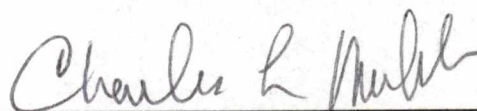


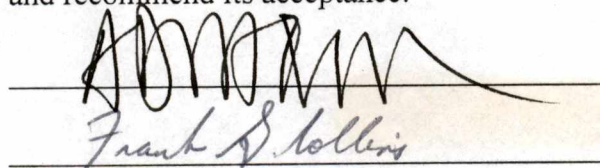
To the Graduate Council:

I am submitting herewith a thesis written by Brian Edward Roebuck entitled "A Method Using Computational Fluid Dynamics for Evaluating a Correlation for Shock Shape with a Temperature Gradient over Spherical Nose Bodies in Perfect Gas Air." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

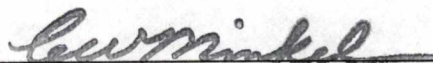


Charles L. Merkle, Major Professor

We have read this thesis  
and recommend its acceptance:



Accepted for the council:



Associate Vice Chancellor and  
Dean of the Graduate School

**A Method Using Computational Fluid Dynamics  
for Evaluating a Correlation for Shock Shape  
with a Temperature Gradient over Spherical  
Nose Bodies in Perfect Gas Air**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee,

Knoxville

Brian Edward Roebuck

December 1998

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## **Abstract**

In this study a correlation for determining shock shape around spherical bodies at supersonic velocity in perfect gas air with a temperature gradient is evaluated using a computational fluid dynamics flow solver. The work is inspired by Russian experimentation with shock shape changes in weakly ionized gases where possible temperature gradients exist in the flow field. Some background information and references are given to support this data. The technique involves the use of a known flow solver (ZTUFF code) with minor modifications made to add the capability of introducing radial temperature gradients across the flow field. The resulting non-uniform flow field produces shock shape results that differ from those obtained in a uniform flow field that can be useful to determine temperature gradients in real flow field scenarios. The shock shape correlation work of Billig (4) is evaluated for accuracy with temperature gradients. The ZTUFF code is used to obtain perfect gas two dimensional axisymmetric inviscid temperature gradient solutions for Mach numbers of 2.35, 5.0 , and 8.0 and Reynolds numbers of 9750, 20616 , and 32064 respectively around a spherical body of 0.019 meters diameter. The correlation is then used to create similar shock shape curves to determine the accuracy of the correlation versus the ZTUFF code results with an identical temperature gradient. It is found that the correlation is accurate for positive linear temperature gradients but not for negative linear temperature gradients over the range of Mach numbers presented herein with inviscid perfect gas solutions.

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## Nomenclature

|            |                                                                       |
|------------|-----------------------------------------------------------------------|
| $a$        | Speed of sound                                                        |
| $\beta$    | Mach angle for spherical body shapes                                  |
| CFL        | Courant number for setting time step in time dependant flow solvers   |
| $k$        | Boltzmann Constant                                                    |
| $m$        | Mass of a particle                                                    |
| $M$        | Mach number                                                           |
| $M_\infty$ | Free stream Mach number                                               |
| $M_l$      | Local Mach number                                                     |
| PTG1       | Non dimensional pressure term for ZTUFF                               |
| PTG2       | Non dimensional temperature term for ZTUFF                            |
| PTG3       | Ratio of specific heats ( $\gamma$ ) term for ZTUFF (non dimensional) |
| Q1         | Non dimensional density term for ZTUFF                                |
| Q2         | Non dimensional x direction velocity term for ZTUFF                   |
| Q3         | Non dimensional y direction velocity term for ZTUFF                   |
| Q4         | Non dimensional z direction velocity term for ZTUFF                   |
| Q5         | Non dimensional energy term for ZTUFF                                 |
| $r$        | Radial distance from sphere centerline to any grid cell center        |
| $r_{MAX}$  | Radial distance from sphere centerline to furthest grid cell center   |
| $R$        | Gas constant                                                          |
| $R$        | Radius of sphere                                                      |
| Re         | Reynolds number                                                       |

|               |                                                                     |
|---------------|---------------------------------------------------------------------|
| $R_c$         | Shock curve radius of curvature in Billig correlation               |
| RF            | Radio frequency energy                                              |
| STUFF         | Space dependant version of TUFF flow solver                         |
| T             | Temperature                                                         |
| $T_l$         | Local gas temperature                                               |
| $T_{LOCAL}$   | Local gas temperature                                               |
| $T_\infty$    | Free stream gas temperature                                         |
| TUFF          | Time dependant Computational Fluid Dynamics flow solver             |
| V             | Gas velocity                                                        |
| $V_\infty$    | Free stream gas velocity                                            |
| X             | Distance from stagnation point of sphere along x axis               |
| ZTUFF         | Zonal version of TUFF flow solver                                   |
| $\delta$      | Shock stand off distance from stagnation point of sphere            |
| $\gamma$      | Ratio of specific heats for air                                     |
| $\rho$        | Density of gas                                                      |
| $\rho_\infty$ | Free stream gas density                                             |
| $\Delta T$    | Change in temperature                                               |
| $\xi$         | Number of quadratic terms used to describe the energy of a particle |

## **Abbreviations**

|     |                                                          |
|-----|----------------------------------------------------------|
| CFD | Computational Fluid Dynamics                             |
| TVD | Total Variation Diminishing (refers to type of CFD code) |
| WIG | Weakly Ionized Gas                                       |

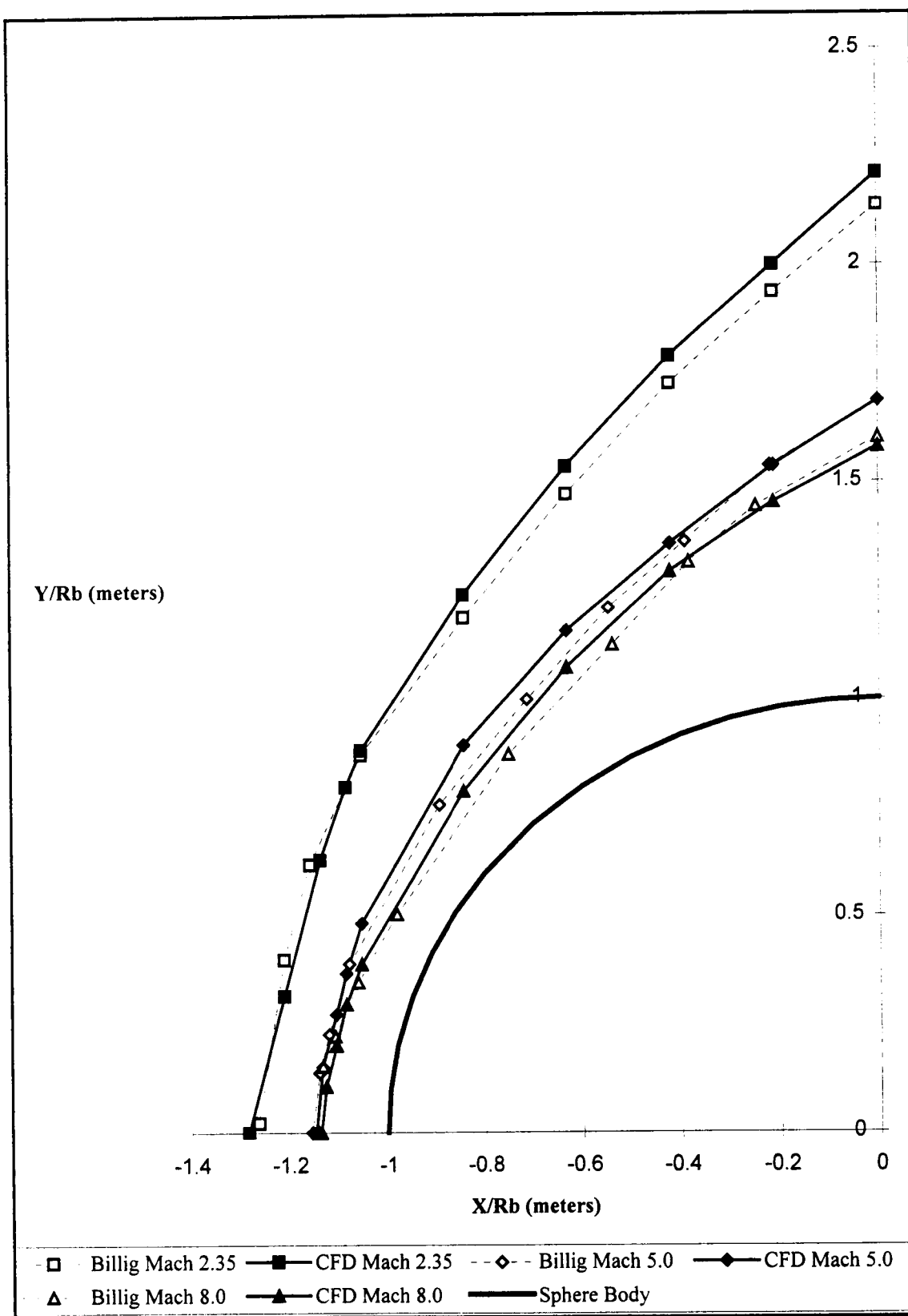
# Chapter I

## Introduction

The study of shock waves around bodies in supersonic and hypersonic flow has traditionally been characterized in simple form using perfect gas air in a uniform flow field. A large body of work has been done with these simplified conditions creating the basis for research into more complex flows. Correlations by Billig [1; 4] and others were devised consisting of simple algebraic equations that allow the researcher to easily create good plots of the shock structure around bodies (including spherical noses) at a wide range of velocities. The Billig correlation accuracy versus CFD for uniform flow is shown in figure 1. This type of correlation is adequate for studying initially uniform flow fields with perfect gas chemistry. Recent experiments require investigation of the effects of possible gradients across the flow field to better understand the results of shock shape seen around a sphere travelling at a supersonic velocity through a weakly ionized gas plasma field. The Russians [2]; [3]; [5]; [9]; [10]; [11]; [13] have experimented with Weakly Ionized Gas (WIG) flow field phenomena from the 1970's to the present. Weakly ionized gas is defined as any gas with an ionization level of 1 part in  $10^5$  -  $10^6$ . Research has been done elsewhere [7] that duplicates and expands on the work done by the Russians. The experiments with plasmas have been done in ballistic ranges, shock tubes, and wind tunnels using various gases at many different Reynolds numbers. The results have been categorized

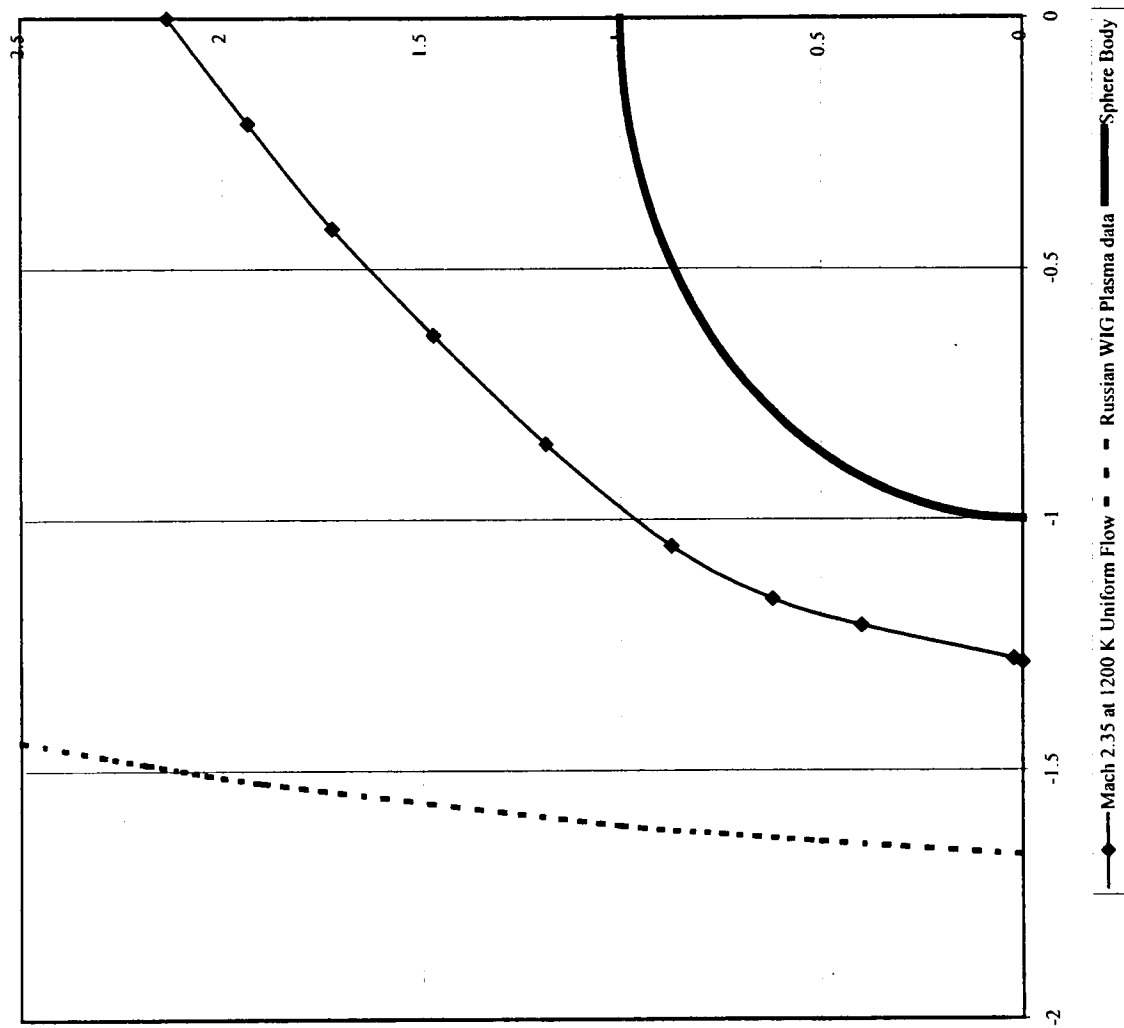
Figure 1 Billig correlation versus CFD results.

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by Hilbun [7] and others as the following changes in the characteristics of a shock in a WIG plasma: the shock velocity increases while the shock front spreads and disperses; shock precursors may appear in some instances; shock strength is reduced and aerodynamic drag is modified; and lastly the heat flux to the surface of the object is reduced in a plasma while the shock standoff distance is increased. Figure 2 shows the change in shock shape from uniform flow at the estimated temperature of the WIG flow (1200 K) for the same Mach number. The change in shock shape and stand off distance is easily seen in this figure. As a consequence of the change in chemistry, energy, and equilibrium several additional flow field gradients may be present in WIG plasma fields. These gradients formed in the weakly ionized gas zone of the flow field may have an effect on the local speed of sound that heavily influences the local shock shape as well as the stand off distance at the stagnation point. For a perfect gas the equation for the speed of sound involves the ratio of specific heats ( $\gamma$ ), the gas constant ( $R$ ), and the temperature ( $T$ ) of the gas. In a perfect gas where  $\gamma$  and  $R$  are constant perhaps the most obvious parameter that can affect the speed of sound is temperature. This change in parameter would also be the simplest approach to solve using Computational Fluid Dynamics flow solvers since the equations governing perfect gases need not be modified in any of the codes now available for supersonic flow solutions. The intent of this study is to investigate the effects of temperature gradients across perfect gas air through which a sphere is passing at supersonic velocity and to evaluate a correlation between shock shape and temperature gradient.

Figure 2. Uniform flow versus WIG flow at Mach 2.35 and 1200 K



Other effects of WIG plasma fields on shock shape will be not be investigated within this thesis.

Developments in Computational Fluid Dynamics have allowed the researcher to model supersonic flow around bodies with good agreement between computational and experimental results. This technique will also be used to investigate temperature gradients in supersonic flow fields with simple modifications to an existing CFD code. The results will then be used to evaluate a correlation for spherical nose bodies in a supersonic flow that will allow perfect gas flow parameters to be obtained from experimental shock shape data in thermally non-uniform flows.

## **Background**

Experimental data gathered by the Russians [2]; [9]; [10]; [11] and others [7] have shown that the shock shape preceding a supersonic sphere is greatly changed as it passes through a WIG plasma field. Experimenting with WIG fields shows the shock in part has a different stand off distance at the stagnation point and exhibits differences in curvature elsewhere. Various methods have been used to acquire experimental data with supersonic flow through weakly ionized gas. Ballistic ranges have launched conductive and non conductive spheres through a plasma, shock tubes have created shock waves within plasmas, and aerodynamic surfaces have been tested in the presence of erosive plasma jets [7]; [9]. The experiments used to inspire the idea for this thesis comes from Russian tests run in ballistic ranges. Ballistic range data using a sphere in air at supersonic velocities provides a chance to observe the

characteristics of plasma shocks in a weakly ionized gas. Stationary zones of plasma can easily be generated along the sphere flight path with instrumentation placed strategically to capture the event. Observations of the plasma during actual experiments usually revealed visually non-uniform glow discharge regions and other inconsistencies in the plasma. It has been observed [15] that often the areas of plasma appeared as parallel vortices. Attempts at measuring the temperatures in the WIG plasma field resulted in apparent temperature gradients and uncertainties as well as the occasional melted tungsten probe tip. It was uncertain if rotational, vibrational, translational, or some combination of these temperatures were being measured. Shadowgraph and the other data and observations suggest that the WIG plasma field used in these experiments contained gradients in some parameters of the flow field ultimately affecting the shape of the shock wave. The presence of a non-uniform glow discharge plasma in experiments suggests that the temperature increases to the gas associated with plasma generation also include temperature gradients in the plasma region of the gas.

Several researchers [2]; [6]; [7]; [13] have attempted to explain the shock shape altering properties of weakly ionized gases. Most have concluded that there are mechanisms in a weakly ionized gas responsible for changing the local speed of sound of the gas that in turn have a significant effect on the shock structure of supersonic flow around bodies. Researchers tend to agree that other phenomena exist in weakly ionized gases that relate to the components of the gas, its' energy state, and how it reacts to the gradients of a shock wave as it passes through the plasma.

The research into weakly ionized gas effects on shock characteristics has included many different types of experiments to create plasma of uniform strength throughout the desired area. This has been especially difficult in ballistic range testing due to the radio frequency (RF) apparatus, cathode plates, and anodes used to create the WIG plasma [2]; [7]; [9]; [10]; [11]. As shown below in figure 3 the Russians and other researchers [7] used a stationary plate as a cathode set just above the flight path of the projectile (sphere) with three parallel quartz tube insulated copper anode rods mounted below the flight path. An appropriate power supply was used to provide the radio frequency energy between them in order to create a weakly ionized gas plasma in the region between the plates (flight path). As stated previously there have been

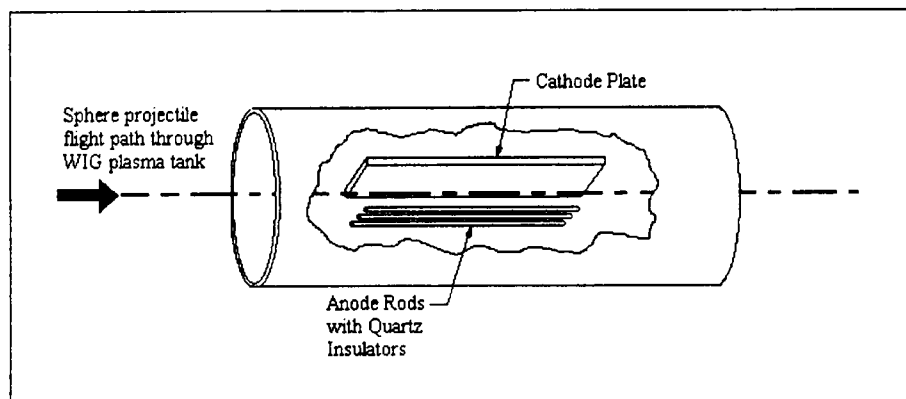


Figure 3. Russian weakly ionized gas (WIG) apparatus as configured in test tank. Cathode length is approximately three meters with a separation distance from the anode rods of approximately 60 millimeters.

attempts to measure the WIG parameters in these regions using various methods and equipment [15] but they have not been very successful to date. The temperature profile has been one of the more difficult parameters to characterize in these experiments. Russian experiments in ballistic ranges used an estimated plasma temperature of 1200 K on the sphere's flight path. Outside Russia experimenters have reported [15] that the use of radio frequency generators described earlier to create a weakly ionized gas results in non-uniform areas of ionization.

In a weakly ionized gas 1 in  $10^5 - 10^6$  of the molecules become positively charged to form ions that coexist with electrons of negative charge and the remaining neutrally charged molecules. The resulting area of ionized molecules moves around mixing with the gas particles around them. The Coulomb force between the ions and electrons keeps the electrons near the ions but their separation allows the electrons to collide with other particles. High gas temperatures can cause dissociation of air molecules. Eventual molecular recombination can result in various combinations of nitrogen and oxygen rather than air. Enough energy is released into the plasma that tungsten probe tips can melt [15] when exposed to the plasma field. Experiments [7] have shown that a shock forming in this type of plasma field creates an electric double layer due to the diffusion of electrons and ions at the shock front. Electrons of negative charge build up in front of the shock while ions of positive charge cluster just behind the shock. The electrons having less mass and smaller collision cross section than the other particles travel more easily across the large gradients in pressure, density, and temperature at the shock front. At the same time the ions stay

behind the shock front restricted in their separation distance from the electrons by the attractive Coulomb force between them. As discussed by Hilbun [7] the Coulomb forces may be one of the principle reasons behind the change seen in shock stand off distance. The large collision cross section ions are forced by Coulomb forces to stay close to the electrons that are in turn attempting to move further ahead of the shock front. The resulting momentum from this phenomenon could result in the increase in shock stand off distance as well as alter the shape of the entire shock wave. On the other hand this non-equilibrium portion of the flow can also lead to temperature increases in the electrons that could exceed the heavier neutral particles by up to fifty times according to Hilbun [7]. The electrons possess a high energy state as they cross the shock front and have a very high temperature when compared to the neutral particles. Vibrational modes of the particles can become excited [2] thus leading to higher vibrational temperatures for the plasma. This increase in flow energy has much to do with the phenomena seen in WIG plasmas. The ability of electrons to cross a supersonic shock boundary allows for the flow behind the shock to influence the flow ahead of the shock. Since the electrons can cross the shock front boundary they can have significant impact upon the gas dynamics before the shock is formed and therefore alter the shock itself due to the change in the gas molecular weight, the energy in the gas, and the Coulomb forces present. The known computational codes written for un-ionized gases do not take into account the possibility of flow parameter information travel upstream across a supersonic shock boundary. In order to use the codes (ZTUFF included) to model some of the effects of WIG plasma flow these non-

equilibrium plasma effects must be broken down into more simple components that CFD codes are written to solve. The effects are broken down into categories of energy addition [2]; [5]; [6], change in chemistry [7], electron travel across the shock, intermolecular forces [2]; [7], and other phenomena. The first two categories can be modeled with temperature changes using a computational fluid dynamics flow solver. The last three categories will take some additional equations, experimental results, and plasma flow property measurements to model. Some of the effects of high temperature electrons throughout the gas could possibly be characterized by thermal gradients across the field. Since it is very difficult to obtain exact temperature variations within a plasma (as well as other measurements) and the plasma field itself is not uniform [15] it is theorized that some amount of temperature non-uniformity has been introduced by the plasma field. These possible non-uniform flow conditions lead to the use of CFD as a tool to investigate the effects of temperature non-uniformity in otherwise uniform flow fields through the modeling of temperature gradient flow fields.

## **Correlation Concepts**

Existing correlations for shock shape were created using perfect gas relations in a uniform flow field. One of these, the Billig correlation, [1]; [4] has been used to attempt to create a similar shock shape to the data taken from ballistic range experiments shooting a sphere through a standing WIG plasma field. In all cases there

was never a way to match experimental shock shape and position results with Billigs' equations using a uniform flow field. Felderman [15] found that using a non-uniform flow field approach did allow near matching of experimental data to the Billig correlation equations by varying the free stream Mach number parameter for the shock stand off equation and the shock curvature equation. Felderman [15] was able to get good matching to the experimental WIG data by using one Mach number to get the correct stand off distance and another Mach number to introduce the shock curvature matching the experimental shock data. Since the Mach number is directly related to temperature by the speed of sound equation ( $a = \sqrt{\gamma RT}$ ) it can be concluded that a temperature gradient across the flow field would affect the shock shape. Changes in the ratio of specific heats would also affect the speed of sound and the shock shape. Ironically changes in this parameter are driven by the local gas temperature which is difficult to measure in the plasma. Local differences in these two parameters can affect the local speed of sound and change the local Mach number of the flow affecting the local Mach angle and hence the overall shock shape. The gas constant R is also changed all across the shock boundary since the molecular weight of the extra electrons contributes to the total gas weight in front of the shock and the deficit of electron weight affects the ion laden gas behind the shock under these conditions. The exact composition of the gas is difficult to ascertain under experimental conditions especially when one considers that the electrons appear to cross the shock boundary ahead of the air molecules creating this difference in molecular make-up on either side of the shock boundary. Experimental data [15] also

shows molecular dissociation is present in air plasma at temperatures near 2000 degrees K with recombination into gas other than air after cooling. Since the static temperature of the Russian experiment plasma [2]; [9] is estimated as 1200 degrees K it is likely the vibrational temperatures are higher due to the intermolecular collisions [2] that could create the dissociation phenomenon. Hilbun [7] reports vibrational temperatures ten times higher in standing WIG plasma fields without the gradient of a shock present.

The speed of sound in WIG plasma can be estimated by using the method outlined in Anderson [1] where the ratio of specific heats is estimated by the equation  $\gamma = 1/\xi (\xi + 2)$  where  $\xi$  is the total number of quadratic terms used to describe the energy of the particle. These quadratic terms represent equations for energy in the form of translational, rotational, and vibrational modes which depend on molecular structure and energy level to be fully excited. For monatomic molecules  $\xi$  equals 3 and for diatomic molecules (air etc.) it equals 5. These values hold true for “normal temperatures” but are changed at high energy levels when the molecules become fully vibrationally excited adding one more quadratic term. For air this occurs at about 600 K or above. When fully vibrationally excited the value of  $\xi$  is 6 for diatomic molecules. Thus the value of  $\gamma$  ranges from 1.333 to 1.4 for air at the temperature range within the scope of this thesis. Further a value of  $\gamma$  for the electrons should be 1.5 to 1.666 since they are a monatomic particle.

Since electrons have such low mass ( $9.109 \times 10^{-31}$  kg) and small collision cross section they appear to act as if they were a separate gas from the ions and neutrals of the WIG plasma. The speed of sound for electrons can be estimated by the familiar speed of sound equation  $a = \sqrt{\gamma RT}$  replacing the gas constant  $R$  with  $k/m$  where  $k$  is the Boltzmann constant and  $m$  is the mass of an electron. For a temperature of 1200 K the speed of sound calculates to approximately 175,000 meters / second. Since the temperature of the WIG electrons could be higher this number could increase accordingly. The speed of sound for the neutrals and ions at the same temperature is approximately 757 meters / second. The electron speed of sound at the above conditions is about 200 times faster than the other particles in the flow. Electrons can cross neutral and ion particle shock boundaries in the WIG flow since they have such a higher speed of sound. As temperatures increase in the flow the difference in sound speed only gets larger while the value of  $\gamma$  for all WIG particles get smaller.

## **Chapter 2**

### **TUFF Code and Modification Details**

The TUFF Computational Fluid Dynamics code was developed by Molvik and Merkle [14] to allow second order accurate solutions to the thin layer Navier Stokes Equations used to model supersonic and hypersonic flow fields. This code is of the Total Variation Diminishing (TVD) finite volume type based on the Osher scheme [8]. The Tuff code employs second order accurate boundary condition routines at each boundary. It is normally configured for air as the fluid however the code is capable of solving viscous, chemically reacting gases in three dimensions in both space marching (STUFF version) and time marching (TUFF version) modes. TUFF is a fully implicit upwinding time dependent code. STUFF has the feature of the much faster converging space dependant mode for modeling fully supersonic flow fields. The original versions of the code have been modified to allow further options to be used for complex geometry problems. These options [12]; [14] were created to allow the use of multiple zonal grids (sub-grids) and various boundary conditions needed with these sub-grids including the grid metrics needed to input an outflow boundary solution from one grid to the inflow boundary of the next grid. This version of the code is also ideal for modification of a single grid problem with the desire to change the inflow boundary conditions from the uniform inflow boundary in the original version of the code. This version of the code with multiple zonal grid and

boundary condition options (sometimes known as ZTUFF) is the version used for the work presented herein.

The ZTUFF code as written could not be configured to model hypersonic flows with radial temperature gradients without some modifications to the flow field parameters. The code normally calculates a uniform flow field as the inflow boundary based on the information supplied in a start-up file. The boundary condition for a typical hypersonic flow solution is normally Dirichlet at the inflow making this set-up correct for most all desired solutions. Modeling a sphere in hypersonic flow with a uniform Dirichlet inflow is easily and accurately done using options in ZTUFF for two dimensional axisymmetric operation. Several runs were made to verify the correct operation of the code and to gain familiarity with the proper operation of all the options. An existing code written by Maus in working with Felderman [15] to create a TUFF compatible grid for a spherical body was used to create the grid for the code runs that modeled the Russian ballistic range sphere shot geometry. This code was slightly modified to write calculated grid point position data to a file for use in the creation of a radial temperature gradient in the flow field. A further modification was made to create the output file (grid file) from this code allowing it to be used with ZTUFF. A line was added to create data for the number of grids used for the solution of the problem (only one grid was used for this problem). All solutions to hypersonic flow problems were nearly identical to those plotted from the Billig correlation [1]; [4] when uniform flow fields were modeled. Some smearing out of the shock, typical for this type of numerical simulation code, is evident in all cases as observed in figure

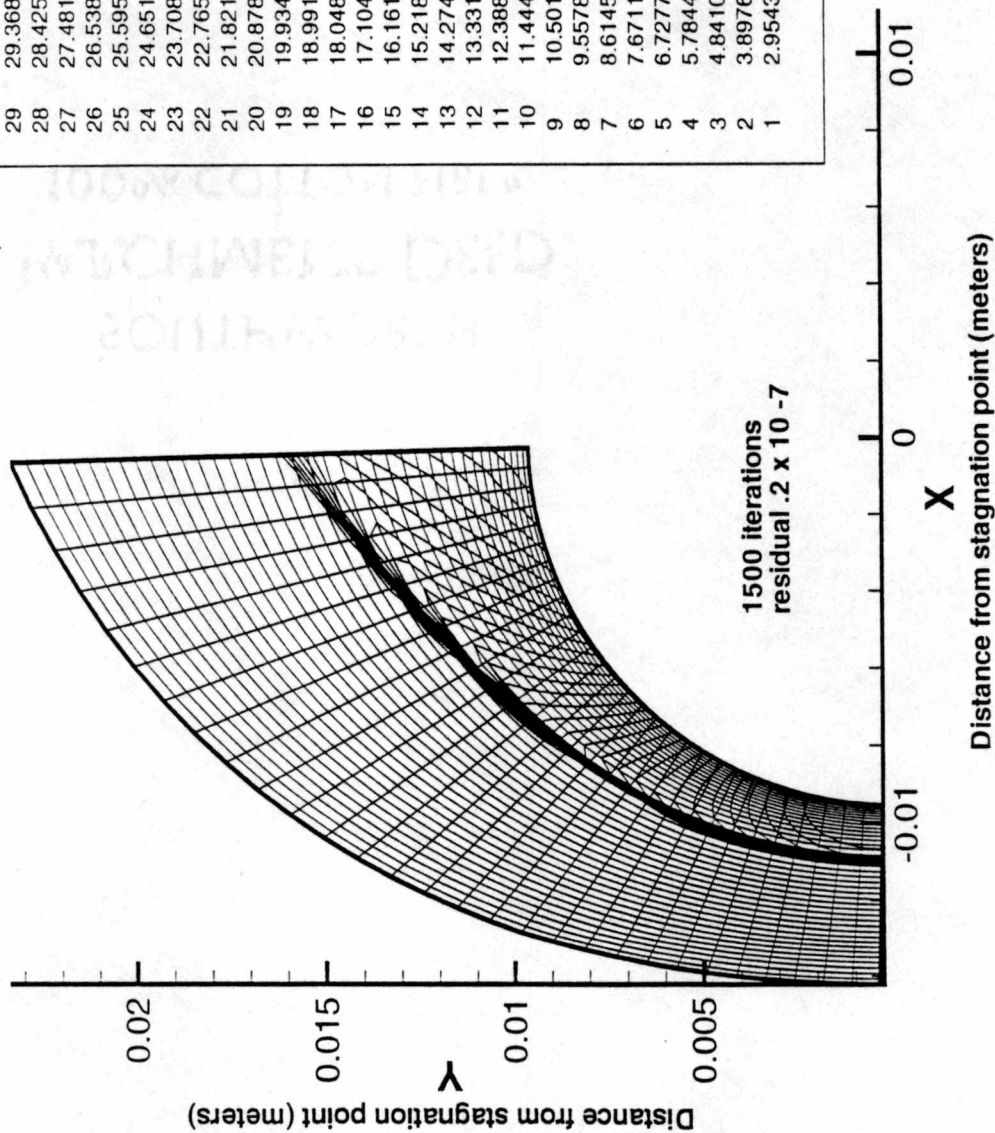
4. A grid size of 31 by 41 points created a good capture of the shock shape whereas doubling the number of points resulted in a slightly less smeared shock where the cost in computational time was more than doubled with no measurable gains in accuracy as shown in figure 5.

The concept for creating a non-uniform flow field begins with the study of how the ZTUFF code functions. In ZTUFF the flow field data for each problem are read in from a file called 'ztufdat' that contains many of the options for operation of the code as well as the inflow data (table 1). These data are then manipulated in a subroutine named 'initia' that applies uniform flow throughout the entire computational domain. Other code options may require calls to additional subroutines to create additional flow field data such as chemistry effects, viscous effects, and other flow parameters. From there the program calls many other subroutines to continue the process of convergence to a solution according to the options selected.

The options selected for running ZTUFF for these simulations of a sphere in hypersonic air were chosen to simplify the problem and be consistent with the work of Billig [4] and others to allow evaluation of a correlation based upon Billig's work. Perfect gas air at relatively low temperatures allows the use of a ratio of specific heats equal to 1.4 over a reasonably large range of Mach numbers. To speed convergence and reduce complexity inviscid flow was modeled in a two dimensional axisymmetric sense. By choosing inviscid flow the Navier-Stokes equations reduce to the Euler

Figure 4. Typical ZTUFF solution to a free stream perfect gas flow at Mach 5.0

### Mach 5.0 free stream



| P | 30      | 29      | 28      | 27      | 26      | 25      | 24      | 23      | 22     | 21      | 20      | 19      | 18      | 17      | 16      | 15      | 14      | 13      | 12      | 11     | 10      | 9       | 8       | 7      | 6       | 5       | 4       | 3       | 2       | 1       |
|---|---------|---------|---------|---------|---------|---------|---------|---------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|---------|---------|---------|---------|
|   | 30.3119 | 29.3685 | 28.4252 | 27.4818 | 26.5384 | 25.5951 | 24.6517 | 23.7083 | 22.765 | 21.8216 | 20.8782 | 19.9349 | 18.9915 | 18.0481 | 17.1048 | 16.1614 | 15.2181 | 14.2747 | 13.3313 | 12.388 | 11.4446 | 10.5012 | 9.55786 | 8.6145 | 7.67114 | 6.72777 | 5.78441 | 4.84104 | 3.89768 | 2.95431 |

Figure 5. 61 x 41 point computational grid solution for Mach 5.0 perfect gas flow.

Mach 5.0 free stream solution  
with 41 x 61 size grid at 1300 K

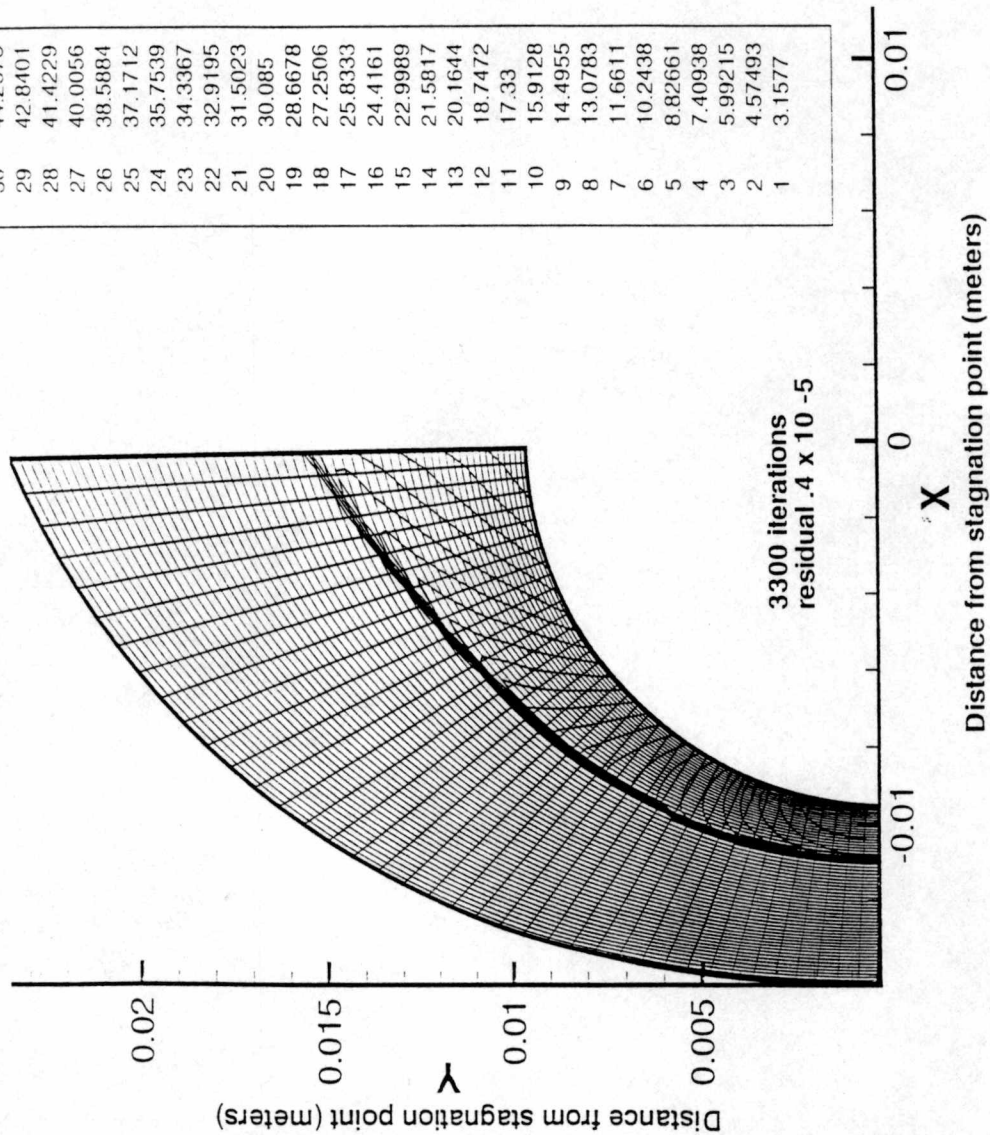


Table 1. ZTUFF input file ('ztufdat') parameters.

|        |                                                                                                                                                                                                               |
|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IDIMEN | Number of dimensions used. ie 2-D Axisymmetric IDIMEN= 2 (or for 3-D = 3) etc.                                                                                                                                |
| IREADQ | Use IREADQ= 0 for the first run and subsequently use 1 for all restarts.                                                                                                                                      |
| IOUT   | Print out frequency for the output file. Usually set to 100 iterations or more.                                                                                                                               |
| CFL    | Courant Number. Start with a small one and work up to larger values each restart.                                                                                                                             |
| VARDT  | Use .True., for variable time steps or .False., for no variable time steps.                                                                                                                                   |
| ITMAX  | Number of Newton (inner) iterations per step. You must use at least 1 iteration.                                                                                                                              |
| NITER  | Number of iterations desired for this run.                                                                                                                                                                    |
| NEIG   | Number of iterations between screen writes.                                                                                                                                                                   |
| TVD    | Total Variation Diminishing algorithm parameter.                                                                                                                                                              |
| PHIOSH | Osher algorithm parameter.                                                                                                                                                                                    |
| EPU    | Set to 0.1                                                                                                                                                                                                    |
| EPC    | Set to 0.1                                                                                                                                                                                                    |
| PITCH  | Used for pitch angle of attack problems. This is zero for sphere models.                                                                                                                                      |
| YAW    | Used for yaw angle of attack problems. This is also zero for sphere models.                                                                                                                                   |
| RINFD  | Density in lb/ft <sup>3</sup> for the inflowing (free stream in this case) flow field.                                                                                                                        |
| QINFD  | Velocity in ft/sec for the inflowing (free stream in this case) flow field.                                                                                                                                   |
| TINFD  | Temperature in degrees R for the inflowing (free stream in this case) flow field.                                                                                                                             |
| CSINF  | Gas chemistry species parameters for the flow gas.                                                                                                                                                            |
| IMODEL | Variable to select which of four modes to run ZTUFF. Use 1 for perfect gas, 2 for equilibrium chemistry, 3 for frozen chemistry, and 4 for non- equilibrium flow.                                             |
| TWALLD | Wall temperature in degrees R of model.                                                                                                                                                                       |
| IAXISY | Use value of 1 for axisymmetric computation or zero otherwise.                                                                                                                                                |
| ITURB  | A value of zero uses no turbulence model.                                                                                                                                                                     |
| IFORCM | Used for force balance calculations when angle of attack model is desired. Set to zero otherwise.                                                                                                             |
| ZMACH  | Mach number of inflowing gas.                                                                                                                                                                                 |
| RE     | Reynolds number of inflowing gas.                                                                                                                                                                             |
| ABASE  | Base diameter for cone models in inches.                                                                                                                                                                      |
| XCG    | Center of gravity of body in the x direction.                                                                                                                                                                 |
| YCG    | Center of gravity of body in the y direction.                                                                                                                                                                 |
| ZCG    | Center of gravity of body in the z direction.                                                                                                                                                                 |
| XEND   | Position of aft end of body in x direction.                                                                                                                                                                   |
| TKEINF | Free stream turbulence value                                                                                                                                                                                  |
| ZMTINF | Free stream                                                                                                                                                                                                   |
| EMSVTY | Body emissivity term.                                                                                                                                                                                         |
| TIMFLT | Time of flight.                                                                                                                                                                                               |
| THRMDF | Thermal body parameter                                                                                                                                                                                        |
| ZKBODY | Body width parameter                                                                                                                                                                                          |
| ITRNSN | Transition parameter                                                                                                                                                                                          |
| XTRNSN | Transition parameter                                                                                                                                                                                          |
| IBC    | Boundary conditions [x,x,x,x,x,x] at [I=1, i=I <sub>max</sub> 1, j=1, j=J <sub>max</sub> 1, k=1, k=K <sub>max</sub> 1], where (1= reflective, 2= nonreflective, 3= fixed, 4= blunt body, 5= continuous, etc). |
| IVBC   | Viscous zone BC's [x,x,x,x,x,x] where 0 = inviscid and 1 = viscous no slip.                                                                                                                                   |
| IVBCT  | Adiabatic BC's [x,x,x,x,x,x] where 0= adiabatic, 1 = const Temp, 2 = Radiative Equilibrium, and 3 = time of flight.                                                                                           |
| IVBCC  | Catalytic BC's [x,x,x,x,x,x] where 0= non catalytic and 1 = catalytic.                                                                                                                                        |
| NZONAL | Zero for no zonal grid option, number of grids otherwise.                                                                                                                                                     |
| IVIS   | Zero for inviscid in i direction.                                                                                                                                                                             |
| JVIS   | Use 1 for viscous in j direction.                                                                                                                                                                             |
| KVIS   | Zero for inviscid in k direction.                                                                                                                                                                             |

equations. To initialize the flow solver with a temperature gradient the entire flow field is recalculated to include a temperature gradient at every cell center consistent with the radial position from the sphere centerline. This is done instead of simply initializing the temperature gradient across only the inflow boundary values. Initializing the entire grid allows the code to more rapidly converge to a solution since an inflow only gradient does not require time (iterations) to propagate the gradient through the domain. Using this initialization has the disadvantage of introducing more instability into the numerical solution in the initial iterations than is evident with uniform flow. The CFL number for the first several hundred iterations must be kept low enough for the solution to damp somewhat before it can be increased to hasten convergence. The use of the option of inner Newton iterations can also be used to speed convergence and has been used for the solutions presented in this study. The inflow boundary must be defined as a "continuation" boundary for this solution which is one of the boundary options available with ZTUFF. This boundary condition requires the inflow parameters to be continuous with time. Later chapters will expand on these concepts and provide greater details.

## Chapter 3

### Temperature Gradient Program

A simple program was written to allow the calculation of all perfect gas flow parameters for each cell in the computational domain with a radial temperature gradient for the two dimensional axisymmetric case. The subroutine 'initia' could have been modified to do what is required for a temperature gradient flow field. This however would have changed the original ZTUFF program to some degree and it was as effective to write a separate small program to change the flow initialization parameters to temperature gradient conditions as changing the subroutine 'initia'. Use of a separate program allows the original code to remain untouched while giving the user freedom to use the option of a temperature gradient flow field initialization. A program called 'infloball' was written for the case of a hypersonic sphere in perfect gas flow using a two dimensional axisymmetric grid. The assumptions for program 'infloball' are that the body is spherical, the coordinate system is cylindrical, the gas is perfect gas air with a ratio of specific heats ( $\gamma$ ) equal to 1.4, and grid point position data in the radial direction can be read in from a file. This program uses output data from ZTUFF to initialize the flow field after running ZTUFF for a few iterations. The uniform flow field data is then transformed to gradient field data using 'infloball' which calculates only those data that are changed by the temperature gradient and writing over the uniform flow data. The modified temperature gradient data in 'infloball' are then written to a restart file that ZTUFF can use to continue to run with.

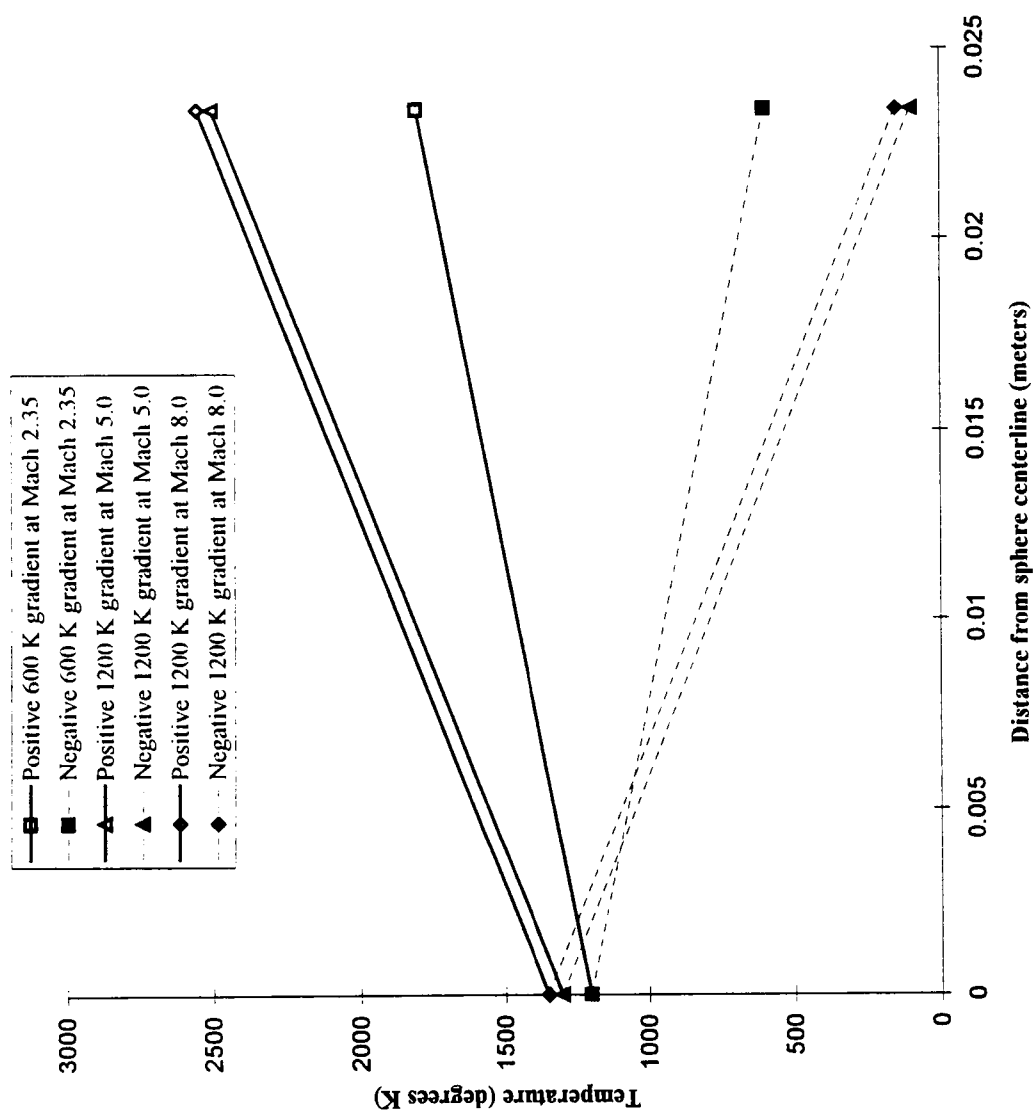
No further changes are required to the flow field data since the inflow boundary condition is set as continuous and all other boundaries remain the same as for a uniform flow field simulation.

The program 'infloball' contains code to read grid point position data from the file 'infrad.grd' which is a file created by the grid generation program that contains data on the radial position of each cell in the grid. Using an equation for linear, parabolic, or other temperature gradient from 'infloball' creates temperature values for each cell center based on radial position from the sphere centerline and the overall temperature difference between the far field and sphere centerline. Temperature difference data must be input into 'infloball' using a simple data file 'deltee.inp' to specify the desired total change in temperature ( $\Delta T$ ) and the type of gradient desired (linear, parabolic, etc). One more file called 'zpgas.inp' is read by 'infloball' to get the matching perfect gas parameters that are also used by 'ZTUFF' for each code run. While the program 'infloball' could have been initialized with flow field data with the same file 'ztufdat' as used for ZTUFF, using a separate file for input of these perfect gas parameters was a more simple way to assure that the resulting temperature gradient field would have correct input data. Note that the perfect gas parameters in 'zpgas.inp' must match the same data in 'ztufdat' for the flow field to be correctly initialized. To illustrate the effect of temperature gradient on shock shape a simple

function was chosen [15] to create useful gradient data across the flow field (see figure 6). The equation  $T_{LOCAL} = T_{\infty} + \Delta T \left( \frac{r}{r_{MAX}} \right)^n$  was devised to allow linear, parabolic, and cubic (  $n = 1, 2$ , and  $3$  respectively ) gradients to be created for temperature where the sphere centerline temperature remained constant. Any suitable function could be substituted in to allow other gradients in the radial direction. Linear and parabolic gradients lead to smooth changes in the shock shape as expected and no other functions were attempted for this body of work. Using a  $\Delta T$  value with either a positive or a negative value would cause far field temperatures to increase or decrease respectively by the absolute value of  $\Delta T$  with the appropriate change in value radially according to the gradient function chosen across the field for all cells. A change in centerline temperature using the method in this thesis involves simply running a free stream solution with the desired centerline temperature uniformly across the flow field. The solution is allowed to run for a hundred iterations to initialize the flow field and the output file used as the start solution for 'infloball' with the desired temperature gradient function and parameters input as described to simulate the gradient flow conditions.

In the process of writing a program compatible with the existing program ZTUFF the importance of creating non-dimensionalized parameters that have the same form as those in ZTUFF cannot be understated. Many CFD solvers use similar equation forms for the equations of motion, energy, and chemistry that differ significantly in the way they are non-dimensionalized. The exact form of these is not

Figure 6 Typical Radial Linear Temperature Gradient



always readily available [16] and difficult to “back out” from the internal program values for these parameters as the solver is run. The following forms are correct for the ZTUFF version of this flow solver for the perfect gas parameters only. The flow parameters calculated for each cell center are non-dimensionalized in the following manner consistent with ZTUFF:

The non-dimensional density term  $Q1 = \frac{\rho}{\rho_{\infty}} = \frac{P_{\infty}}{\rho_{\infty} R T_{\infty}} = \frac{T_{\infty}}{T}$ ,

The non-dimensional x velocity term  $Q2 = \frac{\rho v}{\rho_{\infty} v_{\infty}} = Q1$  since  $v = v_{\infty}$ ,

The non-dimensional y velocity term  $Q3 = 0.0$ ,

The non-dimensional z velocity term  $Q4 = 0.0$ ,

The non-dimensional energy term  $Q5 = \frac{1}{\gamma(\gamma - 1)M_{\infty}^2} + \frac{Q1}{2}$

The non-dimensional pressure term  $PTG1 =$  the value already calculated in subroutine ‘initia’ since this does not change in the case of temperature gradients,

The non-dimensional Temperature term  $PTG2 = \frac{T_{LOCAL}}{T_{\infty}}$  (specified by the temperature gradient equation used in ‘infloball’),

The value for ratio of specific heats for air  $PTG3 = \gamma = 1.4$ .

Using these equations for the flow parameters ‘infloball’ simply recalculates the values and writes them to an array for use by the ZTUFF program for a restart file.

Before using this modified restart file the inflow boundary condition must be specified as a continuation boundary in order to maintain the temperature gradient in a temporal sense throughout the grid. This program is written for perfect gas only but modifications for more complex flows within the abilities of ZTUFF to solve can be made quite easily. Since 'infloball' is based on the ZTUFF subroutine 'initia' it would be possible to create another version of 'infloball' to use the other subroutines in ZTUFF ( as does 'initia') to calculate the other useful flow field parameters of interest. In this case the use of 'ztufdat' to initialize a modified 'infloball' with all the important flow parameters would be the logical choice. The next section concerns obtaining solutions to the hypersonic flow of a sphere in a temperature gradient using the ZTUFF flow solver.

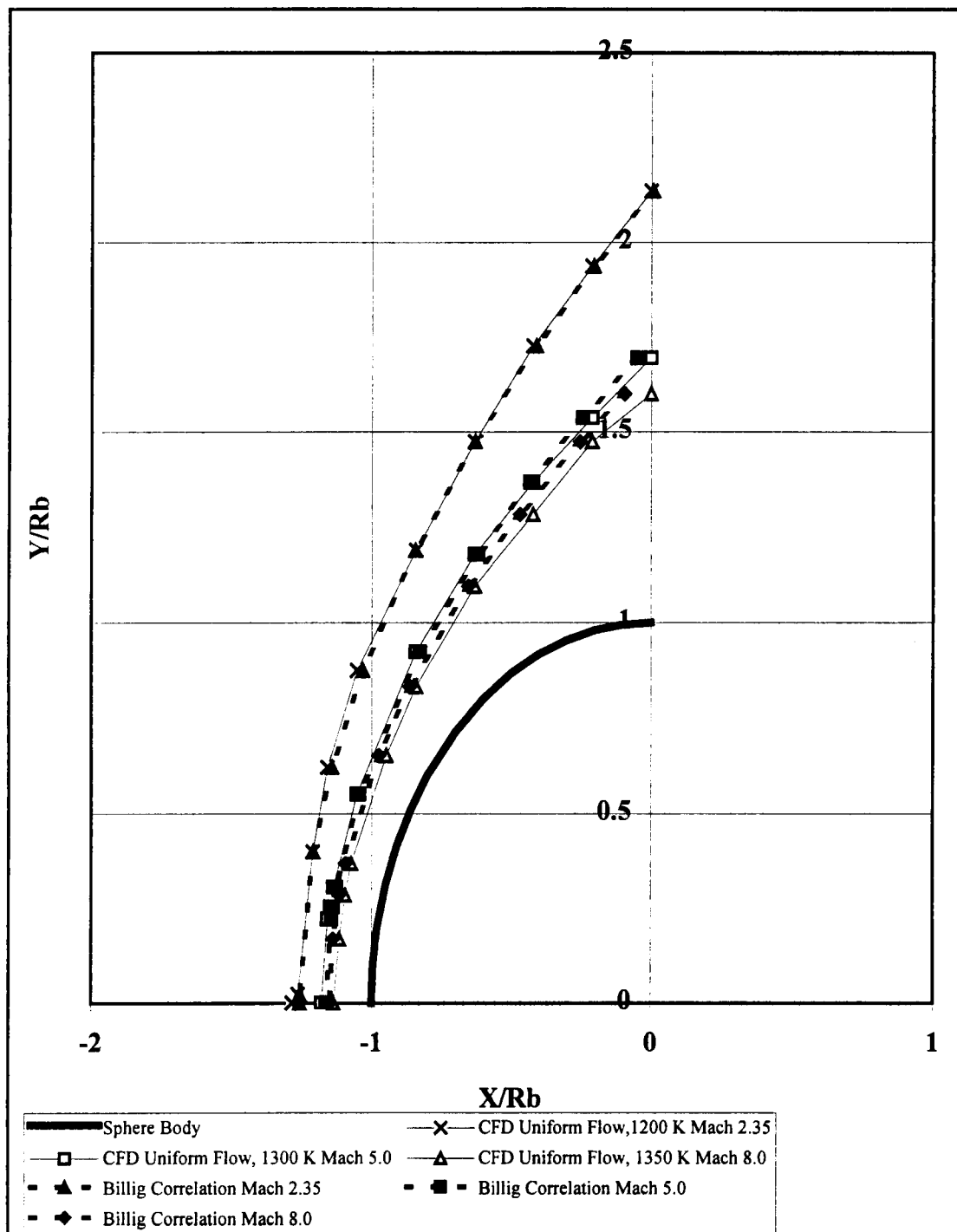
## Chapter 4

### Solutions with a Radial Temperature Gradient

The previous chapters include the background of this thesis and some of the concepts required to use a computational fluid dynamics flow solver to model a perfect gas flow of air with a radial temperature gradient over a sphere at hypersonic velocities. This chapter will detail the method for achieving solutions for temperature gradient flow with ZTUFF and present the results.

To begin any serious study of computational fluid dynamic flow simulations it is wise to run several baseline solutions to assure correct results are obtained, obtain data for comparison, and to familiarize oneself with the operations of the flow solver [16]. Several solutions at various Mach numbers and Reynolds numbers shown in figure 7 were achieved and checked against the shock shape curves from the Billig correlation for accuracy. These baseline solutions were all perfect gas two dimensional axisymmetric inviscid solutions using ZTUFF as the flow solver. The sphere diameter, flow gas (air), grid size, and grid spacing were held constant in all cases. It was desired to duplicate the conditions of the Russian ballistic range experiment [3]; [9]; [10]; [11] with one of these baseline solutions to assure that it matched the non-plasma shot data with reasonable accuracy. With an estimated temperature of 1200 K the Mach number for the Russian data is 2.35. The other solutions (table 2) represent a portion of the range of conditions that the Billig correlation has demonstrated accuracy for in creating shock shapes. These solutions

Figure 7. ZTUFF solutions versus Billig correlation plots for free stream perfect gas.



| <b>Table 2. Flow conditions for ZTUFF solutions and Billig correlation curves.</b> |          |         |                             |       |          |                      |
|------------------------------------------------------------------------------------|----------|---------|-----------------------------|-------|----------|----------------------|
| Mach #                                                                             | Temp (K) | V (m/s) | $\rho$ (Kg/m <sup>3</sup> ) | Re    | P (torr) | $\mu$ (KG/ms)        |
| 2.35                                                                               | 1200     | 1632    | 0.01478                     | 9750  | 40       | $470 \times 10^{-7}$ |
| 5.0                                                                                | 1300     | 3614    | 0.01478                     | 20616 | 40       | $492 \times 10^{-7}$ |
| 8.0                                                                                | 1350     | 5892    | 0.01478                     | 32064 | 40       | $516 \times 10^{-7}$ |

represent conditions from Mach 2 through Mach 8. The resulting ZTUFF inviscid two dimensional axisymmetric solutions in figures 8 through 10 were checked against the curves generated with the Billig correlation and found to be very similar. Grid size can be important in determining solution accuracy. Use of a too few grid points results in fast solutions of poor accuracy. Too many grid points gives good accuracy but takes longer to converge on a solution. It is also important to choose the grid spacing correctly. In this case points are clustered more tightly near the sphere body where the body interacts with the flow making the cell sizes in this region of the grid smaller than those at the far field region. As mentioned previously doubling the grid size to 41 by 61 by 2 points had little effect on accuracy and only served to increase the run time of the solution. The smaller 31 by 41 by 2 point axisymmetric grid was used for all solutions with ZTUFF. Solution to the temperature gradient flow fields was accomplished according to the methods of chapter 2 with the grid described above. At first several different temperature values from sphere centerline to far field

Figure 8. ZTUFF solution for free stream Mach 2.35

### Mach 2.35 at 1200 K free stream flow

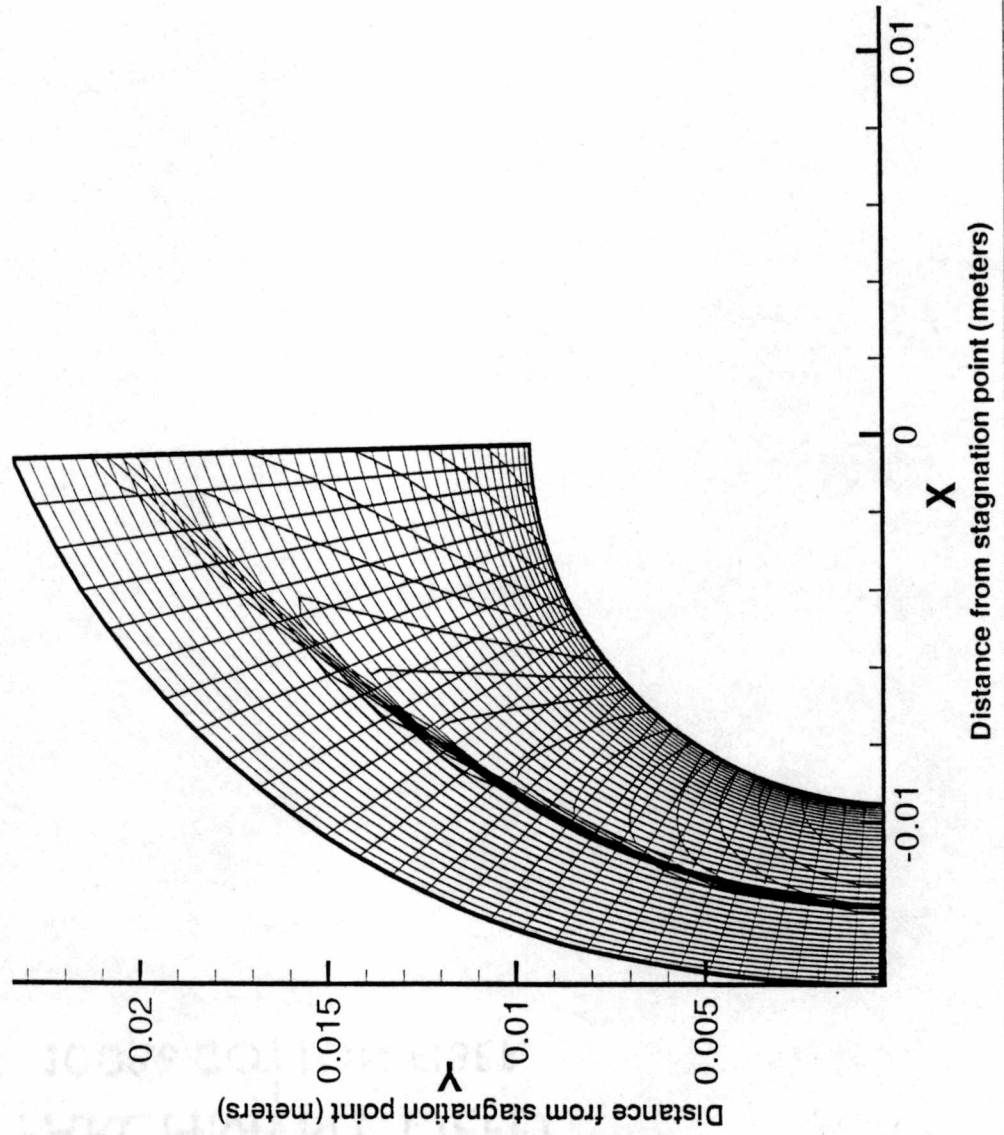


Figure 9. ZTUFF solution for free stream Mach 5.0

Mach 5.0 free stream

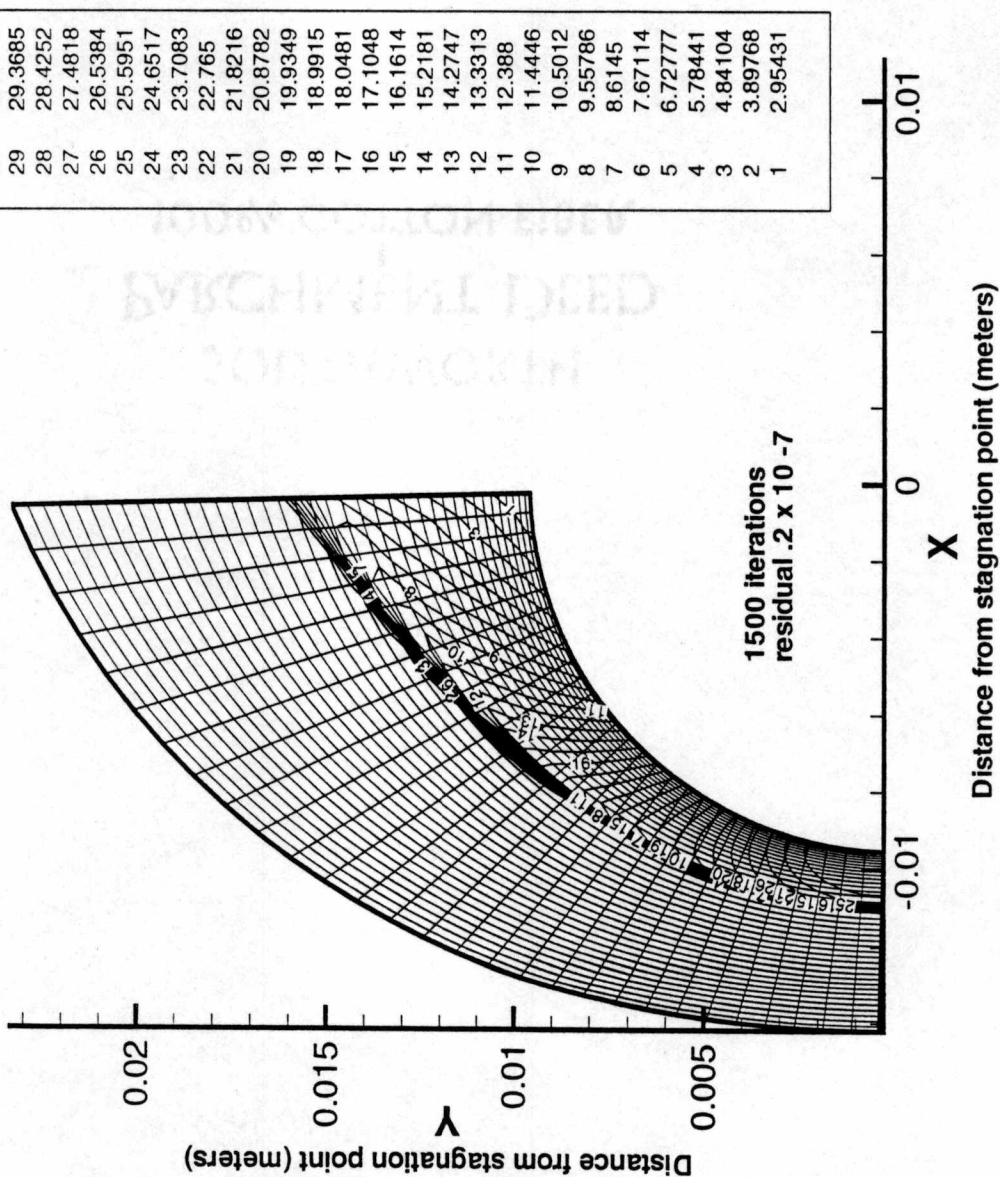
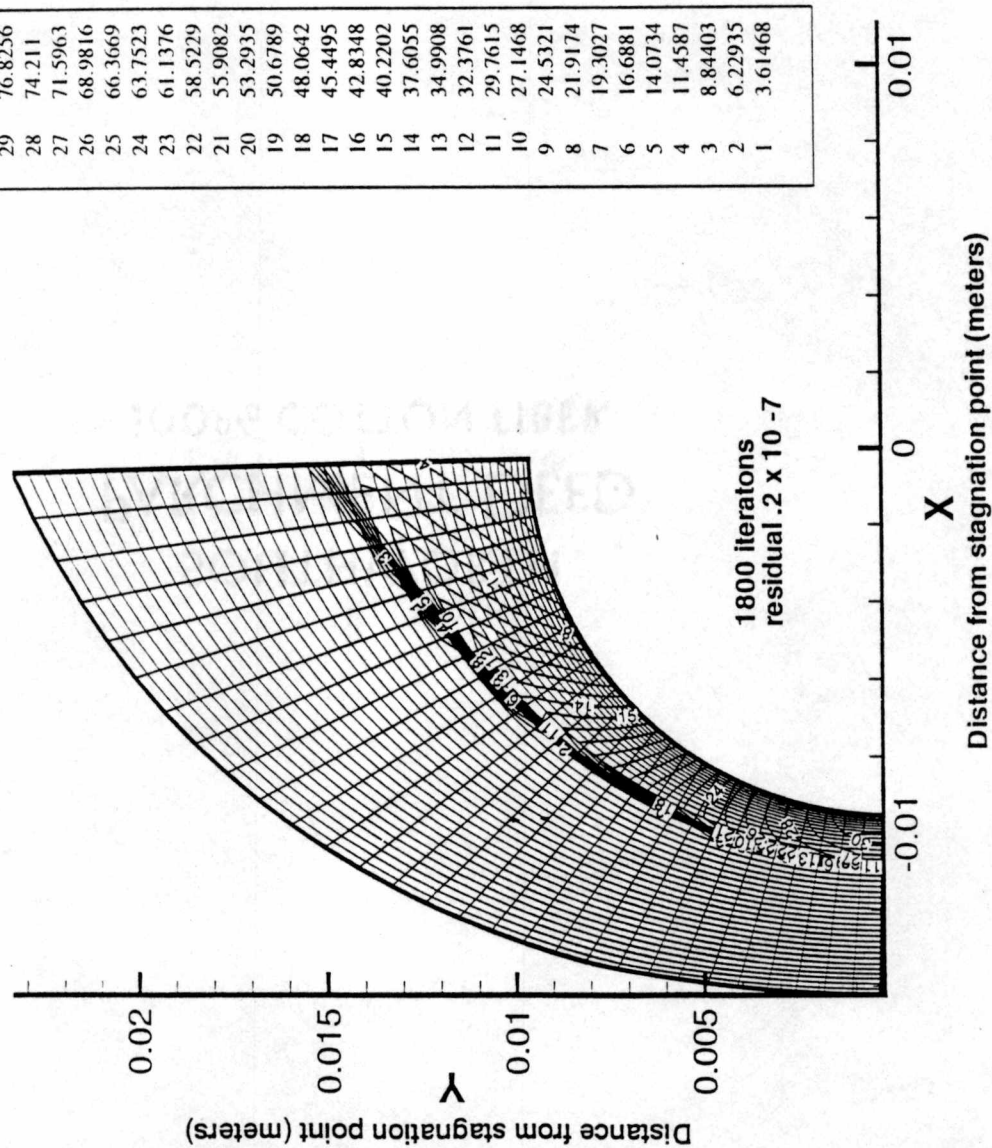


Figure 10. ZTUFF solution for free stream Mach 8.0

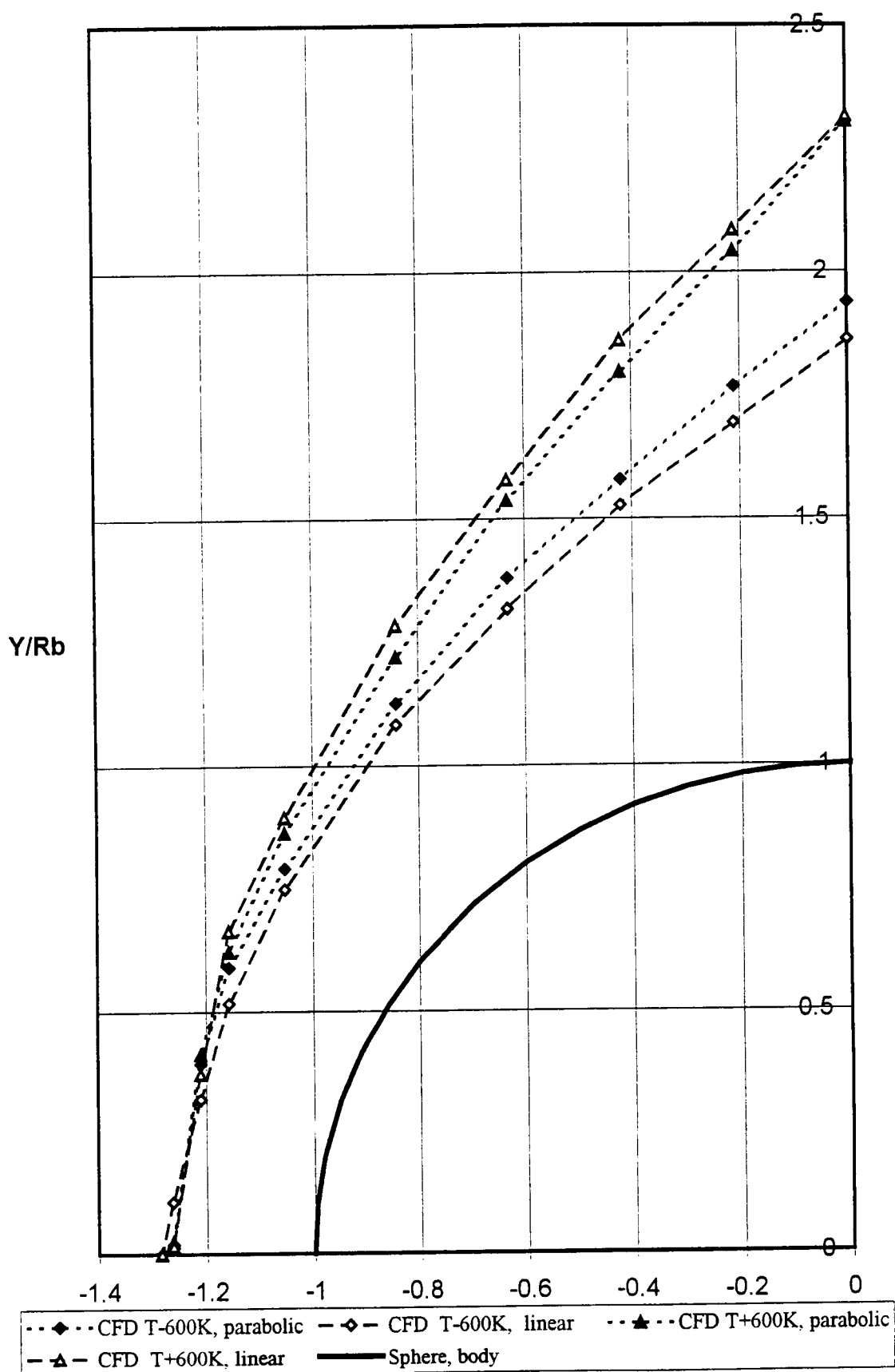
### Mach 8.0 freestream



were used to obtain ZTUFF solutions with both positive and negative temperature gradients. After several runs with a variance of 150, 300, and 600 degree K with a centerline temperature of 1200 degrees K it became evident that the far field temperature had to be changed significantly before much shock shape change manifested itself in the CFD results. This is especially true at the higher Mach numbers since the shock is stronger and develops closer to the body away from the far field boundary where the gradient values are most extreme. Thus for the Mach 2.35 CFD simulations the temperature variance was standardized as plus or minus 600 degrees K. Centerline temperatures were held constant for these simulations so that the effects on shock curve shape could be easily compared between solutions at differing temperature variations. No attempt was made at changing the shock stand off distance to match that of the Russian WIG experiments. The use of temperature changes at the sphere centerline can change the stand off distance if it is desired to do so. A temperature increase will increase the shock stand off distance.

The next experiment in obtaining CFD results involved using either linear or parabolic temperature gradients in the flow field. CFD results showed that a temperature difference of 600 degrees K yielded a reasonable difference in shock shape with either a positive or negative temperature gradient with linear or parabolic variation across the radial direction. Figure 11 shows that there is not a great difference in shock shape change between linear and parabolic gradients at the lowest Mach number (Mach 2.35) thus only linear gradients were used for the remaining solutions using ZTUFF.

Figure 11. Linear versus parabolic gradient solutions at Mach 2.35



The remaining solutions obtained with ZTUFF use a larger temperature variance with a linear gradient in a positive or negative sense from the centerline temperature. Centerline temperatures and other flow parameters varied between the three Mach numbers used in this study as well. The large temperature differential required to make a measurable change in shock shape is in part due to the curving of the shock through the flow field where it stabilizes at points some radial distance away from the far field boundary. At these points the local temperature variance is less than the total temperature variance at the far field boundary and thus the local speed of sound is not affected as much producing less shock shape change from that of uniform flow. This is especially true at higher Mach numbers where the shock curvature toward the sphere body is much greater when using the same grid as for lower Mach number simulations. It must be remembered that the size of the grid relative to the shock shape has to be considered when comparing each Mach number solution from the others for any given temperature gradient. This would also be manifested in a real flow field. In the case of a real flow field where a fixed temperature gradient exists the flight of projectiles through the field at increasing Mach numbers would show less and less change due to the temperature gradient in the shock shape since the overall shock would be stronger and closer to the body where less temperature variance exists. The ZTUFF code solutions therefore can be used to predict the direction and relative magnitude of shock shape change for a real temperature gradient flow field for different Mach numbers.

The solutions at Mach 2.35 were obtained to quantify shock shape information

at a known experimental condition. Solutions were run for positive and negative temperature gradients of 600 degrees K in both linear and parabolic gradients. The results displayed in figure 12 show the shock shape changes due to these gradients. The linear and parabolic gradients result in slightly different curve shapes. As expected the positive gradients add energy to the flow resulting in these shock curves being above the uniform flow case shocks. Conversely the negative temperature gradients result in shocks below the uniform flow shock curves. These solutions were run with initial conditions from a file that is later modified by the program 'infloball' to include those data changed by the temperature gradient imposed on the flow field. Using this initiation file each time for every temperature gradient solution insures a similar behavior of the convergence to the solution. Initially a low CFL (Courant) number of 0.2 is used to establish the numerical process for several hundred iterations. Gradually the CFL can be increased to speed convergence as the solution gains stability. Inner Newton iterations (four in this case) were used to help stability as well. The remainder of the mechanics of convergence to a numerical solution is straightforward. Each solution was run until a minimum residual of  $1 \times 10^{-6}$  was achieved. In some cases the solution would not resolve further and additional iterations proved useless. Each solution was run enough that the shock shape did not change after at least 300 more iterations implying complete convergence in time to the solution.

The solution at Mach 2.35 for a positive temperature gradient in figure 13 shows the shock beginning at the same stand off distance as the free stream case. This

Figure 12. ZTUFF shock shapes for Mach 2.35 free stream and temperature gradient  
flows

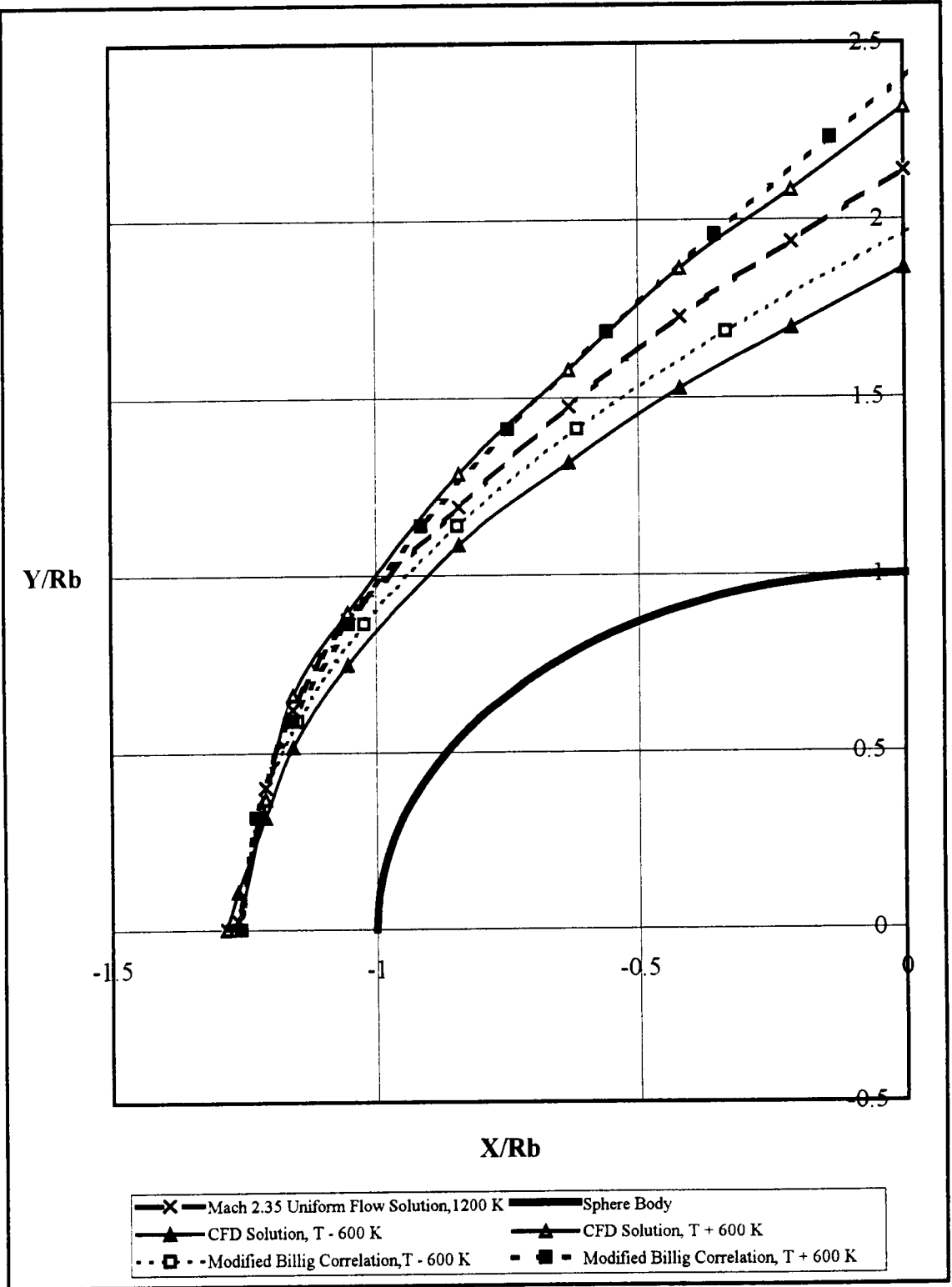
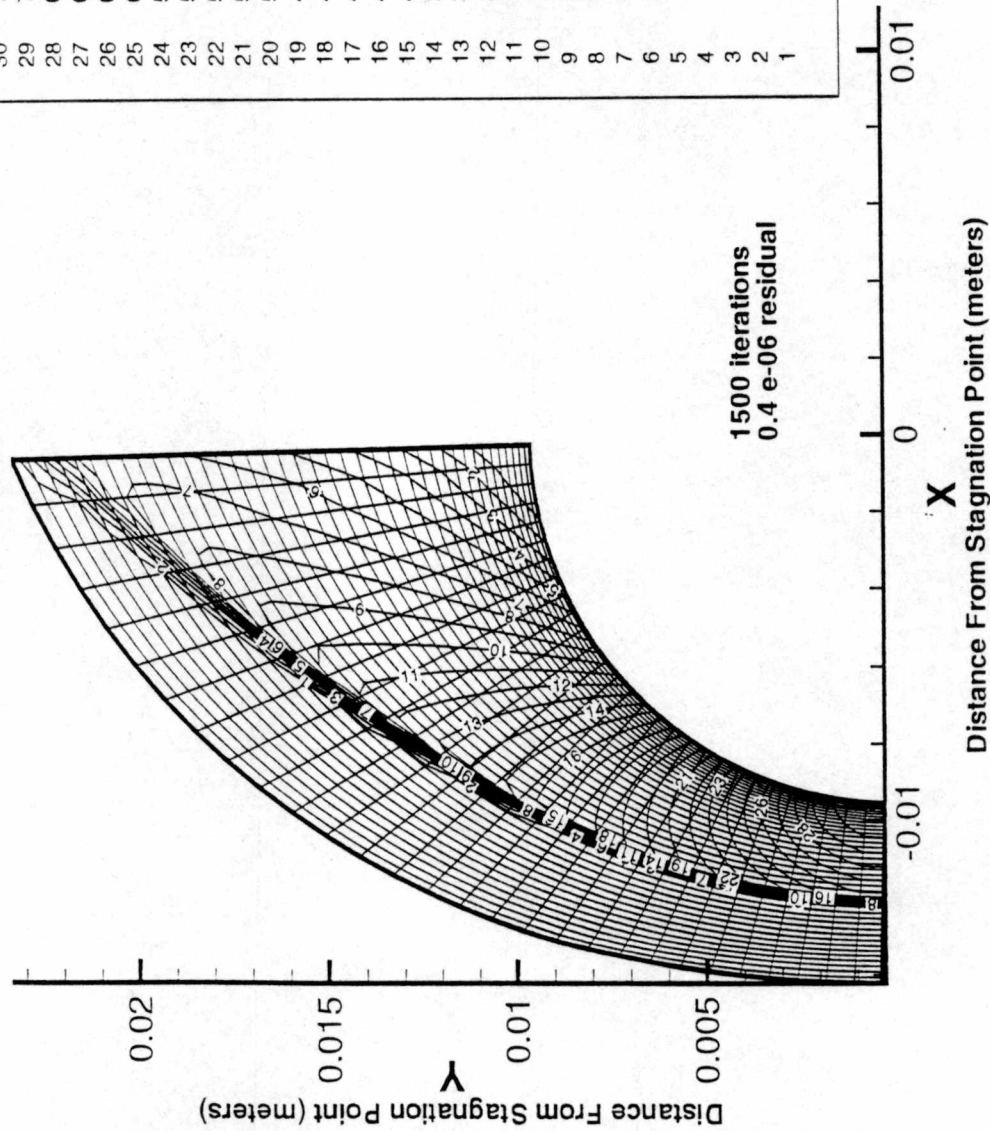


Figure 13. ZTUFF solution for positive 600 degree temperature gradient at Mach  
2.35.

Mach 2.35 with + 600 K gradient



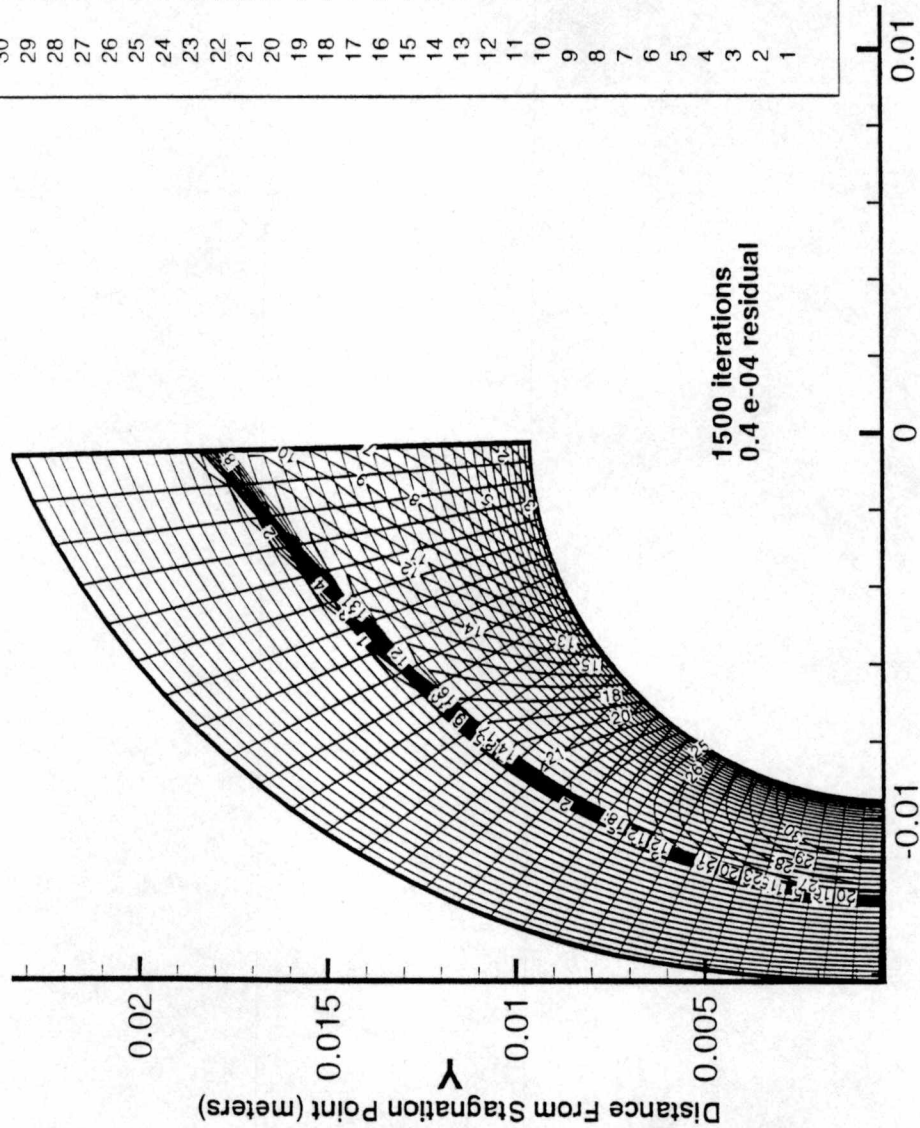
| Level P |         |
|---------|---------|
| 30      | 7.2331  |
| 29      | 7.02184 |
| 28      | 6.81058 |
| 27      | 6.59933 |
| 26      | 6.38807 |
| 25      | 6.17681 |
| 24      | 5.96555 |
| 23      | 5.7543  |
| 22      | 5.54304 |
| 21      | 5.33178 |
| 20      | 5.12053 |
| 19      | 4.90927 |
| 18      | 4.69801 |
| 17      | 4.48676 |
| 16      | 4.2755  |
| 15      | 4.06424 |
| 14      | 3.85298 |
| 13      | 3.64173 |
| 12      | 3.43047 |
| 11      | 3.21921 |
| 10      | 3.00796 |
| 9       | 2.7967  |
| 8       | 2.58544 |
| 7       | 2.37419 |
| 6       | 2.16293 |
| 5       | 1.95167 |
| 4       | 1.74041 |
| 3       | 1.52916 |
| 2       | 1.3179  |
| 1       | 1.10664 |

change is as expected since centerline temperatures are held constant for all of the CFD solutions in this thesis. As the shock progresses towards the far field it begins to show less strength than free stream solutions and eventually reaches near the upper far field boundary of the grid. The temperature difference from the centerline temperature at the point that the shock crosses the outflow boundary is approximately 500 degrees K. This allows this particular solution to be heavily influenced by the temperature gradient compared to the negative gradient solution at Mach 2.35 that will be discussed next. Comparison to the free stream shock shape shown in figure 14 shows the influence of the temperature gradient as the shock progresses out from the sphere centerline. This solution was run with ZTUFF configured with four inner iterations as described in previous chapters to a residual value of  $0.4 \times 10^{-6}$  over 1500 iterations. The solution was slowly converged by using low CFL values of 0.02 to start and increasing every 300 iterations slightly. The use of inner iterations allowed CFL values of as high as 0.5 to be used. Since these solutions are less stable than uniform flow solutions they cannot run at as high CFL numbers and tend to converge more slowly.

The negative gradient solution at Mach 2.35 of figure 14 is quite different than the positive gradient solution. The point that the shock crosses the outflow boundary is much lower in the grid and has a temperature approximately 450 degrees K lower than the centerline temperature. As in the positive gradient solution the difference in this solution from the free stream solution is easily seen. The residual for this solution is  $0.4 \times 10^{-4}$  over 1500 iterations with four Newton inner iterations. This

Figure 14. ZTUFF solution for negative 600 degree K temperature gradient at Mach  
2.35.

# Mach 2.35 with - 600 K gradient



| Level P |         |
|---------|---------|
| 30      | 7.2331  |
| 29      | 7.02184 |
| 28      | 6.81058 |
| 27      | 6.59933 |
| 26      | 6.38807 |
| 25      | 6.17681 |
| 24      | 5.96555 |
| 23      | 5.7543  |
| 22      | 5.54304 |
| 21      | 5.33178 |
| 20      | 5.12053 |
| 19      | 4.90927 |
| 18      | 4.69801 |
| 17      | 4.48676 |
| 16      | 4.2755  |
| 15      | 4.06424 |
| 14      | 3.85298 |
| 13      | 3.64173 |
| 12      | 3.43047 |
| 11      | 3.21921 |
| 10      | 3.00796 |
| 9       | 2.7967  |
| 8       | 2.58544 |
| 7       | 2.37419 |
| 6       | 2.16293 |
| 5       | 1.95167 |
| 4       | 1.74041 |
| 3       | 1.52916 |
| 2       | 1.3179  |
| 1       | 1.10664 |

particular solution showed stability well before the positive gradient case and thus the residual is not indicative of lack of complete convergence of the solution. The outflow boundary also shows a much better developed shock shape than for the positive gradient case. This is likely due to the shock exiting the outflow boundary quite some distance from the upper far field boundary where no interference from the upper boundary exists. Typical CFL numbers higher than the positive gradient case could be used due to the stability of this solution. The highest CFL for this solution was 0.7 again starting with a value of 0.2 for the initial iterations.

Similarly the solutions to the Mach 5.0 and Mach 8.0 cases with linear temperature gradients were obtained. Positive and negative linear temperature gradients of 1200 degrees K were used for these solutions. Note also that the centerline temperatures for all three Mach numbers are somewhat different. The computational grid size and spacing was held constant. In all cases the expected shock shape change occurred where positive gradients produced shocks above the uniform flow case and negative gradients produced curves below it. The change in shock shape with increasing Mach number is less than with the Mach 2.35 case as is explained in the next paragraph.

The Mach 5.0 solutions were initially tried with a linear 600 degree K temperature gradient and run for 1300 iterations to a residual of  $.4 \times 10^{-6}$  before concluding that not much change in shock shape would result from this set of conditions. The typical run was made similarly to the Mach 2.35 cases in that the CFL

number used for the first several hundred iterations was low and slowly increased as the solution gained stability. An initial solution of 100 iterations was used to establish the flow field conditions before introducing the temperature gradient parameters to the flow field and setting the inflow boundary to continuous inflow parameters. Plotting the solution results from time to time as it converged showed that the gradient solution was not very much different than free stream. To assure a good shape change for the correlation the gradient was changed to a 1200 degree K value and the solution was run again. This time it took much longer for the simulation to converge on a steady state solution. Even with this more extreme gradient the shock shape shows little change due to the gradient. Figure 15 shows the modified Billig correlation shock shapes versus the CFD shapes for positive and negative gradients at 1200 degrees K. In this figure the same behavior is seen for both CFD and modified Billig correlation shocks when the gradient is imposed on the flow field. It also shows that they do not differ much from free stream shock shapes at this Mach number. Figure 16 shows the shock crossing the outflow boundary with a positive 1200 degree K gradient at a point where the temperature change is 800 degrees K. Figure 17 illustrates that with a negative gradient this occurs where the temperature change is 650 degrees K. Even though these maxima are higher values than for the Mach 2.35 case there is less change in the shock shape from that of free stream. This is due to the shock being much stronger at Mach 5.0 than at Mach 2.35 where temperature changes must be proportionally stronger to affect the shock shape equally. This effect continues to manifest itself with more prominence at higher Mach numbers.

Figure 15. ZTUFF versus modified Billig solutions for Mach 5.0 flow with a linear  
1200 degree K temperature gradient.

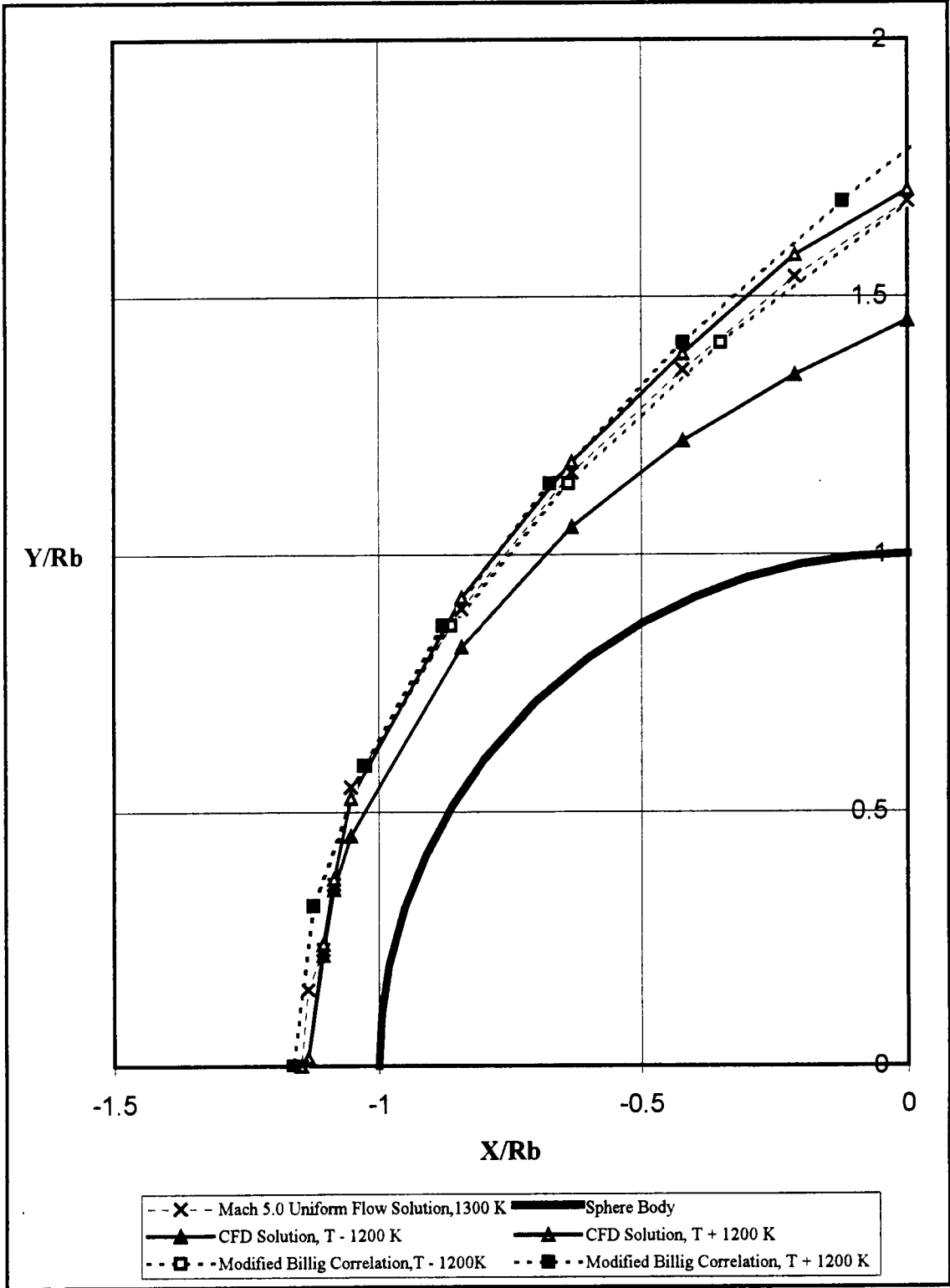


Figure 16. ZTUFF solution for Mach 5.0 flow at 1300 degrees K with a positive  
1200 degree temperature gradient.

# Mach 5.0 with +1200 K gradient

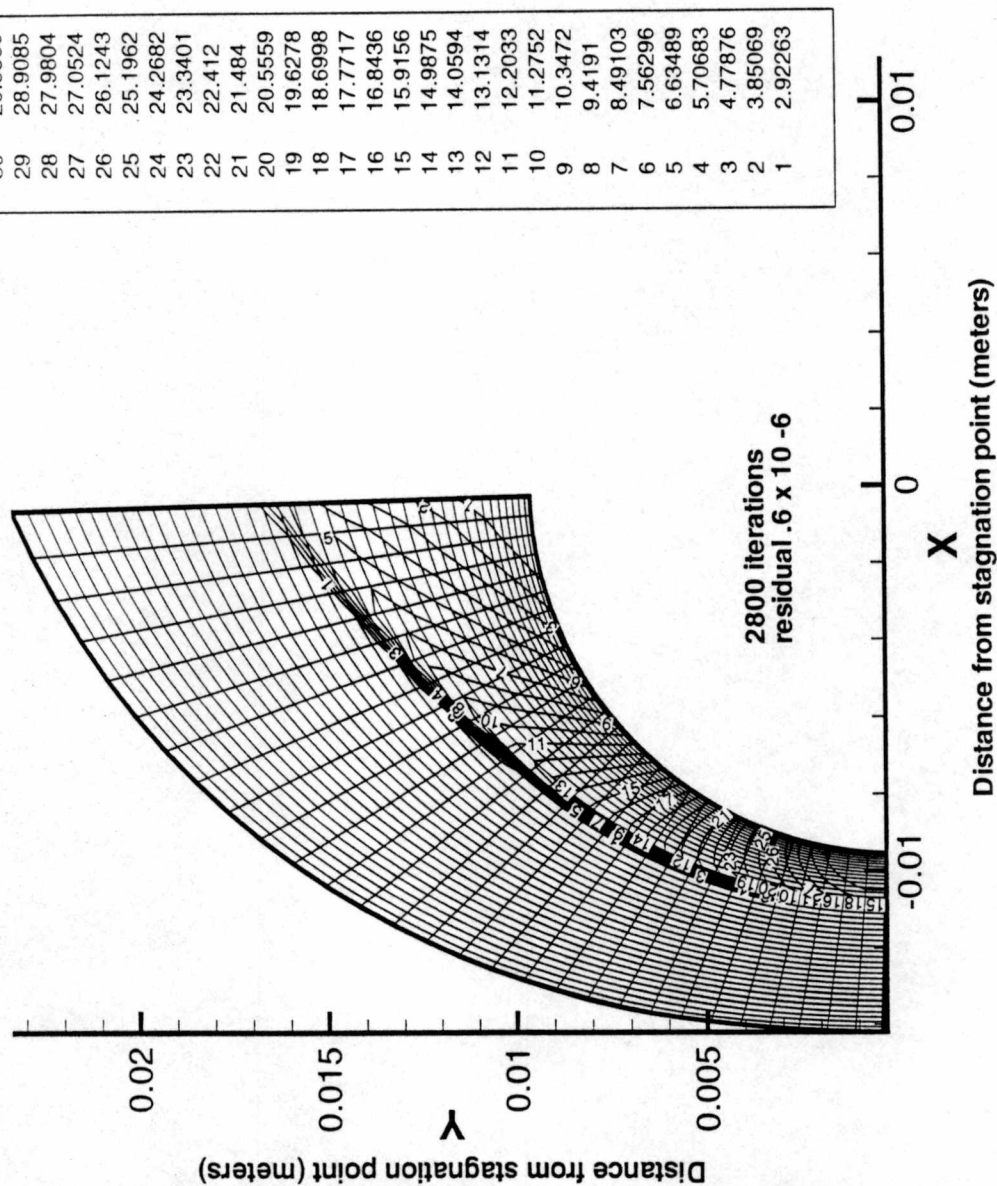
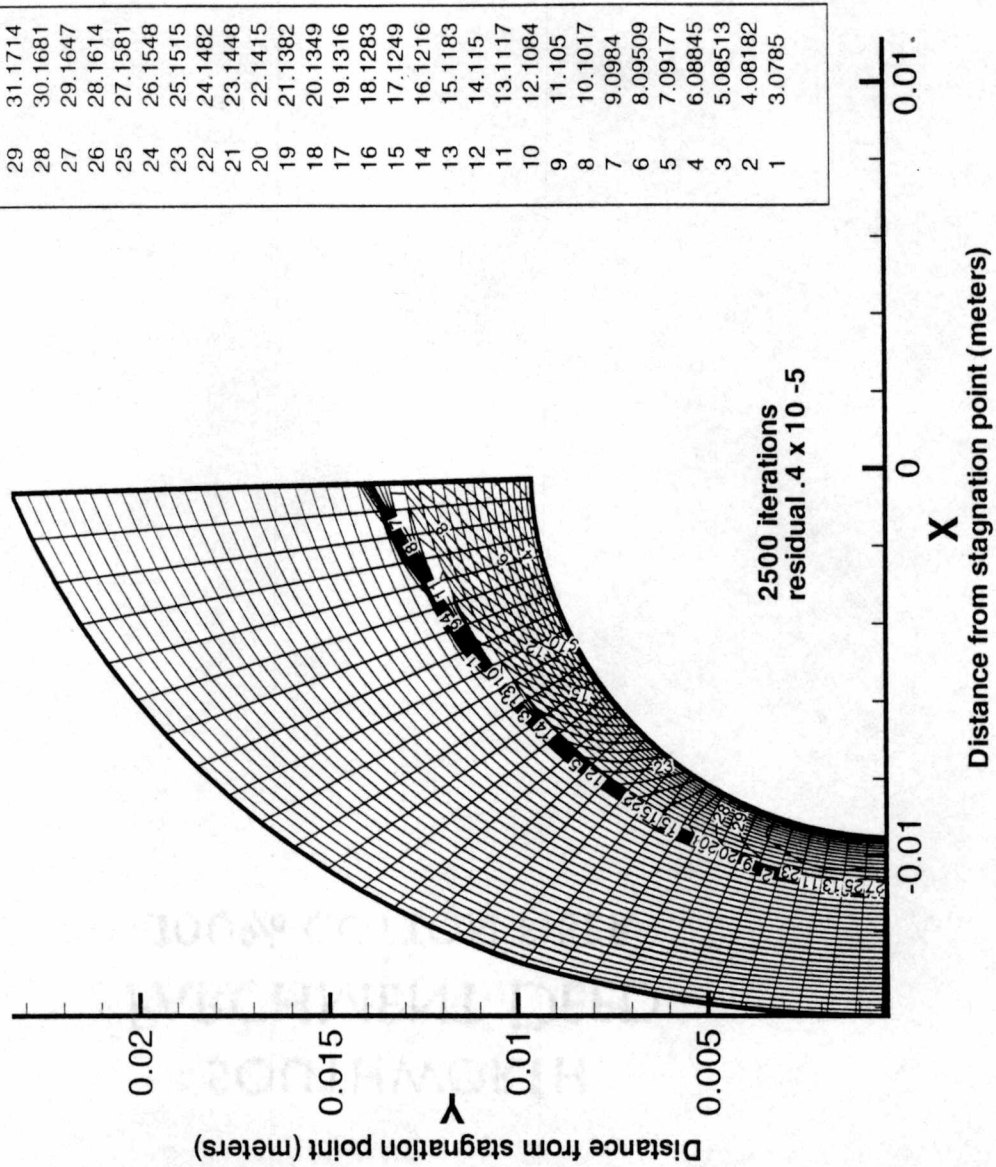


Figure 17. ZTUFF solution for Mach 5.0 flow at 1300 K with a negative 1200 degree  
K temperature gradient.

**Mach 5.0 at 1300 K with a  
-1200 K temperature gradient**



The final condition chosen for these simulations used to evaluate the modified Billig correlation is Mach 8.0 flow at 1350 degrees K with the same density used as the other two Mach numbers for simplicity. The free stream solution run with ZTUFF for this Mach number is very similar to the Mach 5.0 solution and matches the Billig correlation data well as seen in figure 4. Again the larger 1200 degree gradient was chosen for this Mach number since the Mach 5.0 solution showed little variance in shock shape at a 600 degree gradient. This solution ran in a very similar fashion to the Mach 5.0 solution taking many more iterations to converge to steady state than the Mach 2.35 solution. The strength of this shock was also a factor (as in the Mach 5.0 case) in not allowing the temperature gradient to heavily influence shock shape. Both a positive and a negative temperature gradient were modeled with ZTUFF at a Mach 8.0 flow velocity. Figure 18 shows the linear positive and negative gradient flow solutions at Mach 8.0 versus the modified Billig shock shape curves and the free stream curve. At this velocity there is little difference between any of these curves and it becomes increasingly difficult to accurately plot the data gathered from a ZTUFF solution plot where the shock is somewhat smeared out across the grid. The choice of points to plot is subject to individual interpretation and skill. This creates some uncertain plotting results at this Mach number or any higher Mach number. The Mach 8.0 solutions typically took 3000 iterations to converge to a solution of  $10^{-6}$  since very small values of CFL had to be used to maintain stability. The CFL values began at 0.02 and could be increased in 0.02 increments every 300 iterations using four Newton inner iterations. The positive and negative solutions (figures 19 and 20)

Figure 18. ZTUFF versus modified Billig solutions for Mach 8.0 flow with a linear  
1200 degree K temperature gradient.

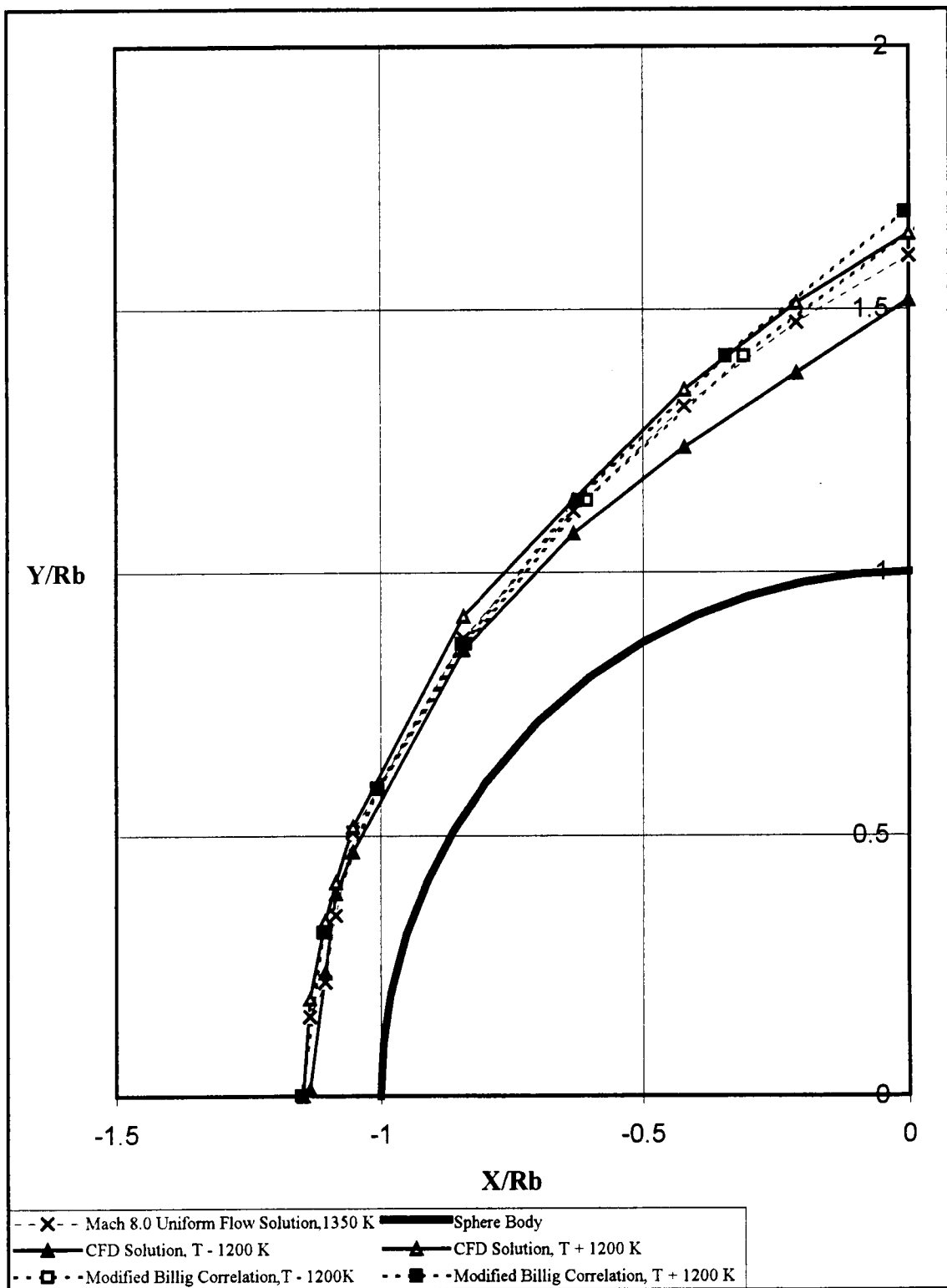


Figure 19. ZTUFF solution for Mach 8.0 at 1350 K with a positive 1200 degree K  
temperature gradient

Mach 8.0 at 1350 K with a  
+1200 K temperature gradient

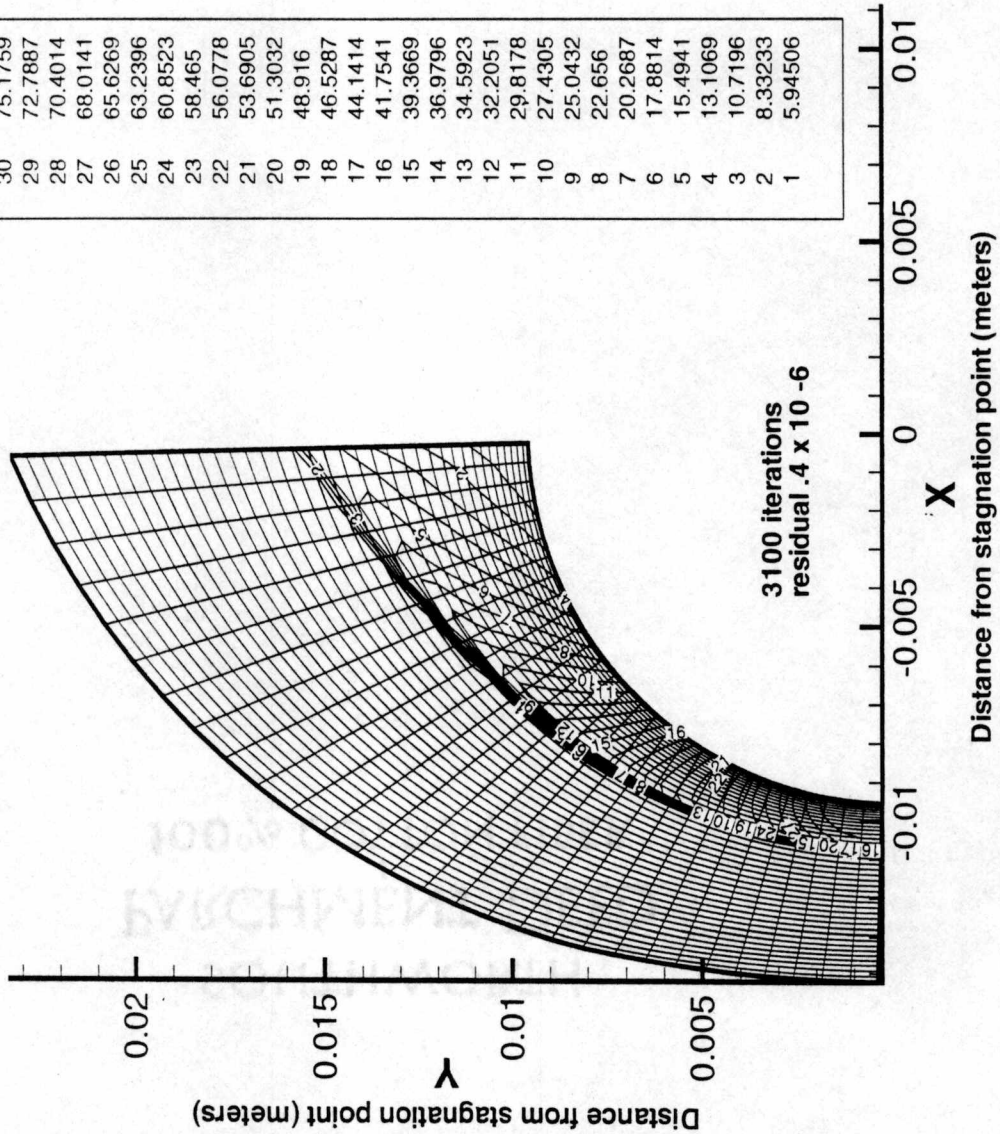
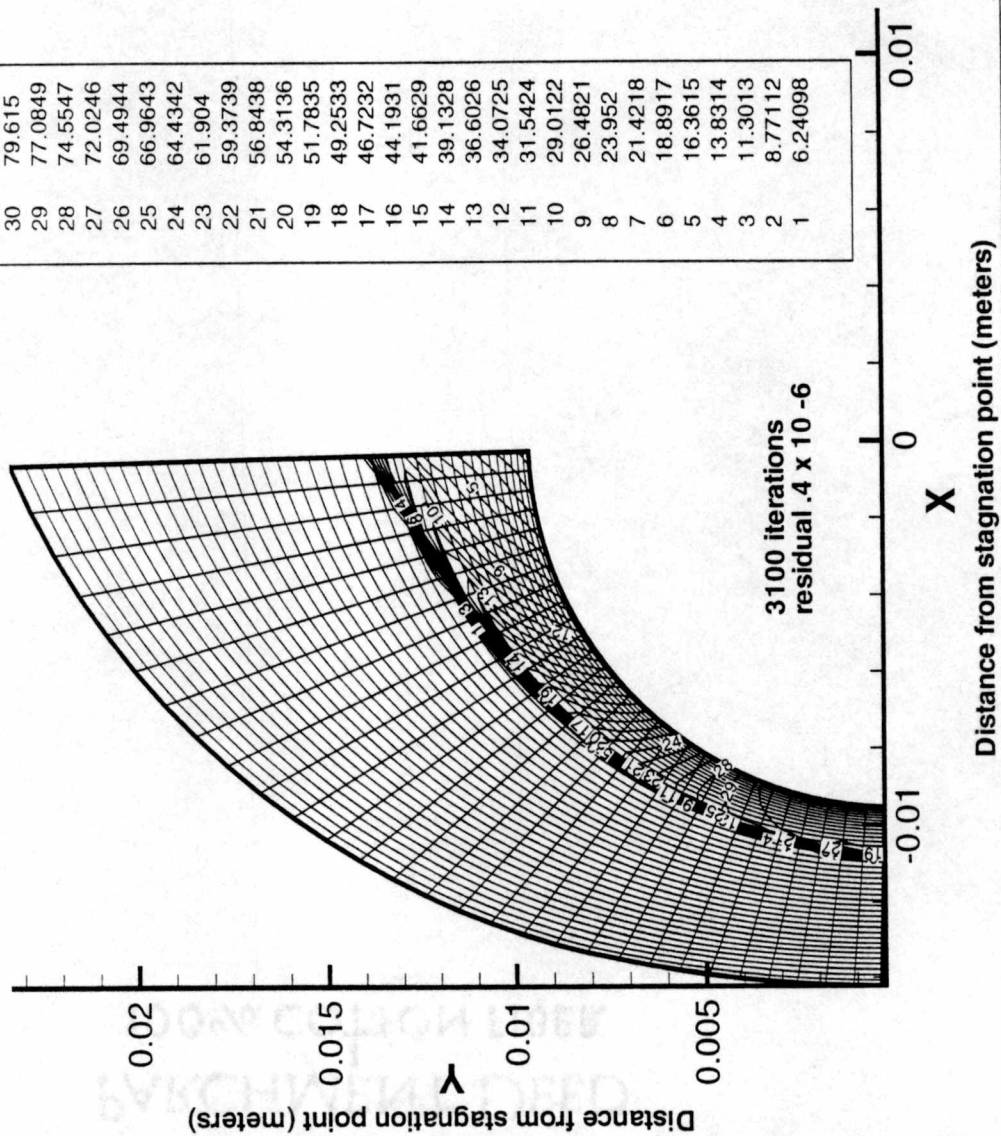


Figure 20. ZTUFF solution for Mach 8.0 flow at 1350 K with a negative 1200 degree  
K temperature gradient

Mach 8.0 at 1350 K with a  
-1200 K temperature gradient

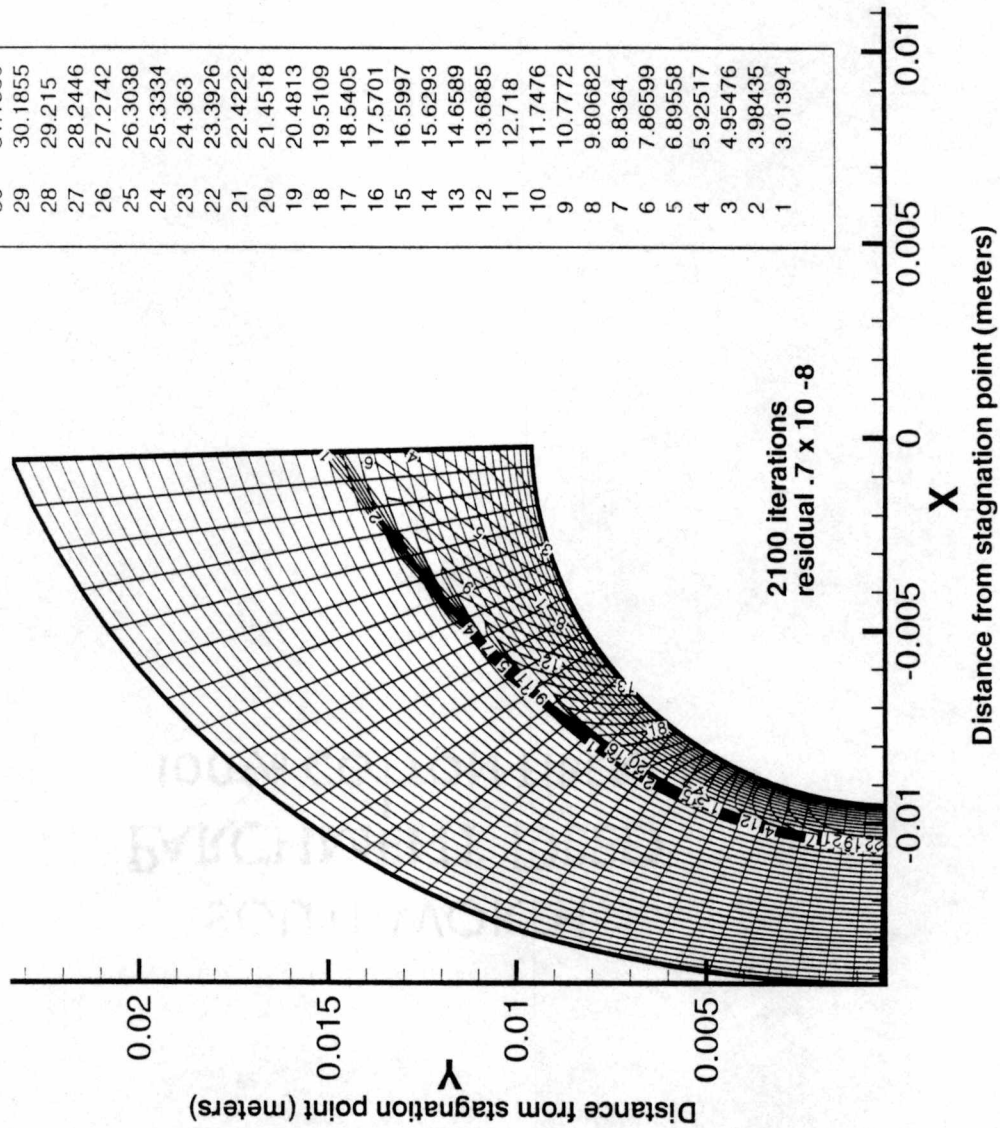


behaved similarly as they converged to a solution. The figures for the Mach 8.0 solutions show very little change in shock shape as well as maximum and minimum pressure values. The modified Billig correlation shows again that the negative temperature gradient solution changed the shock shape more than did the positive gradient solution. Figure 18 also illustrates the curvature of the shock at the outflow boundary in the CFD solution that is not present in the correlation shock curve. This is not as apparent in the negative gradient solution as in the positive gradient solution. Figure 18 shows that the modified Billig curves are very close to the free stream CFD solution curve and that the CFD gradient solutions are further from the CFD free stream curve. In all it is difficult to see much shock curve change due to either temperature gradient at this Mach number.

One further solution was made at Mach 5.0 using the ZTUFF options for non-equilibrium chemistry with a free stream inviscid flow. Using these options in the code the energy in the flow will be reduced from that of perfect gas solutions due to the chemical reactions being modeled. This will change the shock shape throughout the flow and result in a curve that is closer to the sphere body. Since the temperature of the flow was set to 1350 K the resulting flow would be at a high energy level that would result in a strong shock. The shock is modeled with these features in figure 21 for an inviscid 2-D axisymmetric non-equilibrium chemistry flow around the sphere using the 31 x 41 point grid at the Mach 5.0 parameters (table 2). This solution ran well with ZTUFF with CFL values as high as 2.5 as the solution neared convergence.

Figure 21. ZTUFF solution for Mach 5.0 non-equilibrium chemistry free stream flow

### Mach 5.0 1300 K Free Stream Solution with Non-Equilibrium Chemistry



The use of 2-D axisymmetric modeling for these temperature gradient solutions is limited in showing what the entire flow field should be. The gradient is assumed to be radially symmetrical for the ZTUFF solutions and thus are limited in modeling real flow situations for WIG plasma experiments. In reality the temperature would be changing from the cathode plate to the anode rods in a vertical plane with less change in temperature occurring in a horizontal plane. This is due to the flow of energy between cathode and anodes in the plasma region of the experiment. For practical purposes the view of the shadowgraph equipment in the ballistic experiments is across the vertical plane and the axisymmetric solutions given in this thesis represent a good approximation of this view. It is quite possible however the lower half of real WIG flows has a different temperature gradient than the upper half. Further mapping of temperature profiles in plasma fields must be accomplished before attempting to model a three dimensional solution to the flow.

## Chapter 5

### Correlation for Temperature Gradient Flow

The Billig correlation [3] forms the basis for modifications for temperature gradient flow with perfect gas air. The original Billig correlation uses three equations to describe the shock shape for hypersonic spherical nose bodies in air. These equations are given below as:

- 1) Shock stand-off equation

$$\delta/R = 0.143 \exp[3.24 / M^2]$$

- 2) Shock radius of curvature equation at the centerline

$$R_c/R = 1.143 \exp[0.54 / (M-1)^{1.2}]$$

- 3) Shock shape (hyperbola) equation

$$X = R + \delta - R_c \cot^2 \beta \left[ (1 + (y^2 \tan^2 \beta) / R_c^2)^{0.5} - 1 \right] \text{ where } \beta \text{ is}$$

interpreted as the Mach angle in the case of spherical nose tips.

Billig intended that the Mach number “M” in these equations be the free stream Mach number for uniform flow cases which is consistent with a uniform flow field. In searching for a reasonable way to modify these equations for radial temperature gradients it became apparent that using local Mach number changes in the radius of curvature equation (instead of the free stream Mach number) should change the shock shape. This is the same mechanism behind the change in shock shape seen in the

ZTUFF flow solver solutions. Further the local speed of sound equation relies upon the value of the local temperature and thus one can relate Mach number to temperature at each radial point from centerline using perfect gas relations. The relationship of Mach number to temperature in a perfect gas is  $M = V / a$  [where  $a = (\gamma RT)^{0.5}$ ]. Combining these equations yields the equation  $M = V / (\gamma RT)^{0.5}$ . A ratio of the local Mach number to the free stream Mach number based on temperature ratio can be created by the following equation  $\frac{M_l}{M_\infty} = \frac{V / \sqrt{\gamma RT_l}}{V / \sqrt{\gamma RT_\infty}}$  where the subscript  $l$

refers to local properties and the subscript  $\infty$  refers to free stream properties. Note that the temperatures in this equation are stagnation temperatures since the gradient exists in the flow field continuously over time. Both the ZTUFF flow solver and the modified Billig equation use stagnation conditions as the reference for creating shock shape curves due to supersonic flow past spherical bodies. Since the velocity  $V$  of the sphere flying through the air is constant, as are  $\gamma$  and  $R$  (for perfect gas) they cancel

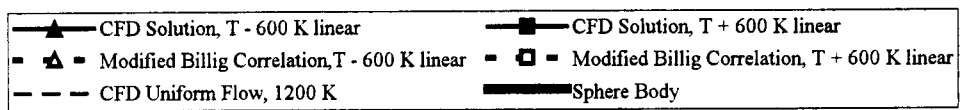
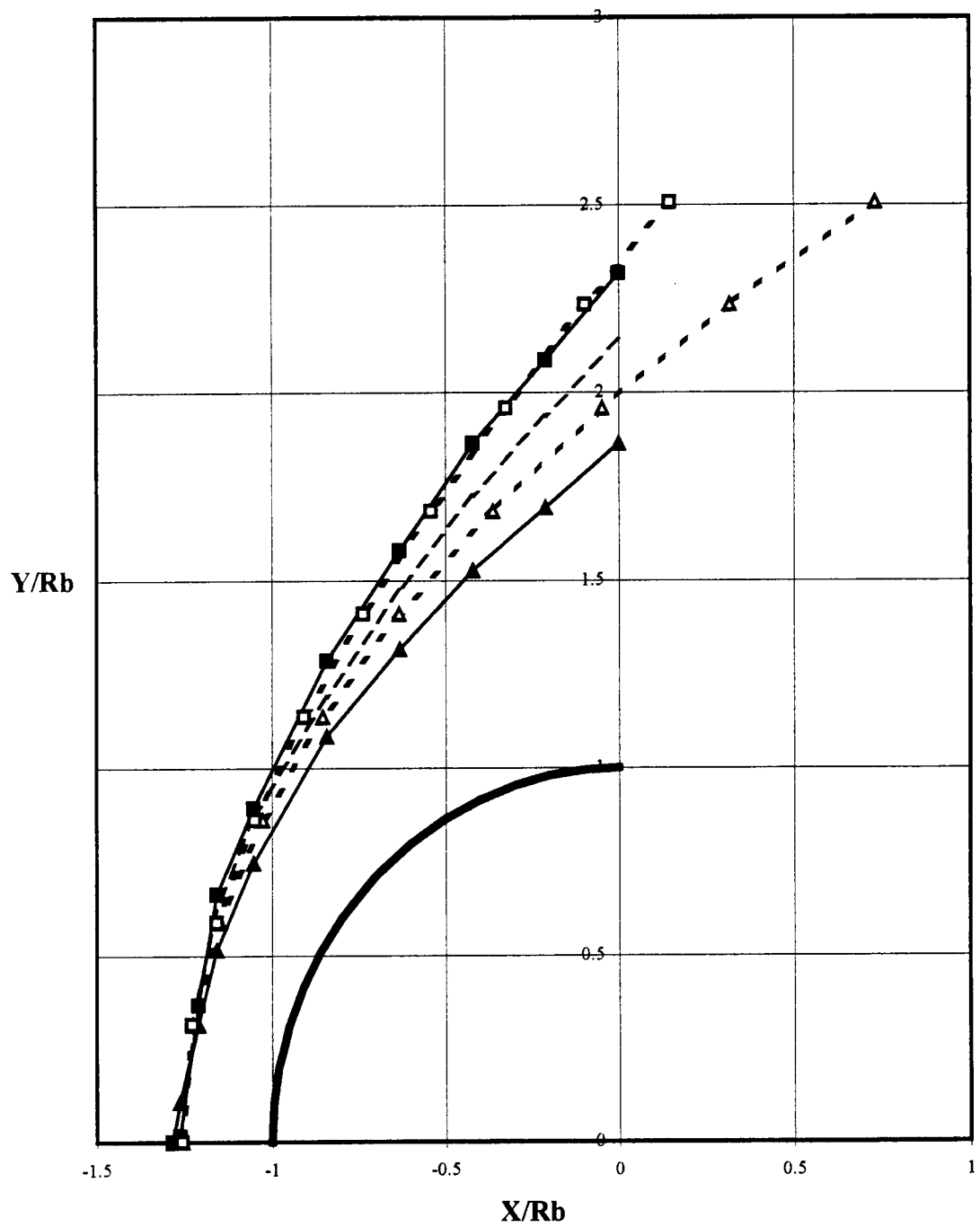
out of the equation to form  $\frac{M_l}{M_\infty} = \frac{\sqrt{T_\infty}}{\sqrt{T_l}}$  that can easily be solved for local Mach

number for any temperature ratio. This equation can be solved for local Mach numbers based on any assumed temperature gradient and plugged in to the Billig correlation equations to generate new shock shape curves. This results in shock shapes that are above the free stream curves for positive gradients and below for negative gradients as expected. Upon plotting the results of this modification it was found that they did not match very well with CFD results. Part of the reason for this

was that the maximum temperature variance was initially plotted at the maximum radial distance of the shock from the sphere centerline. This was done instead of mimicking the CFD results by having less than the maximum variance in temperature relative to the maximum radial shock position at the sphere vertical centerline. To allow a direct comparison between CFD results and correlation results some method to calculate the total variance in temperature from each CFD solution was required. This resulted in a careful evaluation of the shock radial distance from centerline of all CFD solutions. It is then possible to determine the approximate temperature at the maximum radial distance (ie: the shock vertical centerline) along the CFD generated shock shape. The function used in ZTUFF for temperature gradient is used for evaluating the temperature at the maximum radial distance of the shock shape versus the temperature at the grid far field radial distance. The actual total temperature variance for each case was obtained to be used in the matching correlation plots. The resulting correlation plots using this matching technique were much closer to the CFD shock shapes since the temperature along the shock shapes at each axial and radial position were nearly matched. It can be seen in figures 15, 18, and 19 that the correlation modification did not follow the CFD generated curves exactly but was indeed reasonably close to allow accuracy within 10% of the CFD results.

In doing the plots of CFD results it is difficult to get exact values at each desired point along the shock shape curve due to the smearing of the shock solution. For these ZTUFF solutions the typical smearing of the shock took place across four grid cells. This is typical for CFD solutions and makes the actual curves subject to the

Figure 22. ZTUFF versus modified Billig solution for Mach 2.35 flow with a linear  
600 degree K temperature gradient



measurement uncertainties of the individual reading the curves. Unfortunately this introduces some error into the results that is difficult to quantify. It is also possible that the software used to create the shock shapes from the modified Billig correlation in some of the figures used a polynomial curve fit that could over or under exaggerate the shock shape curvature at the end points. Again this could introduce error in comparing the accuracy of the correlation to reproduce the shock shapes seen in the CFD results.

In treating the error induced by the use of computational fluid dynamics for a solution with this geometry and grid characteristics it should be pointed out that the far field and outflow boundaries of the grid get close to the shock on low Mach number positive gradient solutions. This can introduce error in the shock shape seen near the far field boundary due to reflection of pressure waves calculated in the solution. Similarly the outflow boundary is along the sphere vertical axis where no interaction with the wake behind the sphere is calculated. Supersonic flow has the property that no perturbations in the flow downstream can affect the flow upstream. However the sphere boundary along the rear half of the sphere would influence flow near it and eventually propagate perturbations vertically into the flow somewhat affecting shock shape since the vertical components of velocity in the flow are subsonic. The perturbations in pressure etc in the subsonic velocity component allow propagation into the flow field. Indeed this is the very reason a shock shape curve is obtained for each solution. The grid used for solutions did not allow for this effect thus inducing more small errors in the solution. The grid is also somewhat coarse to

allow reasonable amounts of computational time to be used in each solution. As discussed earlier the double sized grid took much more computational time to run and had similar results to the smaller grid used for the work presented in this thesis. The use of larger grids with more grid points does allow the smearing of the shock to be less evident since each cell is much smaller. The smearing across say four cells appears to the observer to be a much finer line when plotted using a larger number of grid points in the computational grid. Another area to consider is the number of pressure contour levels to use in each plot. Using more contours results in the shock appearing even more smeared out in the plot. Careful consideration of how many contours to plot needs to be made to help display results of CFD computations.

All of these contributions to error in the results of CFD solutions make it difficult to define the exact values of shock shape coordinates from each solution plot. Careful manipulation of the results of each solution along with experience with the code and the results allow better shock shapes to be determined with ZTUFF.

## Chapter 6

### Follow on Studies – A Direction for Further Research

In doing this thesis many things were considered and discovered that raise questions about what should be done to further study the temperature gradient flow problem in weakly ionized gases. First it can be assumed that the gas is likely not behaving as a perfect gas due to the high energy state of the WIG plasma as well as the dissociation and recombination induced by this energy. Using the code options in ZTUFF to allow non-equilibrium gas computations with a temperature gradient is one of the first things the researcher should attempt. This would be preceded by modifications to the temperature gradient initialization program 'infloball' to use the subroutines within ZTUFF that allow the correct gas parameters to be calculated for grid initialization. These parameters (such as  $\gamma$ ) will also have some effect on the local speed of sound of the gas in each cell of the computational grid and lead to some difference in the shock shape generated by the code. These can be compared to perfect gas results to see if any quantitative difference occurs and the correlation coefficient modified to correspond to this.

Another logical follow on to this thesis is the use of CFD codes other than ZTUFF to evaluate temperature gradients. Verification of the ZTUFF results and a natural progression to better technique and deeper investigation of temperature gradient flow would provide a host of research possibilities. Use of discontinuous

functions for the gradient could provide insight into the nature of more realistic WIG flow fields since indeed the real world flow is very much non-uniform.

The ZTUFF code (like all other flow solvers) has limitations to what it can model. Currently it can model complex non-equilibrium chemistry flows in three dimensions over multiple grids to allow solutions to flows around realistic bodies of interest. Unfortunately the code does not have the ability at present to model the extremely complex phenomena of weakly ionized gas flow where changes in equilibrium, molecular weight, energy state, vibrational temperature, Coulomb forces between particles, and many other parameters are all taking place. As of this writing there are no computational routines that have this capability. A direction for further research would be in modifying existing codes to model more of the physical processes that occur in WIG flow in the hope that more can be learned with each improvement in modeling capability. For example it would be very interesting to see what effect the Coulomb forces truly have over the shock strength in WIG flow. This could be done in a uniform flow field where it would be desired to quantify the effect if any of this apparent physical phenomenon. The creation of the equations to model this effect, the addition of these into a flow solver, and the added computational time involved make this a formidable task.

As stated in the previous chapter improvement in obtaining solutions can be achieved with a finer grid with more points. This has the effect of narrowing the smearing out of the shock shape seen in the solutions using a relatively small grid. It

would in turn help to allow the researcher to pinpoint the coordinates of various points along the CFD shock shape curves and increase the accuracy of the curves plotted from CFD results using this technique. Further it would be of some benefit to run the solution past the vertical centerline of the sphere into the wake zone to allow for further shock shape detail in the curvature at the most downstream end of the shock. This would allow better definition of the CFD results at the outflow grid boundary used for solutions in this study.

## **Chapter 7**

### **Conclusions**

1. This study has produced a way to evaluate shock shapes produced by spherical nose bodies in perfect gas air flow fields with radial temperature gradients in real flow situations where those gradients may exist. Using the modified Billig correlation a close match to real shock shapes seen in the presence of positive temperature gradients, values for local temperatures, and approximate temperature gradient functions may be obtained. This data can be used to model weakly ionized gas flows with an equivalent energy addition to the flow from temperature only. Until the physics of WIG plasmas are more thoroughly understood this technique can be used as a first step in solving these type flow situations using computational fluid dynamics methods.
2. A method for creating radial temperature gradients in a flow field using the ZTUFF flow solver has been shown within this work. This methodology can be instituted in other CFD codes for use around other body shapes and flow gases as desired. This thesis illustrates the results of several solutions to the radial temperature gradient flow field at a wide range of Mach numbers and Reynolds numbers. The ZTUFF code has demonstrated in this work that it can match both real free stream shock

shape data and free stream shock shapes created with the Billig correlation with good accuracy. It is logical to imply from this that the temperature gradient solutions using ZTUFF are also accurate and lead to an accurate modification to the Billig correlation for this type flow.

3. The results seen in the figures within this thesis show the shock shape change induced by positive and negative temperature gradients for two different techniques. The first technique is the CFD approach described earlier. This approach shows that the negative gradient affects the shock shape more than does the positive gradient for the same change in temperature. This occurs at all three Mach numbers used in this thesis. The effect of modeling higher Mach numbers using CFD shows that there is less change in shock shape with higher Mach numbers and that determining the actual points along the “smeared out” shock solution is difficult. The smearing of the shock along the grid makes it hard to get accurate shock shape curves. This is even more difficult at higher Mach numbers.
4. The second technique for creating shock shapes for temperature gradients involves the creation and verification using CFD results of a modified Billig correlation. The resulting correlation produced shock shape changes that were a good match for positive gradient CFD solutions but did not match the negative gradient CFD solutions very well. This observation is

true for all Mach numbers evaluated in this thesis. The shock shape changes with positive and negative temperature gradients showed symmetry about the free stream shock shape at all Mach numbers. The higher Mach number correlation curves have less difference between free stream and the gradient curves than the lower Mach number curves. At best the correlation predicts the relative change in shock shape for all gradients but can be used to predict a positive gradient with good results.

5. Further CFD results at other Mach numbers, different grid sizes, various flow conditions, and more complex gradients should be solved for and evaluated to further define the correlation and the inherent limitations it may have. The Mach numbers modeled with CFD for this thesis are widely spaced and represent much of the hypersonic realm covered by the original Billig correlation. However limiting the correlation verification to only three solutions does not provide enough data to prove it valuable as a prediction tool for temperature gradient flows. More work on verifying this modified correlation should be done.
6. The CFD results for temperature gradient flow show that not much change is seen in shock shape for large gradients. The sphere diameter is only 0.0019 meters with a grid radius of 0.024 meters as modeled with ZTUFF. Placing a temperature gradient of 1200 degrees K over this small a radius is quite extreme yet the difference seen in shock shape is quite small.

small. Obviously there are more physics to model than can be simulated with a simple temperature gradient introduced into the flow.

7. The plasma has a very small time scale compared to that of normal air. The electrons having very little mass, collision cross section, and high energy have a very high speed of sound compared to air. This has been calculated previously in chapter 1. The difference in sound speed is on the order of 200 times faster for electrons. This is the mechanism that allows transfer of information (as well as the electrons themselves) upstream in front of the shock from areas behind the shock. Simply stated the sphere is moving at a subsonic speed compared to the plasma electrons sound speed and the electron's contribution to the shock shape changes is not a transient event.

In summary this thesis presents a method to use a modified correlation verified with a proven CFD code for temperature gradients in perfect gas air at supersonic and hypersonic Mach numbers. The method works well for positive gradients and with less accuracy with negative gradients. The correlation can be used as a first estimate of the energy changes in perfect gas flows in those cases where shock shape change from free stream conditions has manifested itself. Similarly the gradient flow method shown within this thesis for attaining CFD solutions to gradient flows can be used with ZTUFF and other codes to model flows of this type with good results. This CFD approach can be used with other gradients and flow conditions such

as non-equilibrium chemistry flow models. Further work is desirable to prove the correlation accuracy and to possibly find a better shock curvature equation coefficient to model both the positive and negative temperature gradient shock shapes than is given in this thesis.

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## **Vita**

Brian Roebuck was born in Johnson City, New York on April 25, 1956. He attended public schools there until 1965 when he moved with his family to Cary, North Carolina where he completed High School in 1974. He entered North Carolina State University in 1975 and received his Bachelor of Science Degree in Aerospace Engineering in 1980. He began working for the Naval Ordnance Station in Indian Head, Maryland eventually moving on to Arnold Engineering Development Center, Tullahoma, Tennessee a year later. While working at AEDC he was employed as a test engineer operating many different test cells, a systems engineer, and an installation engineer. In 1992 he enrolled in the University of Tennessee Space Institute graduate school and began work towards a Master of Science Degree in Aerospace Engineering eventually earning this honor in December 1998.

He continues to work at Arnold Engineering Development Center as a systems, operations, and installation engineer in ballistic range and hypersonic flow test facilities.