definition---

PROBLEM DEFINITION

ICORD 0, 1, 2 for cartesian, cylindrical or elliptic coordinates

IASYM 0 - no pitch plane symmetry; 1 - pitch plane symmetry.

ISHOCK Set to 1 if edge 3 is to be fitted by the calculation
(either as a shock or sonic line); otherwise set to 0.
ISHOCK = 1 is only valid for ICORD = 1 or 2. If edge 3 is
to be fitted, the r and phi (cylindrical coordinates)
or s, tau (elliptic coordinates) of the shock location on each
M plane, (SS, SSZ) must be defined, starting from M = 1.

>>>>>Start list of [SS, SSZ]

.20 5.
.20 15.
.20 25.
.20 35.
.20 45.
.20 55.
.20 65.
.20 75.
.20 85.
.20 95.
.20 105.
.20 115.
.20 125.
.20 135.
.20 145.
.20 155.
.20 165.
.20 175.

>>>>>End list

*****MESH DEFINITION*****

IMESHF 0 for uniform mesh in xi direction. 1 for clustered mesh. If
a clustered mesh is to be used, the clustering function (FN) in
the xi direction at the NA cell centers must be defined
starting at cell 1, located adjacent to edge 1 and moving to
edge 3 (usually body to shock).

>>>>>Start list of FN

>>>>>>>>start list

end list

IMESHG 0 for uniform mesh in eta direction. 1 for clustered mesh. If
a clustered mesh is to be used, the clustering function (GN) in
the eta direction at the MA(i) cell centers in each zone must
be defined, starting with zone 1 and ending with zone IZN. Start
with cell 1, located adjacent to edge 1 and end at the cell
adjacent to edge 2. The list for each zone should be started
on a new card.

>>>>>Start list GN

end list

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6.1.3 ZEUS Input File — II

The following ZEUS input file is used for the sharp cone with a 25° half-angle at Mach 20 and 20° incidence (note that the flowfield is initiated with uniform conditions and the START file is not needed):

The following file describes the required input for ZEUS. To execute ZEUS, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the >>>>> and <<<<< symbols. Variables enclosed by [ ] should be placed by themselves on a line. Do not eliminate any lines from this file.

```
VALUE VARIABLE DESCRIPTION

*****INTEGRATION CONTROL*****

50. ZETAEND Terminate calculation if ZETA > ZETAEND.

5000. KEND Terminate calculation if STEP NUMBER > KEND.

.9 FCFL Step size safety factor (I. > FCFL > 0.) Typically use .9 .

1. XKI Interior point limiting constant (2. > XKI > C.) Typically use 1.

0 IAPR 0,1 for approximate or complete Riemann Problem. Typically use C.

Must use 0 for equilibrium air.

0 ISHFLUX 0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock. Typically use 0.

1 ISHANG 0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use C. For equilibrium air, a value of 1 is preferred.


*****BOUNDARY CONDITIONS*****

1 NXKE Number of edges at which default limiter setting won't be used. Default settings are 2 on edges 1 or 3 and C on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE).

>>>>>start list of [KEZ,KEE,XKE]

1 3 0

<<<<<<<end list

0 NSUR Number of edges not featuring default surface types. Default values are 1 on edges 1 and 3 and C on edge 2 and 4. Program will automatically account a fitted shock on edge 3 or fin surfaces on edges 2 or 4. For each edge at which the surface type was not of default, add a line that specifies the zone number (KSUR2), edge number (KSURE) and surface type (KSUR).

>>>>>start list of [KSUR2,KSURE,KSUR]

<<<<<<<end list

.9 DFAC In case of a local wall Mach number which is too small to allow the flow to be turned parallel to the wall, the turn angle is multiplied by the constant DFAC (1. > DFAC > 0.).


*****OUTPUT CONTROL*****

---Printer---

25C IPRINT Print crossflow plane if step number is evenly divided by IPRINT

3 NSKIP Print n planes which are evenly divisible by NSKIP
```
MSKIP  Print m planes which are evenly divisible by MSKIP
ISKIP  Print step size if step number is evenly divided by ISKIP

--- PLOTZA/Force-Pressure Summary ---

JSPPR In default mode, only edge 1 of each zone will be written to PLOTZA. JSPPR is the number of additional edges which are not to be written in the default manner. For each edge added or deleted from this print list, include a line which specifies zone number (JSPPZ), edge number (JSPE) and print code (JSP). JSP = 1 will write this zone edge to PLOTZA, 0 will not.

>>> start list of [JSPPZ, JSPE, JSP]

JSPDIS 1 - print grid point locations for the edges specified by JSPPR.
0 - do not print.

KSKIP Write surface properties on selected edges to PLOTZA if if STEP NUMBER is evenly divisible by KSKIP

NPRT On summary sheet, print surface pressures of edges 2 or 4 if n < NPRT.

DELZA Write to PLOTZA if (ZETA - ZETA at last write) > DELZA

--- PLOTZC (Plot file) ---

IPLDT Write to PLOTZC if STEP NUMBER is evenly divisible by IPLDT.

DELZC Write to PLOTZC if (ZETA - ZETA at last write) > DELZC

IPLOTN Number of target Z stations (ZTARGET) at which PLOTZC will be written. If IPLDT > 0, include a list of these stations on the next line (maximum of 20). Stations must be listed in ascending order.

>>> start ZTARGET list

********** AERODYNAMIC DATA *****

AREF Reference area used in calculating force and moment coefficients.

XLREF Reference length used in calculating moment coefficients and center-of-pressure.

IEFORCE 0, 1 don't, do print force and moments for individual edges.

********** SEPARATION MODELING *****

IVIS 0, 1, 2 for no modeling, clipping, and forced separation. Clipping and forced separation can only be used in conjunction with cylindrical coordinates. If IVIS = 2, specify the number of separation lines (NSEP).

>>> NSEP

For each separation line specify:

ISSIDE - 0 separation line located between 0 and 180 degrees,
1 separation line located between 180 and 360 degrees.

ISEP - number of points used to define the separation line.

ZSEP - Zeta value at which separation is started

ZSEP - Zeta value at which separation is terminated

PHICD - separation angle phiC (degrees)

PHIAD - separation angle phiA (degrees)

BETAIC - separation angle betaC (degrees)

BETAAD - separation angle betaA (degrees)

>>> [ISSIDE, ISEP, ZSEP, ZSEP, PHICD, PHIAD, BETAIC, BETAAD]

A list of ISEP pairs of points (ZEPZ, ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list
for each separation line or a separate line and list in same order as used in the above data.

```
>>>>> start list of ZEPZ, ZEPP
<<<<
```

```

*****GAS TYPE*****
1 IGAS 0-perfect gas; 1-equilibrium air

```

```

*****UNITS *****
1 IUNITS 0-english (p=lbf/ft**2, rho=slug/ft**3, t=rankine, xyz=ft);
1-metric (p=Pa/m**2, rho=kg/m**3, t=kelvin, xyz=m).
All input units must be consistent. Output units are the same.

```

```

*****INITIAL DATA*****
0 IMOD 0,1 for new start or restart respectively. For a restart, the initial flow field is read from TAPE3. Additional information is not needed and the remaining entries in this section should be disregarded. A new start assumes a uniform flow field which is described in the following section.

```

```

--- Mesh Size---
1 IZN Number of zones.
18 NA Number of cells in xi direction (i.e., between edges 1 and 3)
36 MA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

```

```

End list

```

```

--- Flow Properties---
.1 ZETA Zeta coordinate of initial data plane
20. ALPHA Angle of attack (degrees)
0. BETA Angle of yaw (degrees)
20. XMINF Mach number
1185.5 PINF Pressure
.017861 DINF Density

```

```

--- Problem Definition---

```

```

```

```
**********MESH DEFINITION**********

0 IMESHF 0 for uniform mesh in xi direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function ($F_N$) in the xi direction at the NA cell centers must be defined starting at cell 1, located adjacent to edge 1 and moving to edge 3 (usually body to shock).

    >>>>>start list of $F_N$

    >>>>>end list

0 IMESHG 0 for uniform mesh in eta direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function ($G_N$) in the eta direction at the MA($i$) cell centers in each zone must be defined, starting with zone 1 and ending with zone NZN. Start with cell 1, located adjacent to edge 4 and end at the cell adjacent to edge 2. The list for each zone should be started on a new card

    >>>>>>>start list $G_N$

    end list

>>>End list
6.1.4 Results

Conical flow solutions have been computed for a right circular sharp cone with $\theta_c = 25^\circ$ and for Mach 20 at $0^\circ$ incidence. Results are compared with tabulated cone properties by Hudgins $^5$ at an altitude of 100,000 ft. Figure 4 displays surface property comparisons between equilibrium air and calorically perfect results as a function of the hypersonic similarity parameter, $K_e$. Computed results are in good agreement with tabulated results for values of $K_e = 5.18, 8.45,$ and $14.79$. The characteristics of equilibrium chemically reacting air are well predicted which show that for chemically reacting air (1) the pressure is strongly dependent on the mechanical aspects of the flow and not the chemical reactions, (2) the density ratio is higher implying a smaller shock layer thickness, and (3) the equilibrium temperatures are lower than calorically perfect results, a result of the dissociated air. Figure 5 illustrates pressure contours for Mach 20 at $20^\circ$ incidence. Equilibrium air results demonstrate a smaller shock layer thickness as compared to calorically perfect results.

6.2 HYPERSONIC BLUNT NOSE CYLINDER

This case consists of a spherically blunt nosed cylinder at Mach 20, incidences of $0^\circ$ and $20^\circ$, and an altitude of 20,000 meters for equilibrium air. The output for $20^\circ$ is provided in Appendix B. The calculation, which uses a cylindrical coordinate description of the geometry, is divided into two sections. The first is the spherically blunt nose calculation using the program BLUNT2 on a $18 \times 25$ mesh which generates a ZEUS starting solution at $ZETA = .5$. The second computes the cylinder body using a $36 \times 36$ single zone mesh and is terminated at $ZETA = 20$.

6.2.1 Geometry

A description of the edges of the zone are as follows:

EDGE 1: $b = .5, \beta_z = b_\alpha = 0$.
EDGE 2: $\psi = \pi, \psi_z = \psi_r = 0$.
EDGE 3: not needed (shock fitted)
EDGE 4: $\sigma = 0., \sigma_z = \sigma_r = 0$.

The required geometry routines are as follows:

```
SUBROUTINE BCONST(ZETA,BOFZ,BZOFZ)
   C .... THIS SUBROUTINE CALCULATES THE MAJOR AXIS OF AN ELLIPSE
   C   (BOFZ) AND ITS Z DERIVATIVE (BZOFZ)
   RETURN
```

SUBROUTINE EDGE1(IN, ZETA, YY, BT, B2T, BYT)
C......This subroutine defines edge1
C......user defines BT, B2T and BYT as a function of ZETA (ZETA)
C Y or phi (YY) and zone number (IN).
C INPUT: IN - zone number
C ZETA - ZETA
C OUTPUT: BT - x or r location of edge 1
C B2T - z derivative of BT.
C BYT - y derivative of BT.

BT=.5
B2T=0.
BYT=0.
RETURN
END

SUBROUTINE EDGE2(IN, ZETA, XX, THT, THZT, THXT)
C......This subroutine defines edge2
C......user defines THT, THZT and THXT as a function of ZETA (ZETA)
C X or r (XX) and zone number (IN).
C INPUT: IN - zone number
C ZETA - ZETA
C OUTPUT: THT - y or phi location of edge 2
C THZT - z derivative of THT.
C THXT - y derivative of THT.

THT=4.*ATAN(1.)
THZT=0.
THXT=0.
RETURN
END

SUBROUTINE EDGE3(IN, ZETA, PHI, CT, CZT, CYT)
C......user defines CT, CZT, CYT if bow shock is not being tracked.
C Y or phi (YY) and zone number (IN).
C INPUT: IN - zone number
C ZETA - ZETA
C OUTPUT: CT - x or r location of edge 3
C CZT - z derivative of CT.
C CYT - y derivative of CT.

RETURN
END

SUBROUTINE EDGE4(IN, ZETA, XX, SGT, SGZT, SGXT)
C......This subroutine defines edge4
C......the user must provide a definition of SGT, SGZT, SGXT, as a function
C of ZETA (ZETA), X or R (YY) and zone number (IN).
C INPUT: IN - zone number
C ZETA - ZETA
C OUTPUT: SGT - y or phi location of edge 4
C SGZT - z derivative of SGT.
C SGXT - x derivative of SGT.

SGT=0.
SGZT=0.
SGXT=0.
RETURN
END
SUBROUTINE PEDGE(IN,II,ZETA,POUTL,PINL)
C THIS SUBROUTINE CALCULATES THE FIN EDGE LOCATION
C REQUIRED INPUT
C IN - ZONE NUMBER
C II - 1 FOR EDGE 4, 2 FOR EDGE 2
C ZETA - ZETA
C POUTL=0.
PINL=0.
C USER PROVIDES DEFINITION OF POUTL AND PINL
RETURN
END

6.2.2 START File

The start file for 20° incidence is generated using the BLUNT2 program using the following input:

The following file describes the required input for BLUNT2. To execute BLUNT2, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the lines containing the >>>>> and <<< symbols. Do not eliminate any lines from this file.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>*<strong><strong>TITLE-n</strong></strong></td>
<td></td>
</tr>
<tr>
<td>Read in the title of computation using A-format with a maximum of 72 characters.</td>
<td></td>
</tr>
<tr>
<td>&gt;&gt;&gt;&gt;&gt;start title</td>
<td></td>
</tr>
<tr>
<td>Hypersonic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m</td>
<td></td>
</tr>
<tr>
<td>&lt;&lt;&lt;end title</td>
<td></td>
</tr>
<tr>
<td><em><strong><strong>FREESTREAM CONDITIONS</strong></strong></em></td>
<td></td>
</tr>
<tr>
<td>AMINF</td>
<td>Mach number</td>
</tr>
<tr>
<td>PINF</td>
<td>Pressure used if IATMP=0; otherwise, set PINF=1. For English units (IUNITS=0) use lbf/ft<strong>2, and for metric units (IUNITS=1) use N/m</strong>2.</td>
</tr>
<tr>
<td>TINF</td>
<td>Temperature used if IATMP=0; otherwise set TINF=1. For English units (IUNITS=0) use Rankine, and for metric units (IUNITS=1) use Kelvin.</td>
</tr>
<tr>
<td>IATMP</td>
<td>0-use input values of PINF and TINF; 59-use 1959 ARDC Tables; or 62-use 1962 U.S. Standard Tables to compute PINF and TINF.</td>
</tr>
<tr>
<td>ALT</td>
<td>Altitude used if IATMP=59 or 62 to compute PINF and TINF; otherwise, if IATMP=0, set ALT=0. For English units (IUNITS=0) use feet, and for metric units (IUNITS=1) use meters.</td>
</tr>
<tr>
<td>IROG</td>
<td>0, 1-air is a perfect gas or in chemical equilibrium.</td>
</tr>
<tr>
<td>IUNITS</td>
<td>0, 1-dimensions are in English or metric units.</td>
</tr>
</tbody>
</table>
***SPHERE DATA***

- RN Nose radius of the sphere in ft for IUNITS=0 or m for IUNITS=1.
- YMAX Maximum angle (in degrees) over the sphere for which the flow field will be computed. The 0 deg line corresponds to the stagnation streamline. (Typically 120.)
- NMAX Number of mesh points between the body and the shock. (Typically 18)
- MMAX Number of mesh points in the streamwise direction. (Typically 18)
- IMAX Number of time steps. Generally at least 500 steps is needed to converge the solution.

***ZEUS DATA***

- ZSTART Axial distance from the nosetip to the starting plane in ft for IUNITS=0 or m for IUNITS=1.
- ZO Axial distance from the nosetip to the center of the sphere in ft for IUNITS=0 or m for IUNITS=1.
- IASYM 0, 1 - non symmetric or symmetric flowfield computation. If BETA not equal to 0, then set IASYM=0.
- NA Number of mesh points between the body and shock for the ZEUS starting crossflow plane.
- MA Number of mesh points in the circumferential direction for the ZEUS starting crossflow plane.
- ALPHA Angle of attack (in degrees).
- BETA Angle of yaw (in degrees).

6.2.3 ZEUS Input File

The following ZEUS input file is used for the afterbody:

The following file describes the required input for ZEUS. To execute ZEUS, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the lines containing the >>>>> and <<<<< symbols. Variables enclosed by [] should be placed by themselves on a line. Do not eliminate any lines from this file.

---

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZETAE</td>
<td>ZETAEND</td>
<td>Terminate calculation if ZETA &gt; ZETAE.</td>
</tr>
<tr>
<td>5000</td>
<td>KEND</td>
<td>Terminate calculation if STEP NUMBER &gt; KEND.</td>
</tr>
<tr>
<td>.9</td>
<td>FCFL</td>
<td>Step size safety factor (. &gt; FCFL &gt; 0.) Typically use .9.</td>
</tr>
<tr>
<td>1.</td>
<td>XKI</td>
<td>Interior point limiting constant (2. &gt; XKI &gt; 0.) Typically use 1.</td>
</tr>
<tr>
<td>0</td>
<td>IAPR</td>
<td>0,1 for approximate or complete Riemann Problem. Typically use 0. Must use 0 for equilibrium air.</td>
</tr>
<tr>
<td>1</td>
<td>ISHFLUX</td>
<td>0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock.</td>
</tr>
</tbody>
</table>
Typically use 0.

1 ISHANG 0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use 0. For equilibrium air, a value of 1 is preferred.

****BOUNDARY CONDITIONS****

1 NXKE Number of edges at which default limiter setting won't be used. Default settings are 2 on edges 1 or 3 and 0 on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE).

1 1 1.

<<<<end list

0 NSUR Number of edges not featuring default surface types. Default values are 1 on edges 1 and 3 and 0 on edge 2 and 4. Program will automatically account a fitted shock on edge 3 or fin surfaces on edges 2 or 4. For each edge at which the surface type is not of default, add a line that specifies the zone number (KSURZ), edge number (KSURE) and surface type (KSUR).

<<<<start list of [KSURZ,KSURE,KSUR]

<<<<end list

.9 DFAC In case of a local wall Mach number which is too small to allow the flow to be turned parallel to the wall, the turn angle is multiplied by the constant DFAC (1. > DFAC > 0.).

****OUTPUT CONTROL****

---Printer---

250 IPRINT Print crossflow plane if step number is evenly divided by IPRINT

6 NSKIP Print m planes which are evenly divisible by NSKIP

6 MSKIP Print n planes which are evenly divisible by MSKIP

10 ISKIP Print step size if step number is evenly divided by ISKIP

---PLOTZA/Force-Pressure Summary---

0 JSPPR In default mode, only edge 1 of each zone will be written to PLOTZA. JSPPR is the number of additional edges which are not to be written in the default manner. For each edge added or deleted from this print list, include a line which specifies zone number (JSPZ), edge number (JSPE) and print code (JSP). JSP = 1 will write this zone edge to PLOTZA, 0 will not.

<<<<start list of [JSPZ,JSPE,JSP]

<<<<end list
0 JSPDIS 1 - print grid point locations for the edges specified by JSPPR.
   0 - do not print.

40 KSKIP Write surface properties on selected edges to PLOTZA if
   if STEP NUMBER is evenly divisible by KSKIP

100 NPRT On summary sheet, print surface pressures of edges 2 or 4 if
   n < NPRT.

10000. DELZA Write to PLOTZA if (ZETA - ZETA at last write) > DELZA

---PLOTZC (Plot file)

10000 IPLOT Write to PLOTZC if STEP NUMBER is evenly divisible by IPLOT.

10000. DELZC Write to PLOTZC if (ZETA - ZETA at last write) > DELZC

2 IPLOTN Number of target 2 stations (ZTARGET) at which PLOTZC will
   be written. If IPLOTN > 0, include a list of these
   stations on the next line (maximum of 20). Stations must be
   listed in ascending order.

   >>>>>>start ZTARGET list

   0.5 10.

   <<<<<end list

****AERODYNAMIC DATA****

1. AREF Reference area used in calculating force and moment coefficients.

1. XLREF Reference length used in calculating moment coefficients and
   center-of-pressure.

0 IEFORCE 0, 1 don't, do print force and moments for individual edges.

****SEPARATION MODELING****

0 IVIS 0,1,2 for no modeling, clipping, and forced separation. Clipping
   and forced separation can only be used in conjunction with
   cylindrical coordinates. If IVIS = 2, specify the number of
   separation lines (NSEP).

   >>>>>> NSEP

   <<<<<
   For each separation line specify:
   ISSIDE - 0 separation line located between 0 and 180 degrees,
      1 separation line located between 180 and 360 degrees.
   ISEP - number of points used to define the separation line.
   ZSSEP - Zeta value at which separation is started
   ZESEP - Zeta value at which separation is terminated
   PHICD - separation angle phiC (degrees)
   PHIAD - separation angle phiA (degrees)
   BETACD - separation angle BetaC (degrees)
   BETAAD - separation angle BetaA (degrees)

   >>>>>> (ISSIDE, ISEP, ZSSEP, ZESEP, PHICD, PHIAD, BETACD, BETAAD)
A list of ISEP pairs of points (ZEPZ, ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list for each separation line on a separate line and list in same order as used in the above data.

>>>>> start list of ZEPZ, ZEPP

---- Mesh Size ----

() IZN Number of zones.
() MA Number of cells in xi direction (i.e., between edges 1 and 3)
() NA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

>>>>> Start list of MA for each zone

---- Flow Properties ----

() ZETA Zeta coordinate of initial data plane
() ALPHA Angle of attack (degrees)
() BETA Angle of yaw (degrees)
() XMINF Mach number
() PINF Pressure
() DINF Density
---Problem Definition---

**PROBLEM DEFINITION**

- **ICORD**
  - 0,1,2 for cartesian, cylindrical or elliptic coordinates

- **IASYM**
  - 0 - no pitch plane symmetry; 1 - pitch plane symmetry.

- **ISHOCK**
  - Set to 1 if edge 3 is to be fitted by the calculation (either as a shock or sonic line); otherwise set to 0.
  - ISHOCK = 1 is only valid for ICORD = 1 or 2. If edge 3 is to be fitted, the r and phi (cylindrical coordinates) or s, tau (elliptic coordinates) of the shock location on each M plane, (SS, SSZ) must be defined, starting from M = 1, etc.,

```plaintext
>>>Start list of [SS,SSZ]
>>>End list
```

****MESH DEFINITION****

- **IMESHF**
  - 0 for uniform mesh in xi direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (FN) in the xi direction at the NA cell centers must be defined starting at cell 1, located adjacent to edge 1 and moving to edge 3 (usually body to shock).

```plaintext
>>>Start list of FN
>>>End list
```

- **IMESHG**
  - 0 for uniform mesh in eta direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (GN) in the eta direction at the MA(i) cell centers in each zone must be defined, starting with zone 1 and ending with zone IZN. Start with cell 1, located adjacent to edge 4, and end at the cell adjacent to edge 2. The list for each zone should be started on a new card.

```plaintext
>>>>>>>Start list GN
<<<<<<<end list
```

#### 6.2.4 Results

Computations were performed for a spherically blunt nosed cylinder at an altitude of 20 km for Mach 20 at 0° and 20° incidences. ZEUS computations are compared with computed results of Palmer\(^6\) for 0° incidence. Density and temperature contour plots in Figures 6 and 7 compare well for both calorically perfect and equilibrium air. ZEUS predicts the exhibited higher densities and thinner shock layer and lower temperatures associated with the chemically reacting air. Figure 8 illustrates density contours for the 20° incidence case at an axial station 9.5 diameters downstream.
6.3 HYPERSONIC AIRCRAFT

The hypersonic aircraft configuration\textsuperscript{17} of Figure 9 was computed at Mach 24.5 at 1° angle of incidence. A uniform 36 x 18 single zone mesh was implemented over the nose cone. For the wing section, the flow field was rezoned into two zones with each zone containing a 72 x 36 uniform mesh. Here, the outer boundary, edge 3, was defined outside the bow shock in the free stream.

6.3.1 Geometry — Nose Section

A description of the edges of the zone are as follows:

EDGE 1: \( b = \zeta \tan \theta_c, \quad b_z = \tan \theta_c, \quad b_\phi = 0. \)

EDGE 2: \( \psi = \pi, \quad \psi_z = \psi_r = 0. \)

EDGE 3: not needed (shock fitted)

EDGE 4: \( \sigma = 0., \quad \sigma_z = \sigma_r = 0. \)

The required geometry routines are as follows:

```
SUBROUTINE BCONST(ZETA, BOFZ, BZOFZ)
C ....... THIS SUBROUTINE CALCULATES THE MAJOR AXIS OF AN ELLIPSE
C (BOFZ) AND ITS Z DERIVATIVE (BZOFZ)
RETURN
END
```

```
SUBROUTINE EDGE1(IN, ZETA, YY, BT, BZT, BYT)
C ....... THIS SUBROUTINE DEFINES EDGE1
C ..... USER DEFINES BT, BZT AND BYT AS A FUNCTION OF ZETA (ZETA)
C Y OR PHI (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: BT - X OR R LOCATION OF EDGE 1
C BZT - Z DERIVATIVE OF BT.
C BYT - Y DERIVATIVE OF BT.

BYT=0.
BZT=0.
BT=5.08333
IF (ZETA.LE. 63.0) THEN
THETAC=4.6
PI=4.*ATAN(I.)
RAD=PI/180.
THETAR=THETAC*RAD
BT=ZETA*TAN(THETAR)
BZT=TAN(THETAR)
BYT=0.
ENDIF
```

39
SUBROUTINE EDGE2(IN, ZETA, XX, THT, THZT, THXT)
C ....THIS SUBROUTINE DEFINES EDGE2
C ....USER DEFINES THT, THZT AND THXT AS A FUNCTION OF ZETA (ZETA)
C X OR R (XX) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: THT - Y OR PHI LOCATION OF EDGE 2
C THZT - Z DERIVATIVE OF THT.
C THXT - X DERIVATIVE OF THT.

THT=4.*ATAN(1.)
THXT=0.
THZT=0.
RETURN
END

SUBROUTINE EDGE3(IN, ZETA, PHI, CT, CZT, CXT)
C ....USER DEFINES CT, CZT, CYT IF BOW SHOCK IS NOT BEING TRACKED.
C Y OR PHI (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: CT - X OR R LOCATION OF EDGE 3
C CZT - Z DERIVATIVE OF CT.
C CYT - Y DERIVATIVE OF CT.

RETURN
END

SUBROUTINE EDGE4(IN, ZETA, XX, SGT, SGZT, SGXT)
C ....THIS SUBROUTINE DEFINES EDGE4
C ....THE USER MUST PROVIDE A DEFINITION OF SGT, SGZT, SGXT, AS A FUNCTION
C OF ZETA (ZETA), X OR R (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: SGT - Y OR PHI LOCATION OF EDGE 4
C SGZT - Z DERIVATIVE OF SGT.
C SGXT - X DERIVATIVE OF SGT.

SGT=0.
SGXT=0.
SGZT=0.
RETURN
END

SUBROUTINE PEDGE(IN, II, ZETA, POUTL, PINL)
C THIS SUBROUTINE CALCULATES THE FIN EDGE LOCATION
C REQUIRED INPUT
C IN - ZONE NUMBER
C II - 1 FOR EDGE 4, 2 FOR EDGE 2
C ZETA - ZETA
C
C ....USER PROVIDES DEFINITION OF POUTL AND PINL
POUTL=0.
PINL=0.
6.3.2 Zeus Input File - Nose Section

The following input file is used for the hypersonic aircraft nose section run at Mach 24.5 and 1° incidence. Computations were initiated from uniform free stream conditions.

The following file describes the required input for ZEUS. To execute ZEUS, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the >>>>> and <<<<< symbols. Variable enclosed by [] should be placed by themselves on a line. Do not eliminate any lines from this file.

---

**VALUE VARIABLE DESCRIPTION**

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.</td>
<td>ZETAEND</td>
<td>Terminate calculation if ZETA &gt; ZETAEND.</td>
</tr>
<tr>
<td>5000.</td>
<td>KEND</td>
<td>Terminate calculation if STEP NUMBER &gt; KEND.</td>
</tr>
<tr>
<td>.9</td>
<td>FCFL</td>
<td>Step size safety factor (1. &gt; FCFL &gt; 0.) Typically use .9.</td>
</tr>
<tr>
<td>1.</td>
<td>XKI</td>
<td>Interior point limiting constant (2. &gt; XKI &gt; 0.) Typically use 1.</td>
</tr>
<tr>
<td>0</td>
<td>IAPR</td>
<td>0,1 for approximate or complete Riemann Problem. Typically use 0. Must use 0 for equilibrium air.</td>
</tr>
<tr>
<td>0</td>
<td>ISHFLUX</td>
<td>0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock. Typically use 0.</td>
</tr>
<tr>
<td>1</td>
<td>ISHANG</td>
<td>0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use 0. For equilibrium air, a value of 1 is preferred.</td>
</tr>
</tbody>
</table>

---

**BOUNDARY CONDITIONS**

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NXKE</td>
<td>Number of edges at which default limiter setting won’t be used. Default settings are 2 on edges 1 or 3 and 0 on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE).</td>
</tr>
<tr>
<td>0</td>
<td>NSUR</td>
<td>Number of edges not featuring default surface types. Default values are 1 on edges 1 and 3 and 0 on edge 2 and 4. Program will automatically account a fitted shock on edge 3 or fin surfaces on edges 2 or 4. For each edge at which the surface type is not of default, add a line that specifies the zone number(KSURZ), edge number(KSURE) and surface type (KSUR).</td>
</tr>
</tbody>
</table>
| .9    | DFAC     | In case of a local wall Mach number which is to small to allow the flow to be turned parallel to the wall, the turn angle is
multiplied by the constant DFAC (1 > DFAC > 0.).

*****OUTPUT CONTROL*****

---Printer---

250 IPRINT Print crossflow plane if step number is evenly divided by IPRINT
1 NSKIP Print n planes which are evenly divisible by NSKIP
3 MSKIP Print m planes which are evenly divisible by MSKIP
1 ISKIP Print step size if step number is evenly divided by ISKIP

---PLOTZA/Force-Pressure Summary---

0 JSPPR In default mode, only edge 1 of each zone will be written to PLOTZA. JSPPR is the number of additional edges which are not to be written in the default manner. For each edge added or deleted from this print list, include a line which specifies zone number (JSPZ), edge number (JSPE) and print code (JSP). JSP = 1 will write this zone edge to PLOTZA, 0 will not.

>>> start list of [JSPZ,JSPE,JSP]
<<<end list

0 JSPDIS 1 - print grid point locations for the edges specified by JSPPR. 0 - do not print.
5 KSKIP Write surface properties on selected edges to PLOTZA if if STEP NUMBER is evenly divisible by KSKIP
100 NPRT On summary sheet, print surface pressures of edges 2 or 4 if n < NPRT.
1000. DELZA Write to PLOTZA if (ZETA - ZETA at last write) > DELZA

---PLOTZC (Plot file)

1000 IPLOT Write to PLOTZC if STEP NUMBER is evenly divisible by IPLOT.
1000. DELZC Write to PLOTZC if (ZETA - ZETA at last write) > DELZC
2 IPEOTN Number of target Z stations (ZTARGET) at which PLOTZC will be written. If IPEOTN > 0, Include a list of these stations on the next line (maximum of 20). Stations must be listed in ascending order.

>>> start ZTARGET list

<<<end list

*****AERODYNAMIC DATA*****

1. AREF Reference area used in calculating force and moment coefficients.
1. XLREF Reference length used in calculating moment coefficients and center-of-pressure.
0 IEFORCE 0, 1 don't, do print force and moments for individual edges.

*****SEPARATION MODELING*****

0 IVIS 0, 1, 2 for no modeling, clipping, and forced separation. Clipping and forced separation can only be used in conjunction with cylindrical coordinates. If IVIS = 2, specify the number of separation lines (NSEP).

>>> NSEP

For each separation line specify:
ISSIDE - 0 separation line located between 0 and 180 degrees,
1 separation line located between 180 and 360 degrees.

ISEP - number of points used to define the separation line.
ZSSEP - Zeta value at which separation is started
ZESEP - Zeta value at which separation is terminated
PHICD - separation angle phiC (degrees)
PHIAD - separation angle phiA (degrees)
BETACD - separation angle BetaC (degrees)
BETAAD - separation angle BetaA (degrees)

[ISSIDE, ISEP, ZSSEP, ZESEP, PHICD, PHIAD, BETACD, BETAAD]

A list of ISEP pairs of points (ZEPZ, ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list for each separation line on a separate line and list in same order as used in the above data.

--- Mesh Size---
IZN Number of zones.
NA Number of cells in xi direction (i.e., between edges 1 and 3)
MA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

--- Flow Properties---
ZETA Zeta coordinate of initial data plane
ALPHA Angle of attack (degrees)
BETA Angle of yaw (degrees)
XMINF Mach number
PINF Pressure
DINF Density
---Problem Definition---

PROBLEM DEFINITION

1 ICORD 0,1,2 for cartesian, cylindrical or elliptic coordinates
1 IASYM 0 - no pitch plane symmetry; 1 - pitch plane symmetry.
1 ISHOCK Set to 1 if edge 3 is to be fitted by the calculation (either as a shock or sonic line); otherwise set to 0.

ISHOCK = 1 is only valid for ICORD = 1 or 2. If edge 3 is to be fitted, the r and phi (cylindrical coordinates) or s, tau (elliptic coordinates) of the shock location on each M plane, (SS, SSZ) must be defined, starting from M = 1, etc..

>>>>>Start list of [SS,SSZ]

.01  5.
.01  15.
.01  25.
.01  35.
.01  45.
.01  55.
.01  65.
.01  75.
.01  85.
.01  95.
.01 105.
.01 115.
.01 125.
.01 135.
.01 145.
.01 155.
.01 165.
.01 175.

>>>>>End list

*****MESH DEFINITION*****

0 IMESHF 0 for uniform mesh in xi direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (FN) in the xi direction at the NA cell centers must be defined starting at cell 1, located adjacent to edge 1 and moving to edge 3 (usually body to shock).

>>>>>start list of FN

>>>>>end list

0 IMESHG 0 for uniform mesh in eta direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (GN) in the eta direction at the MA(i) cell centers in each zone must be defined, starting with zone 1 and ending with zone IZN. Start with cell 1, located adjacent to edge 4, and end at the cell adjacent to edge 2. The list for each zone should be started on a new card

>>>>>start list GN

end list

end list

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6.3.3 Geometry — Wing Section

This section of the hypersonic aircraft is run using a two zone model with NA=72, MAZ(1)=36 and MAZ(2)=36 mesh. The geometry is as follows:

ZONE 1, EDGE 1: \( b = \zeta \tan \theta_c, b_z = \tan \theta_c, b_\phi = 0 \).
ZONE 1, EDGE 2: top of the wing surface, OFFSET = \( \pi/2 \).
ZONE 1, EDGE 3: outer boundary defined outside the bow shock in the free stream.
ZONE 1, EDGE 4: leeward pitch plane symmetry.
ZONE 2, EDGE 1: \( b = \zeta \tan \theta_c, b_z = \tan \theta_c, b_\phi = 0 \).
ZONE 2, EDGE 2: windward pitch plane symmetry.
ZONE 2, EDGE 3: outer boundary defined outside the bow shock in the free stream.
ZONE 2, EDGE 4: bottom of the wing surface, OFFSET = \( \pi/2 \).

The top of the wing surface is described in terms of \( b_I, b_{I_s} \) and \( x_m \) parameters for a flat fin surface (described in Reference 2) as follows:

\[
\begin{align*}
    x_0 &= -2.048642 \\
    x_{LE} &= x_0 - (\zeta - 33.75) \tan 1^\circ \\
    y_{LE} &= (\zeta - 33.75) \tan 12^\circ \\
    x_{ru} &= 2x_0 - x_{LE} \\
    y_{ru} &= 0 \\
    x_m &= (x_{LE} - x_{ru})/(y_{LE} - y_{ru}) \\
    b_I &= x_{ru} \\
    b_{I_s} &= \tan 1^\circ
\end{align*}
\]

Similarly, for the bottom of the wing surface,

\[
\begin{align*}
    x_0 &= -2.048642 \\
    x_{LE} &= x_0 - (\zeta - 33.75) \tan 1^\circ \\
    x_m &= 0 \\
    b_I &= x_{LE} \\
    b_{I_s} &= -\tan 1^\circ
\end{align*}
\]

Knowledge of \( b_I, b_{I_s} \) and \( x_m \) allows the appropriate \( \sigma \) and \( \upsilon \) functions to be calculated using coding described in Reference 2. The wing edges are computed as follows:
Inner Edge: \( \omega = 0 \)

\[ \Omega = 0 \quad \text{if } z < 48.717 \]

Outer Edge: \( \Omega = \sqrt{x_{LE}^2 + y_{LE}^2} \) otherwise

The required geometry routines for the wing section are as follows:

SUBROUTINE BCONST(ZETA, BOFZ, B2OFZ)
C.....THIS SUBROUTINE CALCULATES THE MAJOR AXIS OF AN ELLIPSE
C (BOFZ) AND ITS Z DERIVATIVE (B2OFZ)
RETURN
END

SUBROUTINE EDGE1(IN, ZETA, YY, BT, BZT, BYT)
C.....THIS SUBROUTINE DEFINES EDGE1
C.....USER DEFINES BT, BZT AND BYT AS A FUNCTION OF ZETA (ZETA)
C Y OR PHI (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: BT - X OR R LOCATION OF EDGE 1
C BZT - Z DERIVATIVE OF BT.
C BYT - Y DERIVATIVE OF BT.
BT=0.
BZT=0.
BT=5.08333
IF(ZETA.LE.63.0)THEN
THETAC=4.6
PI=4.*ATAN(1.)
RAD=PI/180.
THETAR=THETAC*RAD
BT=ZETA*TAN(THETAR)
BZT=TAN(THETAR)
BYT=0.
ENDIF
RETURN
END

SUBROUTINE EDGE2(IN, ZETA, XX, THT, THZT, THXT)
C.....THIS SUBROUTINE DEFINES EDGE2
C.....USER DEFINES THT, THZT AND THXT AS A FUNCTION OF ZETA (ZETA)
C X OR R (XX) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: THT - Y OR PHI LOCATION OF EDGE 2
C THZT - Z DERIVATIVE OF THT.
C THXT - X DERIVATIVE OF THT.
CI
PI=4.*ATAN(1.)
RAD=PI/180.
IF(IN.EQ.1)THEN
OFFSET=PI/2.
TAN12=TAN(12.*RAD)
TAN1=TAN(1.*RAD)
Y0=0.
X0=-2.048642
YLE=(ZETA-33.75)*TA.12
XLE=X0-(ZETA-33.75)*TAN1
RLE=SQRT(XLE*XLE+YLE*YLE)
XBWI=XLE
XRU=2.*X0-XBWI
YRU=0.
IF (XX.LE.RLE.AND.ZETA.GE.48.717) THEN
   XM=(XLE-XRU)/(YLE-YRU)
   BI=XRU
   BIZ=TAN1
ELSE
   XM=(XLE-X0)/(YLE-Y0)
   BI=X0
   BIZ=0.
ENDIF
ELSE IF(IN.EQ.2) THEN
   OFFSET=PI
   XM=0.
   BI=0.
   BIZ=0.
ENDIF
XM2P1=XM*XM+1.
SINT=(BI/XX+XM*SQR.(XM2P1-(BI/XX)**2))/XM2P1
COST=SQRT(1.-SINT*SINT)
C1=COST+XM*SINT
THT=OFFSET-ASIN(SINT)
THXT=BI/(XX*XX*C1)
THZT=-BIZ/(XX*C1)
RETURN
END
SUBROUTINE EDGE3(IN, ZETA, PI, CT, CZT, CYT)
C....USER DEFINES CT,CZT,CYT IF BOW SHOCK IS NOT BEING TRACKED.
C     X OR PHI (YY) AND ZONE NUMBER (IN).
C     INPUT: IN - ZONE NUMBER
C     ZETA - ZETA
C     OUTPUT: CT - X OR R LOCATION OF EDGE 3
C     CZT - Z DERIVATIVE OF CT.
C     CYT - Y DERIVATIVE OF CT.
C
PT=4.*ATAN(1.)
RAD=PI/180.
BT=5.08333
IF (ZETA.LE.63.0) THEN
   TAN4P6=TAN(4.6*RAD)
   BT=ZETA*TAN4P6
ENDIF
CFAC1=1.3
CT1=BT*CFAC1
CZT=TAN4P6*CFAC1
CXT=0.
CT2=0.

IF(ZETA.GT.48.717) THEN
  CFAC2=1.1
  TAN12=TAN(12.*RAD)
  TAN1=TAN(1.*RAD)
  X0=-2.048642
  YLE=(ZETA-33.75)*TAN12
  XLE=X0-(ZETA-33.75)*TAN1
  RLE=SQRT(XLE*XLE+YLE*YLE)
  CT2=RLE*CFAC2
  CZT2=CFAC2*(-TAN1*XLE+TAN12*YLE)/RLE
ENDIF
CT=AMAX1(CT1,CT2)
IF(CT2.GE.CT1)CZT=CZT2
RETURN
END

SUBROUTINE EDGE4(IN, ZETA, XX, SGT, SGZT, SGXT)

C.....THIS SUBROUTINE DEFINES EDGE4
C.....THE USER MUST PROVIDE A DEFINITION OF SGT, SGZT, SGXT, AS A FUNCTION
C OF ZETA (ZETA), X OR R (YY) AND ZONE NUMBER (IN).
C INPUT: IN - ZONE NUMBER
C ZETA - ZETA
C OUTPUT: SGT - Y OR PHI LOCATION OF EDGE 4
C SGZT - Z DERIVATIVE OF SGT.
C SGXT - X DERIVATIVE OF SGT.
C
PI=4.*ATAN(1.)
RAD=PI/180.
IF(IN.EQ.1) THEN
  OFFSET=0.
  XM=0.
  BI=0.
  BIZ=0.
ELSE IF(IN.EQ.2) THEN
  OFFSET=PI/2.
  TAN12=TAN(12.*RAD)
  TAN1=TAN(1.*RAD)
  Y0=0.
  X0=-2.048642
  YLE=(ZETA-33.75)*TAN12
  XLE=X0-(ZETA-33.75)*TAN1
  RLE=SQRT(XLE*XLE+YLE*YLE)
  IF(XX.LE.RLE.AND.ZETA.GE.48.717) THEN
    XM=0.
    BI=XLE
    BIZ=-TAN1
  ELSE
    XM=(XLE-X0)/(YLE-Y0)
    BI=X0
    BIZ=0.
  ENDIF
ENDIF
ENDIF
XM2P1=XM*XM+1.
SINT=(BI/XX+XM*SQRT(XM2P1-)(BI/XX)**2))/XM2P1
COST=SQRT(1.-SINT*SINT)
C1=COST+XM*SINT
SGT=OFFSET-ASIN(SINT)
SGXT=BI/(XX*XX*C1)
SGZT=-BIZ/(XX*C1)
RETURN
END
SUBROUTINE PEDGE(IN,II,ZETA,POUTL,PINL)
C
THIS SUBROUTINE CALCULATES THE FIN EDGE LOCATION
C
REQUIRED INPUT
C
IN - ZONE NUMBER
C
II - 1 FOR EDGE 4, 2 FOR EDGE 2
C
ZETA - ZETA
C
C......USER PROVIDES DEFINITION OF POUTL AND PINL
POUTL=0.
PINC=0.
IF(ZETA.GE.48.717)THEN
IF((IN.EQ.1.AND.II.EQ.2).OR.(IN.EQ.2.AND.II.EQ.1))THEN
PI=4.*ATAN(1.)
RAD=PI/180.
TAN12=TAN(12.*RAD)
TAN1=TAN(1.*RAD)
X0=-2.048642
YLE=(ZETA-33.75)*TAN12
XLE=X0-(ZETA-33.75)*TAN1
POUTL=SQRT(XLE*XLE+YLE*YLE)
ENDIF
ENDIF
RETURN
END

6.3.4 CONVERT Input File

The flow field is rezoned from a one zone 36 x 18 mesh into two zones each with a 72 x 36 mesh using the program CONVERT. The input file for CONVERT is as follows:

INPUT file for CONVERT. To execute, append the geometry subroutines BCONST, EDGE1, EDGE2, EDGE3, EDGE4, and PEDGE to CONVERT and execute using this file as input, with () replaced by the desired values and required lists inserted between lines containing >>>>> and <<<<<. Do not delete or add any lines to this file.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IASYMN</td>
<td>symmetry of the final flow field; 1 - symmetric</td>
</tr>
</tbody>
</table>
6.3.5 Zeus Input File — Wing Section

The following ZEUS input file is used for the wing section:

<table>
<thead>
<tr>
<th>VALUE</th>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>114.25</td>
<td>ZETAEND</td>
<td>Terminate calculation if ZETA &gt; ZETAEND.</td>
</tr>
<tr>
<td>5000.</td>
<td>KEND</td>
<td>Terminate calculation if STEP NUMBER &gt; KEND.</td>
</tr>
<tr>
<td>.9</td>
<td>FCFL</td>
<td>Step size safety factor (1. &gt; FCFL &gt; 0.) Typically use .9.</td>
</tr>
<tr>
<td>1.</td>
<td>XKI</td>
<td>Interior point limiting constant (2. &gt; XKI &gt; 0.) Typically use 1.</td>
</tr>
<tr>
<td>0</td>
<td>IAPR</td>
<td>0,1 for approximate or complete Riemann Problem. Typically use 0.</td>
</tr>
</tbody>
</table>
Must use 0 for equilibrium air.

0 ISHFLUX 0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock. Typically use 0.

1 ISHANG 0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use 0. For equilibrium air, a value of 1 is preferred.

*****BOUNDARY CONDITIONS*****

0 NXKE Number of edges at which default limiter setting won’t be used. Default settings are 2 on edges 1 or 3 and 0 on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE)

>>>start list of [KEZ,KEE,XKE]

<<<<end list

2 NSUR Number of edges not featuring default surface types. Default values are 1 on edges 1 and 3 and 0 on edge 2 and 4. Program will automatically account a fitted shock on edge 3 or fin surfaces on edges 2 or 4. For each edge at which the surface type is not of default, add a line that specifies the zone number (KSURZ), edge number (KSURE) and surface type (KSUR).

>>>start list of [KSURZ,KSURE,KSUR]

<<<<end list

.9 DFAC In case of a local wall Mach number which is to small to allow the flow to be turned parallel to the wall, the turn angle is multiplied by the constant DFAC (1. > DFAC > 0.).

*****OUTPUT CONTROL*****

---Printer---

200 IPRINT Print crossflow plane if step number is evenly divided by IPRINT
1 NSKIP Print n planes which are evenly divisible by NSKIP
6 MSKIP Print m planes which are evenly divisible by MSKIP
1 ISKIP Print step size if step number is evenly divided by ISKIP

---PLOTZA/Force-Pressure Summary---

2 JSPFR In default mode, only edge 1 of each zone will be written to PLOTZA. JSPFR is the number of additional edges which are not to be written in the default manner. For each edge added or deleted from this print list, include a line which specifies zone number (JSPZ), edge number (JSPF) and print code (JSP).

JSP = 1 will write this zone edge to PLOTZA. 0 will not.

>>>start list of [JSPZ,JSPF,JSP]

<<<<end list

0 JSPDIS 1 - print grid point locations for the edges specified by JSPFR. 0 - do not print.

1 KSKIP Write surface properties on selected edges to PLOTZA if if STEP NUMBER is evenly divisible by KSKIP
### NAVSWC TR 91-86

**100 NPRT**
On summary sheet, print surface pressures of edges 2 or 4 if \( n < NPRT \).

**1000. DELZA**
Write to PLOTZA if \( (ZETA - ZETA \text{ at last write}) > DELZA \)

--- PLOTZC (Plot file)

**1000. IPLOT**
Write to PLOTZC if STEP NUMBER is evenly divisible by IPLOT.

**1000. DELZC**
Write to PLOTZC if \( (ZETA - ZETA \text{ at last write}) > DELZC \)

**2 IPLOTN**
Number of target Z stations (ZTARGET) at which PLOTZC will be written. If IPLOTN > 0, include a list of these stations on the next line (maximum of 20). Stations must be listed in ascending order.

```plaintext
63.917 108.67
```

---

### *****AERODYNAMIC DATA*****

1. **AREF**
Reference area used in calculating force and moment coefficients.

1. **XLREF**
Reference length used in calculating moment coefficients and center-of-pressure.

0 **IEFORCE**
0, 1 don’t, do print force and moments for individual edges.

### *****SEPARATION MODELING*****

0 **IVIS**
0,1,2 for no modeling, clipping, and forced separation. Clipping and forced separation can only be used in conjunction with cylindrical coordinates. If IVIS = 2, specify the number of separation lines (NSEP).

```plaintext
>>> NSEP
```

For each separation line specify:

- **ISSIDE** - 0 separation line located between 0 and 180 degrees,
  - 1 separation line located between 180 and 360 degrees.

- **ISEP** - number of points used to define the separation line.

- **ZSSEP** - Zeta value at which separation is started

- **ZESEP** - Zeta value at which separation is terminated

- **PHICD** - separation angle phiC (degrees)

- **PHIAD** - separation angle phiA (degrees)

- **BETACD** - separation angle BetaC (degrees)

- **BETAAD** - separation angle BetaA (degrees)

```plaintext
[ISSIDE,ISEP,ZSSEP,ZESEP,PHICD,PHIAD,BETACD,BETAAD]
```

A list of ISEP pairs of points (ZEPZ, ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list for each separation line on a separate line and list in same order as used in the above data.

```plaintext
>>> start list of ZEPZ, ZEPP
```

---

### *****GAS TYPE*****

1 **IGAS**
0-perfect gas; 1-equilibrium air

---

### *****UNITS *****

0 **IUNITS**
0-english \((p=\text{lb/ft}^2, \rho=\text{slug/ft}^3, t=\text{rankine}, xyz=\text{ft})\);
1-metric \((p=n/m^2, \quad \rho=kg/m^3, \quad t=kelvin, \quad xyz=m)\).

All input units must be consistent. Output units are the same.

****INITIAL DATA****

1 IMOD 0,1 for new start or restart respectively. For a restart, the initial flow field is read from TAPE3. Additional information is not needed and the remaining entries in this section should be disregarded. A new start assumes a uniform flow field which is described in the following section.

--- Mesh Size ---

IZN Number of zones.
NA Number of cells in xi direction (i.e., between edges 1 and 3)
MA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

>>>>>Start list of MA for each zone
<<<<<<end list

--- Flow Properties ---

ZETA Zeta coordinate of initial data plane
ALPHA Angle of attack (degrees)
BETA Angle of yaw (degrees)
XMINF Mach number
PINF Pressure
DINF Density

--- Problem Definition ---

ICORD 0,1,2 for cartesian, cylindrical or elliptic coordinates
IASYM 0 - no pitch plane symmetry; 1 - pitch plane symmetry.
ISHOCK Set to 1 if edge 3 is to be fitted by the calculation (either as a shock or sonic line); otherwise set to 0. ISHOCK = 1 is only valid for ICORD =1 or 2. If edge 3 is to be fitted, the r and phi (cylindrical coordinates) or s, tau (elliptic coordinates) of the shock location on each M plane, (SS, SSZ) must be defined, starting from M = 1, etc.,

>>>>>Start list of [SS,SSZ]
<<<<<<End list

****MESH DEFINITION****

0 IMESHF 0 for uniform mesh in xi direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (FN) in the xi direction at the NA cell centers must be defined starting at cell 1, located adjacent to edge 1 and moving to edge 3 (usually body to shock).

>>>>>start list of FN
<<<<<<end list

0 IMESHG 0 for uniform mesh in eta direction. 1 for clustered mesh. If a clustered mesh is to be used, the clustering function (GN) in

53
the eta direction at the MA(i) cell centers in each zone must be defined, starting with zone 1 and ending with zone IZN. Start with cell 1, located adjacent to edge 4, and end at the cell adjacent to edge 2. The list for each zone should be started on a new card.

```

6.3.6 Results

Computations were performed for the hypersonic airplane configuration of Figure 9 at Mach 24.5 and 1° incidence. A comparison of pressure profiles between ZEUS and the Parabolized Navier-Stokes computations of Korte\(^\text{17}\) on the windward symmetry plane at \(z = 108.67\) feet shows good agreement except near the surface where viscous effects are not predicted by ZEUS. In Figure 10, pressure contours are also computed at an axial station near the end of the body \((z = 108.67\) feet) for equilibrium air. Computations illustrate good agreement except in the vicinity of the wing tip where ZEUS does not effectively predict the viscous layer.

6.4 CONCLUDING REMARKS

The ZEUS code has been extended to high Mach numbers by incorporating the high-temperature effects of air in chemical equilibrium. These high-temperature effects are accounted for by using the curve fits of Reference 10 to compute the thermodynamic properties of equilibrium air.

Various hypersonic missile-type bodies were computed including sharp cones, a spherically blunt nosed cylinder and a hypersonic aircraft. ZEUS predicted the smaller shock layer thickness and lower temperatures characteristic of equilibrium chemically reacting air. The computed ZEUS results compare well with measured high-temperature effects and other computational efforts except in regions where viscous effects are dominant. This enhanced version of ZEUS is an economic predictive tool for missiles and will help provide accurate predictions in support of future hypersonic weapons.
FIGURE 1. CARTESIAN AND CYLINDRICAL COORDINATE SYSTEM FOR ZEUS, A SPACE-MARCHING EULER SOLVER
FIGURE 2. CONTROL VOLUME NOMENCLATURE
FIGURE 3. FLOW DISCONTINUITIES IN THE CASE $\frac{V_{\infty}}{a} > 1$ (A.) OBLIQUE SHOCK WAVE (B.) EXPANSION FAN
FIGURE 4. SURFACE (A.) PRESSURES (B.) DENSITIES (C.) TEMPERATURES ON CONES AT AN ALTITUDE OF 100,000 FT. A COMPARISON BETWEEN CALORICALLY PERFECT AND EQUILIBRIUM AIR RESULTS FOR ZEUS AND HUDGINS\textsuperscript{15} COMPUTATIONS
FIGURE 5. COMPUTED PRESSURE CONTOURS FOR A SHARP CONE WITH A 25° HALF-ANGLE AT MACH 20, AN INCIDENCE OF 20°, AND AN ALTITUDE OF 100,000 FT. RESULTS ARE COMPARED BETWEEN (A.) EQUILIBRIUM AIR AND (B.) CALORICALLY PERFECT AIR.
FIGURE 6. DENSITY CONTOURS FOR A HYPersonic SPHERICALLY BLUNT NOSED CYLINDER AT MACH 20 AND AN INCIDENCE OF 0° FOR (A.) CALORICALLY PERFECT AND (B.) EQUILIBRIUM CHEMICALLY REACTING AIR. RESULTS ARE COMPARED WITH COMPUTATIONS OF ZEUS AND PALMER\textsuperscript{16}
FIGURE 7. TEMPERATURE CONTOURS FOR A HYPERSONIC SPHERICALLY BLUNT NOSED CYLINDER AT MACH 20 AND AN INCIDENCE OF 0° FOR (A.) CALORICALLY PERFECT AND (B.) EQUILIBRIUM CHEMICALLY REACTING AIR. RESULTS ARE COMPARED WITH COMPUTATIONS OF ZEUS AND PALMER\textsuperscript{16}
FIGURE 8. COMPUTED DENSITY CONTOURS FOR A HYPERSONIC SPHERICALLY BLUNT NOSED CYLINDER AT MACH 20 AND AN INCIDENCE OF 20° FOR EQUILIBRIUM AIR AT AN AXIAL STATION 9.5 DIAMETERS DOWNSTREAM
Generic hypersonic airplane configuration.\textsuperscript{17}

\textbf{FIGURE 9. COMPARISON OF COMPUTED PRESSURE PROFILES FOR EQUILIBRIUM AIR ON THE WINDWARD SYMMETRY PLANE AT MACH 24.5, AN INCIDENCE OF 1° AND Z = 108.67 FT FOR ZEUS AND THE PNS SOLUTIONS OF KORTE\textsuperscript{17}}
FIGURE 10. COMPARISON OF COMPUTED PRESSURE CONTOURS FOR EQUILIBRIUM AIR AT MACH 24.5, AN INCIDENCE OF 1° AND Z = 108.67 FT FOR ZEUS AND THE PNS SOLUTIONS OF KORTE$^{17}$
REFERENCES

The following file describes the required input for ZEUS. To execute ZEUS, replace the () symbols in the value column with the desired variable value. Add information supporting specific options between the >>>>> and <<<<< symbols. Variables enclosed by [] should be placed by themselves on a line. Do not eliminate any lines from this file.

VALUE VARIABLE DESCRIPTION

*****INTEGRATION CONTROL*****
() ZETAEND Terminate calculation if ZETA > ZETAEND.
() KEND Terminate calculation if STEP NUMBER > KEND.
() FCFL Step size safety factor (1. > FCFL > 0.) Typically use .9.
() XKI Interior point limiting constant (2. > XKI > 0.) Typically use 1.
() IAPR 0,1 for approximate or complete Riemann Problem. Typically use 0. Must use 0 for equilibrium air.
() ISHFLUX 0,1 for using complete Riemann Problem or freestream properties to compute the flux at the cell edge next to the bow shock. Typically use 0.
() ISHANG 0,1 for using complete Riemann Problem or Roe averaged variables to compute shock angle. Typically use 0. For equilibrium air, a value of 1 is preferred.

*****BOUNDARY CONDITIONS*****
() NXKE Number of edges at which default limiter setting won't be used. Default settings are 2 on edges 1 or 3 and 0 on edges 2 or 4. For each edge at which the default limiter is non-standard, add a line containing the following information: zone number (KEZ), edge number (KEE) and limiter value (XKE)

<><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><>
---Printer---

() IPRINT  Print crossflow plane if step number is evenly divided by IPRINT
() NSKIP  Print n planes which are evenly divisible by NSKIP
() MSKIP  Print m planes which are evenly divisible by MSKIP
() ISKIP  Print step size if step number is evenly divided by ISKIP

---PLOTZA/Force-Pressure Summary---

() JSPPR  In default mode, only edge 1 of each zone will be written to
PLOTZA. JSPPR is the number of additional edges which are not
to be written in the default manner. For each edge added or
deleted from this print list, include a line which specifies
zone number (JSPZ), edge number (JSPE) and print code (JSP).
JSP = 1 will write this zone edge to PLOTZA, 0 will not.

>>>start list of [JSPZ,JSPE,JSP]

() JSPDIS 1 - print grid point locations for the edges specified by JSPPR.
0 - do not print.
() NSKIP Write surface properties on selected edges to PLOTZA if
if STEP NUMBER is evenly divisible by NSKIP
() NPRT On summary sheet, print surface pressures of edges 2 or 4 if
n < NPRT.
() DELZA  Write to PLOTZA if (ZETA - ZETA at last write) > DELZA

---PLOTZC (Plot file)

() IPLOT  Write to PLOTZC if STEP NUMBER is evenly divisible by IPLOT.
() DELZC  Write to PLOTZC if (ZETA - ZETA at last write) > DELZC
() IPLOTN  Number of target Z stations (ZTARGET) at which PLOTZC will
be written. If IPLOTN > 0, include a list of these
stations on the next line (maximum of 20). Stations must be
listed in ascending order.

>>>start ZTARGET list

*****AERODYNAMIC DATA*****

() AREF  Reference area used in calculating force and moment coefficients.
() XLREF  Reference length used in calculating moment coefficients and
center-of-pressure.
() IEFORCE 0, 1 don't, do print force and moments for individual edges.

*****SEPARATION MODELING*****

() IVIS  0,1,2 for no modeling, clipping, and forced separation. Clipping
and forced separation can only be used in conjunction with
cylindrical coordinates. If IVIS = 2, specify the number of
separation lines (NSEP).

>>> NSEP

For each separation line specify:
ISSIDE - 0, separation line located between 0 and 180 degrees,
1, separation line located between 180 and 360 degrees.
ISEP - number of points used to define the separation line.
ZSEP - Zeta value at which separation is started
ZSEP - Zeta value at which separation is terminated
PHIC - separation angle phiC (degrees)
PHIA - separation angle phiA (degrees)
BETAC - separation angle BetaC (degrees)
BETAA - separation angle BetaA (degrees)

>>> [ISSIDE, ISEP, ZSEP, PHIC, PHIA, BETAC, BETAA]
A list of ISEP pairs of points (ZEPZ, ZEPP) describing the zeta and phi coordinates of the separation line. This list should start at the most forward section and move aft. Start the list for each separation line on a separate line and list in same order as used in the above data.

ientos list of ZEPZ, ZEPP

*****GAS TYPE*****

() IGAS 0 - perfect gas; 1 - equilibrium air

*****UNITS*****

() IUNITS 0 - english (p=lbf/ft**2, rho=slug/ft**3, t=rankine, xyz=ft);
1 - metric (p=n/m**2, rho=kg/m**3, t=kelvin, xyz=m).
All input units must be consistent. Output units are the same.

*****INITIAL DATA*****

() IMOD 0, 1 for new start or restart respectively. For a restart, the initial flow field is read from TAPE3. Additional information is not needed and the remaining entries in this section should be disregarded. A new start assumes a uniform flow field which is described in the following section.

--- Mesh Size ---

() IZN Number of zones.
() NA Number of cells in xi direction (i.e., between edges 1 and 3)
() MA Number of cells in eta direction (i.e., between edge 4 of zone 1 and edge 2 of zone IZN)

List the number of M planes in each zone, starting from zone 1 and ending at zone MA.

>>>>> Start list of MA for each zone

--- Flow Properties ---

() ZETA Zeta coordinate of initial data plane
() ALPHA Angle of attack (degrees)
() BETA Angle of yaw (degrees)
() XMINF Mach number
() PINF Pressure
() DINF Density

--- Problem Definition ---

() ICORD 0, 1, 2 for cartesian, cylindrical or elliptic coordinates
() IASYM 0 - no pitch plane symmetry; 1 - pitch plane symmetry.
() ISHOCK Set to 1 if edge 3 is to be fitted by the calculation (either as a shock or sonic line); otherwise set to 0. ISHOCK = 1 is only valid for ICORD = 1 or 2. If edge 3 is to be fitted, the r and phi (cylindrical coordinates) or s, tau (elliptic coordinates) of the shock location on each M plane, (SS, SSZ) must be defined, starting from M = 1, etc.,

>>>>> Start list of [SS, SSZ]

---Mesh Definition---

() IMESHF 0 for uniform mesh in xi direction. 1 for clustered mesh. If
a clustered mesh is to be used, the clustering function (FN) in
the xi direction at the NA cell centers must be defined
starting at cell 1, located adjacent to edge 1 and moving to
edge 3 (usually body to shock).
   >>>>>> start list of FN
   >>>>>> end list

() IMESHG 0 for uniform mesh in eta direction. 1 for clustered mesh. If
a clustered mesh is to be used, the clustering function (GN) in
the eta direction at the MA(i) cell centers in each zone must
be defined, starting with zone 1 and ending with zone IZN. Start
with cell 1, located adjacent to edge 4, and end at the cell
adjacent to edge 2. The list for each zone should be started
on a new card
   >>>>>>>>>> start list GN
   end list<>>>>>>
APPENDIX B
SAMPLE CASE OUTPUT

B.1 HYPERSONIC SHARP CONE

B.1.1 ZEUS Output — II

```
1

****** INTEGRATION CONTROL ******
ICON0    1
ZETA    0.10000
ZETEND  50.00000
KSTART   0
KEND    5000
FCFL    0.90000
XMI    1.00000
IAPR    0
ISHFLUX 0
ISHANG  1
(CARTESIAN, 1-CYLINDRICAL COORDINATES)
(INITIAL ZETA)
(MAXIMUM ZETA)
(INITIAL STEP NUMBER)
(MAXIMUM STEP NUMBER)
(CFL SAFETY FACTOR)
(INTEIOR POINT LIMITER)
(0-APPROXIMATE RIEMANN PROBLEM)
(1-COMPLETE RIEMANN PROBLEM)
(FLUX AT SHOCK- 0-RIEMANN PROBLEM)
(1-FREESTREAM PROPERTIES)
(SHOCK ANGLE- 0-RIEMANN PROBLEM)
(1-ROE AVERAGED VARIABLES)

****** BOUNDARY CONDITIONS ******
NAME    1
NSUR    0
DFAC    0.9000
ISHOCK 1
IASYM  1
(SHOCK, 0-NO SHOCK ON EDGE 3)
(NO SYMMETRY- PITCH PLANE SYMMETRY)
(REDUCE TURNS WHICH ARE TOO LARGE BY DFAC)

SURFACE POINT LIMITER
ZONE  EDGE 1   EDGE 2   EDGE 3   EDGE 4
1  2.000 0.000 0.000  0.000

SURFACE TYPE
ZONE  EDGE 1   EDGE 2   EDGE 3   EDGE 4
1  1  0  1  0

****** OUTPUT CONTROL ******
PRINTER (file 6)
IPRINT 250
ISKIP 3
MSKIP 6
(PRINT FLOW FIELD IF STEP NUMBER IS EVENLY DIVISIBLE BY IPRINT)
(PRINT STEP SIZE IF STEP NUMBER IS EVENLY DIVISIBLE BY ISKIP)
(PRINT M PLANES WHICH ARE EVENLY DIVISIBLE BY MSKIP)

B-1
```
PRESSURE SUMMARY (POLTA)

PRESIP = 50 (PRINT SURFACE PRESSURE IF STEP NUMBER IS EVENLY DIVISIBLE BY PRESIP)

PRPT = 100 (DON'T PRINT POINTS IF STEP MOD PRPT)

DELTA = 10000.000 (PRINT SURFACE PRESSURE EVERY ZETA = DELTA)

JSTEP = 0 (NUMBER OF NON DEFAULT EDGES)

JSPOS = 0 (PRINT SURFACE GRID POINT LOCATIONS)

SURFACE PRESSURE OUTPUT CONTROL: 0-DON'T PRINT, 1-PRINT

STEP 1: EDGE 1 EDGE 2 EDGE 3 EDGE 4
1 1 0 0 0

PLOT FILE (POLTIC)

IPLOT = 10000 WRITE TO POLTIC IF STEP NUMBER IS EVENLY DIVISIBLE BY IPLOT

DELZP = 10000.000 (WRITE SURFACE GRID POINT LOCATIONS)

SURFACE PRESSURE OUTPUT CONTROL: 0-DON'T PRINT, 1-PRINT

IPLOTN = 0 NUMBER OF TARGET PLOT STATIONS

AERODYNAMICS DATA****

AREY = 1.0000 (REFERENCE AREA)

AREL = 1.0000 (REFERENCE LENGTH)

IFORCE = 0 (0 = DONT; 1 = DO PRINT EDGE LOADS)

SEPARATION MODELING*****

IVIS = 0 (0 = INVISID, 1 = CLIPPING, 2 = FORCED SEPARATION)

GAS TYPE*****

IGAS = 1 (0-PERFECT, 1-EQUILIBRIUM AIR)

UNITS*****

UNITS = 0 (0-ENGLISH, 1-METRIC)

INITIAL DATA PLANE****

IMOD = 0 (0 SELF START; 1 FROM TAPE S-APT)

MACH = 20.0000 (FREE-STREAM MACH NUMBER)

AREA = 20.0000 (ANGLE OF ATTACK)

R = 0.0000 (RADIUS ANGLE)

PFR = 1185.5000 (FREE-STREAM PRESSURE)

DIF = 1.78632E-02 (FREE-STREAM DENSITY)

MO = 1.72691E-12 (STAGNATION ENTHALPY)

SINF = 0.0000 (FREE-STREAM ENTHALPY)

IZ F = 1 (NUMBER OF ZONES)

NA = 18 (DEGREES BETWEEN EDGES 1 AND 3)

MA = 36 (NUMBER OF ZONES)

MA/ZONE = 36

IMESHF = 0 (0-UNIFORM MESH, 1-CLUSTERED MESH)

BETWEEN EDGES 1 AND 3)

IMESHG = 0 (0-UNIFORM, 1-CLUSTERED MESH

BETWEEN EDGES 2 AND 4)

STEP = 0 BETA = 1.0000000E-01 DIETA = 0.0000000E+00

MACH N. = 2.0000000E-01 ALPHA = 2.0000000E+00 BETA = 0.0000000E+00

ZONE N. = 1

CELL PLANE M -

C = 3.666323E-02 CO = -3.107630E-01 CT = 0.0000000E+00 VX = 9.9954833E-06

Y = 4.6330766E-01 BY = 0.0000000E+00 VY = 0.0000000E+00 VZ = 0.0000000E+00

N S T P D U W E X Y
X 1 1 1.85500E+03 1.74150E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
16 3 2.40500E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
13 3 2.22500E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
10 3 1.05000E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
7 3 1.05000E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
4 3 1.35000E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03
1.5 3.36680E+03 1.85500E+03 2.07950E+03 9.77533E+03 5.71777E+03 7.68700E+03 2.02721E+03

B - 2
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**NAVSWC TR 91-86**

**CELL PLANE M = 12**

C = 3.000000E+01 CE = -3.107613E-01 CT = 0.000000E+00 VX = 5.372995E-01 8.439174E-01 0.000000E+00 0.000000E+00 0.000000E+00 ISUN 3

**CELL PLANE M = 24**

C = 3.000000E+01 CE = -3.107613E-01 CT = 0.000000E+00 VX = 4.643976E+02 4.643976E+00 0.000000E+00 0.000000E+00 0.000000E+00 ISUN 3

**CELL PLANE M = 36**

C = 3.000000E+01 CE = -3.107613E-01 CT = 0.000000E+00 VX = -9.904823E-01 4.381929E+02 0.000000E+00 0.000000E+00 0.000000E+00 ISUN 3

---

**LEFT EDGE PLANE GEOMETRY**

X  Y  Z  S1  S2  S3  S4  S5  DVE  DVE  DVE  DVE  ISUN

---

**LEFT EDGE PLANE**

CEF = 2.542262E+01 BEF = 2.331393E+01

---

**B-3**
### NAVSWC TR 91-86

#### Table 1: Surface Pressures

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<td>0.197E-05</td>
<td>0.197E-05</td>
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</table>

**Note:**
- **ZETA** represents different surface pressures on the ZETA model.
- **1** through **10** denote different angles of attack and Mach numbers.
- The table provides detailed surface pressures at various conditions.

---

#### Table 2: Surface Pressures

<table>
<thead>
<tr>
<th>ZETA</th>
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<th>3</th>
<th>4</th>
<th>5</th>
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<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<tbody>
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<td>0.104</td>
<td>0.592E-05</td>
<td>0.348E-05</td>
<td>0.197E-05</td>
<td>0.197E-05</td>
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<td>0.235E-05</td>
<td>0.356E-05</td>
<td>0.267E-05</td>
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<td>0.273E-05</td>
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<td>0.197E-05</td>
<td>0.21E-05</td>
<td>0.235E-05</td>
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<td>0.273E-05</td>
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<tr>
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<td>0.273E-05</td>
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</table>

**Note:**
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- **1** through **10** denote different angles of attack and Mach numbers.
- The table provides detailed surface pressures at various conditions.

---

#### Table 3: Surface Pressures

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<tbody>
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<td>0.348E-05</td>
<td>0.197E-05</td>
<td>0.197E-05</td>
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<td>0.273E-05</td>
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<tr>
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<td>0.592E-05</td>
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</table>

**Note:**
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- **1** through **10** denote different angles of attack and Mach numbers.
- The table provides detailed surface pressures at various conditions.

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#### Table 4: Surface Pressures

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<td>0.356E-05</td>
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<td>0.273E-05</td>
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</tbody>
</table>

**Note:**
- **ZETA** represents different surface pressures on the ZETA model.
- **1** through **10** denote different angles of attack and Mach numbers.
- The table provides detailed surface pressures at various conditions.

---

**Note:**
- The tables above represent various surface pressures for different ZETA models and 10 different angles of attack.
- The Mach numbers range from 1.000 to 2.500.
- The angles of attack range from 0.000 to 2.000 degrees.
- The tables are designed to evaluate the aerodynamic performance of the ZETA models at various conditions.
- The data is presented in a structured format for easy analysis.
B.2 HYPERSONIC BLUNT NOSE CYLINDER

B.2.1 BLUNT2 Output

1. Hypersonic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

EXTERNAL PARAMETERS: "RENSNE- 0 0 1 0 0 0 0 0 0

| TEST (1) | 1.0000E+04 |
| TEST (2) | 4.0000E-03 |
| TEST (3) | 5.0000E+04 |
| TEST (4) | 5.0000E+04 |
| TEST (5) | 5.0000E+04 |
| TEST (11) | 1.0000E+04 |
| TEST (12) | 1.0000E+04 |

| IG = 1 | AIR |
| 2.8705E+02 | 1.0000E+00 | 1.3990E+00 | 2.3215E+03 | 1.0000E+00 | 0.0265E+01 | 2.3222E+02 | 3.1450E+01 |

1. DEL = 1.0000000E+00
2. INMAX = 2000
3. IJSYM = 1
4. NSTREM = 9
5. FTCONV = 1.0000000E+00
6. IUNITS = 1
7. RN = 5.0000000E+00
8. RN = 5.0000000E+00
9. RN = 5.0000000E+00
10. RN = 5.0000000E+00
11. RN = 5.0000000E+00
12. RN = 5.0000000E+00
13. RN = 5.0000000E+00
14. RN = 5.0000000E+00
15. RN = 5.0000000E+00
16. RN = 5.0000000E+00

FREE STREAM CONDITIONS

ALTITUDE = 20000
1959 ARDC TABLES

| 15.52098E+03 | 2.53209E+04 | 2.16967E+05 | 2.0000000E+01 |
| 1.09458E-03 | 2.14662E+02 | 1.00000E+00 | 1.36678E+00 | 1.36678E-06 |

91 ENTRIES IN SHOCK TABLE |

| U1/01/MW | 1.00000E+00 |
| U1/01/MAX | 1.00000E+00 |

PSTAG = 2.9485E+05
TSTAG = 3.3519E+05
RHOSTG = 1.09458E+03
GSTAG = 1.1845E+00
HTOT = 1.7468E+07

PHS = 2.8032E+06
TSH = 3.3519E+05
RHOSTH = 1.09458E+03
GSH = 1.1845E+00
HSH = 1.7468E+07
SRSH = 3.8222E+01
AMSH = 2.4524E+01

SHH = 7.0792311E+01

1. Hypersonic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

DEFAULT SPHERICAL GEOMETRY USED

RN = 5.00000E+00

1. Hypersonic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

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<th>RBTH</th>
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B-6
### Hyperbolic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

<table>
<thead>
<tr>
<th>STP</th>
<th>TIME</th>
<th>DELTA</th>
<th>PSTAG</th>
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<th>UWI/01(MIN)</th>
<th>UWI/01(MAX)</th>
<th>UWI/QI(MIN)</th>
<th>UWI/QI(MAX)</th>
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### Hyperbolic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

<table>
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<th>TIME</th>
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### Hyperbolic Blunt Nose Cylinder, M=20, Alpha=0, Alt=20,000 m

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**PLANE M = 24**  
**PHI = 0.1750**

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**PLANE M = 30**  
**PHI = 0.1470**

B-10
B.2.2 ZEUS Output

1. **PROGRAM ZEUS**

B-11
**NAVSWC TR 91–86**

****INTEGRATION CONTROL****

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<tbody>
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<tr>
<td>INIT</td>
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<tr>
<td>MINT</td>
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</tr>
<tr>
<td>MAXI</td>
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<tr>
<td>CFL</td>
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<td>IAFR</td>
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(0-CARTESIAN, 1-CYLINDRICAL COORDINATES)

(INITIAL ZETA)

(INITIAL STEP NUMBER)

(MAXIMUM STEP NUMBER)

(CFL SAFETY FACTOR)

(INNER POINT LIMITER)

(0-APPROXIMATE Riemann Problem)

(1-COMPLETE Riemann Problem)

(FLUX AT SHOCK-0-Riemann Problem)

(1-PRESTREAM PROPERTIES)

(SHOCK ANGLE - 0-Riemann Problem)

(1-MOE AVERAGED VARIABLES)

****BOUNDARY CONDITIONS****

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<td>DFAC</td>
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<td>ISHOCK</td>
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<td>IASYM</td>
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(NUMBER OF EDGES WITH NON-DEFAULT LIMITER SETTINGS)

(NUMBER OF EDGES WITH NON-DEFAULT SURFACE TYPE)

(REDUCE TURNS WHICH ARE TOO LARGE BY DFAC)

(1-SHOCK, 0-NO SHOCK ON EDGE 3)

(0-NO SYMPETRY, 1-PITCH PLANE SYMMETRY)

SURFACE POINT LIMITER

<table>
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<tr>
<th>ZOMP</th>
<th>EDGE 1</th>
<th>EDGE 2</th>
<th>EDGE 3</th>
<th>EDGE 4</th>
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<td>1</td>
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SURFACE TYPE

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<th>EDGE 3</th>
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****OUTPUT CONTROL****

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<tr>
<td>IPRINT</td>
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<tr>
<td>ISKIP</td>
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<tr>
<td>NSKIP</td>
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<tr>
<td>MSKIP</td>
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(PRINT FLOW FIELD IF STEP NUMBER IS EVENLY DIVISIBLE BY IPRINT)

(PRINT STEP SIZE IF STEP NUMBER IS EVENLY DIVISIBLE BY ISKIP)

(PRINT M PLACES WHICH ARE EVENLY DIVISIBLE BY MSKIP)

(PRINT M PLACES WHICH ARE EVENLY DIVISIBLE BY MSKIP)

PRESSURE SUMMARY (PLOTZA)

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<td>NPTT</td>
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<td>JSPPR</td>
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<td>JSOIS</td>
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(PRINT SURFACE PRESSURE IF STEP NUMBER IS EVENLY DIVISIBLE BY KSkip)

(DON'T PRINT POINTS IF NPTT)

(PRINT SURFACE PRESSURE EVERY ZETA = DELZA)

(NUMBER OF NON-DEFAULT EDGES)

(PRINT SURFACE GRID POINT LOCATIONS)

SURFACE PRESSURE OUTPUT CONTROL: 0-DON'T PRINT, 1-PRINT.

<table>
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<tr>
<th>ZONE</th>
<th>EDGE 1</th>
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<th>EDGE 3</th>
<th>EDGE 4</th>
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PLOT FILE (PLOTZC)

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(WRITE TO PLOTZC IF STEP NUMBER IS EVENLY DIVISIBLE BY IPLOT)

(WRITE TO PLOTZC IF STEP NUMBER IS EVENLY DIVISIBLE BY IPLOT)

(NUMBER OF TARGET PLOT STATIONS)

(0.5 DATA 10.00000)

****AERODYNAMICS DATA****

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(REFERENCE AREA)

(REFERENCE LENGTH)

(0 = DO PRINT, 1 = DONT)

****SEPARATION MODELING****

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<tr>
<td>VISL</td>
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</table>

(0 = DON'T CLIP, 1 = CLIPPING)

(0 = DONT, 1 = DO FORCE SEPARATION)

****GAS TYPE****
**NAVSWC TR 91-86**

**IGAS** = 1 (O-PERFECT EQUILIBRIUM AIR)

**UNITS** = 1 (O-ENGLISH, 1-METRIC)

**INITIAL DATA PLANE**

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<tr>
<td>BETA</td>
<td>0.0000 (YAW ANGLE)</td>
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<td>FINT</td>
<td>559.8779 (FREE-STREAM PRESSURE)</td>
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<tr>
<td>NO</td>
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<td>DIPF</td>
<td>0.0000 (FREE-STREAM ENTHALPY)</td>
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<tr>
<td>INX</td>
<td>1 (NUMBER OF ZONES)</td>
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<tr>
<td>MA</td>
<td>36 (CELLS BETWEEN EDGES 1 AND 3)</td>
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<tr>
<td>MA/E</td>
<td>36 (TOTAL CELLS BETWEEN EDGES 2 AND 4)</td>
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**CELL PLANE**

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B-13
### NAVSWC TR 91-86

**SECANT METHOD IN DECODE DID NOT CONVERGE FOR M,N**

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<th>S3</th>
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**LEFT EDGE PLANE CEFT**

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<th>S2</th>
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(1)
**Abstract**

The extension and application of the ZEUS code to high, hypersonic Mach numbers by incorporating high-temperature equilibrium air or "real gas" effects is described. This approach is important for accurate aerodynamic predictions in sonic weapons. The ZEUS code is a space-marching Euler solver. It uses an automatic multiple zone grid generation technique and a finite volume, second-order Godunov scheme for steady supersonic flow. High-temperature effects are achieved by using curve fits of the thermodynamic properties of equilibrium air. Sample calculations for a sharp cone and a blunt-nosed cylinder are provided.
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