INVISCID BLUNT BODY SHOCK LAYERS
Two-Dimensional Symmetric and Axysymmetric Flows

by

Gino Moretti

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POLYTECHNIC INSTITUTE OF BROOKLYN
DEPARTMENT of
AEROSPACE ENGINEERING and
APPLIED MECHANICS
June 1968

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PIBAL REPORT NO. 68-15
INVISCID BLUNT BODY SHOCK LAYERS
(Two-Dimensional Symmetric and Axisymmetric Flows)

by

Gino Moretti

This research was conducted under the sponsorship of the Office of Naval Research under Contract No. Nonr 839(34), Project No. NR 061-135.

Polytechnic Institute of Brooklyn
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The results of a time-dependent computation of blunt body
shock layers for two-dimensional symmetric and axisymmetric flows
are presented in a systematic form for a range of values of the
free stream Mach number and bodies of different shapes and variable
bluntness.

A brief discussion of the relevant features of the computa-
tional technique is given. The results are presented in a graphical
form; the graphs have been produced by the computer.

* This research was conducted under the sponsorship of the Office
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NR 061-135.

** Professor, Department of Aerospace Engineering and Applied Mechanics.
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1. **Introduction**

The main features of the flow field about the blunt nose of a vehicle flying at supersonic speed are, qualitatively, well-known. A complete, detailed description of the flow, however, is hard to obtain. Formulae for the determination of some relevant parameters are available, which generally rely on simplifying assumptions. More detailed results can be achieved through the use of numerical techniques on high-speed computers. *

One of these techniques, which was considered for the first time in 1965 (Refs. 1 and 2) appeared as well-suited for practical purposes. As in most numerical procedures, the flow field is computed at the nodal points of a mesh. The mesh covers the shock layer only. Its fineness is controlled by two parameters in plane and axisymmetric problems, and by three parameters in three-dimensional problems. Obviously, the finer the mesh, the longer the computational time required to obtain the solution. ** One important advantage of the technique resides in the fact that, even when an extremely coarse mesh is used, the values at the nodal points may be sufficiently accurate to provide a useful

---


** In problems involving two space parameters, halving the mesh size in both directions lengthens the computational time by a factor of 8. A factor of 16 is related to the halving of the mesh size in all three directions in a three-dimensional problem.
preliminary description of the flow field. If the mesh is coarse, the computational time is of the order of a few seconds. By increasing the number of nodal points, not only more detailed information is obtained but the accuracy is increased. A computation which requires about two minutes of machine operation yields results whose accuracy is generally greater than that of the most sophisticated experiments. In this connection, it may be noted that the use of a very coarse mesh is conceptually similar to the application of the method of integral relations (Ref. 3) with one or two strips. However, the present technique does not require a reformulation of the equations if the fineness of the mesh is increased, but merely a change in the two, or three, integers which define the number of nodal points.

Therefore, it was considered appropriate to perform a systematic series of computations with a twofold purpose:

1) to test the technique in the widest possible range of body shapes and flow properties, and

2) to provide a parametric compilation of cases which are of practical interest, in the hope that it could be used as a quick reference for neighboring cases.

Part of the results are published in the present report. Since the object of the report is a compilation and discussion of

*All time estimates are based on actual computations performed on the CDC 6600 computer.
results, only a few words will be spent to describe the procedure used to obtain them. In what follows, the main features of the technique will be recalled from the previous communications referred to above and the adoption of new frames of reference will be justified.

2. Outline of the Computational Technique

For the sake of simplicity, we will focus our attention on the two-dimensional case. Let AB (Figs. 1 and 2) be a section of the body, CD a section of the shock wave, EF the sonic line. In Refs. 1 and 2, the equations of motion are written in a Cartesian frame (x,y). A natural boundary of the region to be computed is then

![FIG. 1](image1)

![FIG. 2](image2)
the closed line ABDCA, which has a segment, BD, parallel to the x-axis. Such a choice is possible only if (i) the body slope is positive up to a point inside the supersonic region, and (ii) the sonic line does not intersect the upper boundary. Both limitations are particularly severe if the free stream Mach number is low.

The present computations have been performed after reformulating the equations of motion in a polar \((r, \theta)\) frame, as in Fig. 2. In the axisymmetric case, a spherical frame \((r, \theta, \phi)\) is used, with the polar axis along the body centerline. In any meridional plane the section of the flow field appears again as in Fig. 2.

As in Ref. 2, the region to be computed is first mapped onto a rectangle (Fig. 3) by linearly stretching the \(r\)-coordinate between shock and body. New coordinates, \(\xi\), \(Y\) and \(T\) are introduced,
defined by
\[ \zeta = \frac{r - r_{\text{body}}}{r_{\text{shock}} - r_{\text{body}}} \]
\[ Y = n = 0 \]
\[ T = t \]

where \( t \) is the time.

To compute interior points, the equations of motion are reformulated in terms of the new independent variables. Then the derivatives of the equations of motion with respect to \( \zeta, Y \) and \( T \) are formally evaluated. From such a system of equations the first and second order derivatives of density \( \rho \), velocity components \( u \) and \( v \), and entropy \( S \) with respect to \( T \) can be expressed as functions of first and second order derivatives of the same parameters with respect to \( \zeta \) and \( Y \). The increment of any parameter \( f(f,\zeta,u,v,S) \) in a time step, \( t \), is computed as
\[ \Delta f = \frac{3f}{\partial T} \Delta T + \frac{1}{2} \frac{3^2 f}{\partial T^2} \Delta T^2 \]

The time step at each nodal point is taken equal to
\[ \frac{\Delta s}{1.5(q+a)} \]

where \( q = (u^2 + v^2)^{\frac{1}{2}} \), \( a \) is the local speed of sound, and \( \Delta s \) is the length of the shorter local side of a mesh quadrangle in the physical plane. At the end of each step, the local increments are linearly interpolated to a common time step, chosen as the smallest
of the local time steps.

Shock and body points are computed differently. In both cases the pressure is determined by a modified method of characteristics, as outlined in Ref. 2. At shock points a complete system of equations is obtained by considering the Rankine-Hugoniot conditions for a moving shock. The system is then solved by iterating on a preliminary guess until the relative error in the velocity component normal to the shock is less than a prescribed tolerance, ε.

At body points, two additional conditions are obtained by writing that the entropy is constant for a moving particle and by using the momentum equation for the tangential velocity. Again, the complete system is solved by iterating on a preliminary guess until the error in the distance between the body and the initial point on the characteristic is less than ε.

The computation is started by assuming a parabolic shape of the shock and prescribing a linear distribution of Mach numbers on the body. The shock is initially assumed at rest. The values of pressure (p), c, u, v, and S are computed behind the shock and at the body, and linearly distributed at the interior points of the mesh.

3. Presentation of the Numerical Results

The computational program has options to output partial results at any stage as well as at the end of the run. These include the mesh coordinates, the pressure, density, velocity components,
entropy and Mach number at each mesh point. To get a direct feeling for the properties of the flow field, plots are necessary. Such plots, together with some typical numerical information, are obtained by processing the final output of the programs on a Stromberg-Carlson 4020 cathode tube display machine. Two pages of plots are printed, as shown in this report. It will be recalled that only two-dimensional symmetric and axisymmetric flows of a perfect gas are considered at this time.

In the first page, the physical nature of the flow is described by the free stream Mach number and the value of the ratio of specific heats, \( \gamma \). The shape of the body and the extent of the computed region are shown in the figures of the second page and in the lower left figure in the first page. The number of mesh intervals is indicated in the first page; the first number denotes the number of intervals between shock and body and the second number denotes the number of intervals along the body.

As an example, in Fig. 4 a mesh is shown which corresponds to the legend "4 BY 6 MESH". The mesh points on the body are marked by short lines pointing toward the origin of coordinates. The origin is the intersection of the upper boundary line and the centerline of the body.
The standoff distance is expressed in arbitrary units. The abscissa of the stagnation point is expressed in the same units. The latter can be measured on the drawings, starting from the origin, and the unit length can thus be determined. As a rule, the unit length has a simple geometrical meaning in relationship with the geometry of the body. If the cross-section of the nose is a circle, the unit length is its radius; if the cross-section is an ellipse, the unit length is its major semi-axis; if the cross-section is a rectangle with a rounded shoulder, the unit length is the height of the rectangle. Finally, if the cross-section is a parabola, it is defined by

\[ y^2 = 2(x + x_0) + 4 \]

Also, in the first page the number of time steps and the value of \( \varepsilon \) (called "TOLERANCE") used in the computation of shock and body points are shown. The values of the pressure printed in the first page are referred to the free stream pressure. The theoretical and computed values of the pressure at the stagnation point are printed, together with the relative error,

\[ E = \frac{P_{st(comp)} - P_{st(theor)}}{P_{st(theor)}} \]

The temperatures printed in the first page are referred to the free stream temperature. Again, the theoretical and computed values of the temperature at the stagnation point are printed, together with
The computed values of pressure, density and temperature at the body point where $M=1$, divided by the computed values of pressure, density and temperature at the stagnation point respectively are also printed, with their relative errors with respect to the theoretical ratios.

In the right-hand side of the first page, pressure, Mach number, and temperature along the body surface are plotted. The pressure is scaled to the computed pressure at the stagnation point and the temperature is scaled to the computed temperature at the stagnation point. The abscissae of these plots are angles, $\alpha$ (in degrees) measured between the centerline and a line joining the body point to the origin (Fig. 5).

In the bottom left of the first page and in the second page the body and shock geometries are repeated five times. In the figure of the first page, some streamlines are drawn. In a steady motion the
streamlines can be defined either as lines of constant entropy or as lines of constant total pressure. When the first is used, $S$ is defined as

$$S = \ln\left(\frac{p}{p_\infty}\right) - \gamma \ln\left(\frac{\rho}{\rho_\infty}\right)$$

and the lines of constant entropy are spaced by $1/20$ of the value of $S$ at the stagnation point. Sometimes such a spacing does not provide enough information. In this case, lines of constant total pressure are used, spaced by $1/20$ of the value of $p$ at the stagnation point. As a proof of the equivalence of the two definitions, Fig. 6 shows, on the left, lines of constant entropy and, on the right, lines of constant total pressure for the same case, a two-dimensional flow about a circle at a free stream Mach number of 4. When superposed, the two figures match perfectly.

Fig. 6
The other figures are self-explanatory. To interpret them quantitatively, it must be kept in mind that the values of the Mach number on the M=constant lines are spaced .1 apart. The sonic line is drawn heavier than the other lines. The isobars correspond to constant values of $p/p_{st}$ .05 apart. The isopycnics correspond to constant values of $\rho/\rho_{st}$ .05 apart. The isotherms correspond to constant values of $T/T_{st}$ .025 apart.

4. Discussion

In the present report, only results for the two-dimensional and the axisymmetric problems and for a perfect gas at constant $\gamma$ are presented. In addition, one single program has been used for the computation of all the two-dimensional cases and one single program for all the axisymmetric cases,* regardless of the geometry of the body. In other words, no special effort was made to achieve a greater accuracy in cases of a challenging geometry (very blunt ellipses, flat-faced bodies) and we wished to explore the range of acceptability of such basic programs.

A. Mesh-size effects

To study the effect of mesh-size on accuracy, a two-dimensional flow about a circle at $M_\infty$=4 was computed five times, using the following meshes:

*These programs are labelled 2E and 2F, respectively.
<table>
<thead>
<tr>
<th>Run No.</th>
<th>199</th>
<th>200</th>
<th>201</th>
<th>202</th>
<th>203</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh</td>
<td>2 x 4</td>
<td>3 x 5</td>
<td>5 x 8</td>
<td>7 x 12</td>
<td>10 x 16</td>
</tr>
<tr>
<td>Total number of steps</td>
<td>160</td>
<td>240</td>
<td>400</td>
<td>560</td>
<td>800</td>
</tr>
<tr>
<td>Total time at final step</td>
<td>6.354</td>
<td>7.590</td>
<td>7.861</td>
<td>7.395</td>
<td>7.948</td>
</tr>
</tbody>
</table>

(the time is scaled to $r_o \sqrt{\frac{r_o}{p_\infty}}$, where $r_o$ is the radius of the circle and $c_\infty$ and $p_\infty$ are the free stream values of density and pressure, respectively). In Figs. 7 and 8, the time history of some representative parameters is shown for the coarsest and the finest mesh of the set above. In the top and bottom parts of the figures respectively, the standoff distance and the pressure at the stagnation point are plotted (the latter is scaled to the free stream pressure). The middle part is the plot of the logarithm (base 10) of the difference between the maximum and minimum values of the velocity of the shock points, divided by the free stream velocity. Since the time-dependent computation aims at reaching a steady state, the first and third functions should asymptotically tend to a constant value, and the second function should tend to $-\infty$. One can see from the graphs that the stagnation point pressure and the standoff distance reach a steady state in a relatively short time, whereas the shock wave is never perfectly at rest. This last feature is a result of the finiteness of the mesh, of the tolerance accepted in the iterations, and of the limited capacity of the computer. However, for all practical purposes, a
Fig.
Fig. 8
shock wave whose velocity is five orders of magnitude smaller than the free stream velocity is a steady configuration.

No major differences can be noted between Fig. 7 and Fig. 8, despite the strong difference in mesh-size. The final results of all the cases mentioned above show, obviously, a better and smoother definition of values as the mesh-size is made finer and finer. The general trend of the curves, however, is the same in all cases. In addition, from a quantitative point-of-view, the differences between different cases at each point are surprisingly small.

One can conclude that, in a case where the body shape is fairly smooth, preliminary estimates can be made with a fast, inexpensive run using a very coarse mesh. To make the point clearer, the dependence of some relevant parameters on mesh-size is shown in Fig. 9. The first plot shows the logarithm (base 10) of the relative error in pressure and temperature, as computed at the stagnation point. These errors seem to level off at a value of about $10^{-4}$, probably because of the worsening of round-off effects with decreasing mesh-size. The second plot shows similar errors in $p$, $\rho$, and $T$ as computed at the critical point on the body. Here it must be noted that the critical point itself and all the attached values are computed by linear interpolation between adjacent points on the body. Therefore, the accuracy is affected in different ways for different mesh-sizes (the relative location of the critical point in a mesh interval is not the same in two different cases), and this explains a greater scattering in the plot. A line has
been drawn to represent an estimate of the errors and it shows the same trend as the two lines in the first plot. The third plot shows the standoff distance whose third significant figure seems rather hard to stabilize. Finally, the fourth plot shows the location of the critical points on the body and on the shock (measured in the polar frame of reference in degrees).

![Graphs showing relative errors, stand-off distance, and location of critical points.]

**FIG. 9**

To get an idea of the price one has to pay for a greater accuracy, here is a comparison of computational times for the five cases above, taking the time for case 199 as the unit:

<table>
<thead>
<tr>
<th>Run No.</th>
<th>199</th>
<th>200</th>
<th>201</th>
<th>202</th>
<th>203</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational time</td>
<td>1</td>
<td>2.5</td>
<td>10</td>
<td>28</td>
<td>73.5</td>
</tr>
</tbody>
</table>

(the time for Run 203 is about 3 minutes on the CDC 6600).
In order to test the mesh-size effect on a body of a more complicated geometry, runs No. 169 and 270 were made. Their time histories are shown in Figs. 10 and 11, respectively. At the end of run 169 (400 steps), the standoff distance is not yet perfectly stabilized. A better situation is achieved in run 270, only because the computation runs for a longer physical time. In the final plots, the pressure and temperature distributions on the body are not substantially different between the two runs. The Mach number distribution on the body is quite different in the region of high curvature. This results from a seemingly intrinsic difficulty in computing velocities on the body where the curvature is high. More comments on this matter will be found under D. The general trends of constant Mach number lines, isobars, isopycnics, isotherms, and streamlines is the same in both cases and let us once again draw the conclusion that, for a preliminary, inexpensive evaluation of the shock layer, a coarse mesh can be used.

B. Tolerance effect

Some runs were made with different values of the tolerance in the shock and body point iterations, namely, $\varepsilon=10^{-4}$, $10^{-5}$, and $10^{-6}$. No appreciable differences were observed, and $\varepsilon=10^{-5}$ was adopted uniformly throughout the present set of runs.

C. Number of time steps necessary to achieve convergence

In all runs, plots as in Fig. 10 were made. As a general rule, the stagnation pressure is the first parameter to become stabilized.
Fig. 10
Fig. 12
Fig. 13
However, if one is interested in obtaining an accurate description of the entire flow field, it would be a mistake to use the stagnation pressure as a criterion for stopping the computation. The standoff distance takes much longer to stabilize. Moreover, the logarithmic plot of the shock wave velocity range shows that an overall stabilization of the shock wave is achieved only after a long time has elapsed. There are evidently a number of wavelets travelling over the computational region, which sometimes are hard to damp. From a physical point-of-view, an inviscid flow does not provide any mechanism for the damping of such wavelets, except on the shock wave itself. We find a similar behavior in our numerical computations since their artificial viscosity is purposely kept very low.

No attempt is made at this time to analyze the propagation and damping of wavelets in the numerical computations in relation to the propagation and damping of sound waves in the present problem. Here we simply show the patterns obtained in a specific case, a two-dimensional flow field about a 5:1 ellipse at $M_\infty = 20$.

Fig. 12 is obtained by stopping the computation at step 1000. The constant Mach number lines and the isobars seem to be pretty smooth, but the isopycnics and the isotherms are full of ripples. Fig. 13 is obtained at step 2000. Now all wavelets are practically damped. For the sake of completeness, Fig. 14 shows the time history of the run up to step 2000. Between step 1000 and step 2000 the shock velocity range drops by an order of magnitude.
In a practical case, one must decide when to stop a computation by compromising between his need for accuracy and the available computational time. If a computation has to be stopped prematurely, smoother curves can be obtained by a crude averaging of values. Fig. 15 shows how the plots of Fig. 12 look like after averaging. Of course, these curves do not exactly fall on top of the curves of Fig. 13; however, they are qualitatively correct and probably good for all practical purposes.

Another important conclusion has been reached through the present numerical experimentation. For an arbitrarily prescribed set of initial conditions, the first phase of the transient is always very active. All the major changes take place in the first 5% of the total time necessary to achieve smooth results. Therefore, the discussion above is practically independent of the choice of initial conditions.

D. Mach number and bluntness effects

To study the effect of bluntness on accuracy, we have run several cases for bodies with an elliptical nose, the ratio of the two axes of the ellipse being taken as a measure of the bluntness. An ellipse with a bluntness of 1 is a circle; an ellipse with a bluntness of 6 is almost a flat-faced body with a rounded shoulder.

However, it turned out that a study of the bluntness effect could not be achieved independently of a study of the free stream Mach number effect. Fig. 16 shows the Mach number and bluntness.
Fig. 14
Fig. 15
parameters for the cases presented in this report (for both the two-dimensional and the axisymmetric problem).

No computations were made for a bluntness parameter greater than 6. * Below 6, some of the cases had to be discarded because the results were evidently poor (the relative errors mentioned in section 3 were too high; the plots were far from being smooth). Some other cases did not even run to completion. In general, it seems that, for a given free stream Mach number, the results worsen with increasing bluntness; the program fails for values of

* See, however, a preliminary survey of flat-faced bodies under E.
the bluntness parameter above a limiting value. Such a limiting value is a function of the free stream Mach number; the lower the Mach number, the lower the limiting bluntness.

These limitations were, in a way, expected. Neither program has been tailored for handling high curvature effects on the body. The truncation errors due to the linear interpolations performed in computing the values on the wall grow excessively if the curvature of the particle paths and the consequent rate of change of physical parameters are too high. Such errors propagate within the shock layer and are steadily generated at each computational step. If we accept the hypothesis, mentioned under C, that the damping of the error waves is mostly due to a dissipative mechanism at the shock, we should conclude that a weak shock is less capable of producing damping than a strong shock. At a low Mach number, not only the error waves in the shock layer are harder to eliminate (and may even become unstable) but the shock itself is more sensitive to such perturbations and tends to wrinkle. It is interesting to note that, at very low Mach numbers, the shock wave is actually extremely sensitive to all perturbations, and it is hard to keep it stable in an experiment. However, it is not the intention here to suggest any quantitative correlation between the natural phenomenon and the present numerical effects. This is, at least, premature. It should be noted, also, that at a low Mach number the disturbance field to be computed becomes very large in comparison
to the body size. Consequently, the overall accuracy tends to deteriorate. We would rather say that it is surprising how far one can force the bluntness, and how close to 1 the Mach number can be taken, with still acceptable results, and that this can be done without increasing the number of mesh points over 200 and without providing any special treatment for high curvature walls.

How to improve the situation at low Mach numbers and high bluntness is, at this time, hard to say. Any modification to the program which increases the artificial viscosity is not advisable. With a mesh as coarse as the ones used here (and let us recall that the object of the present program is to minimize the computation time), the artificial viscosity is bound to deface the whole flow pattern (when the flow tends to become steady, the time derivatives become smaller and smaller and eventually their effect is nullified by an equal and opposite contribution of the artificial terms).

One can note that the Mach number on the wall tends to oscillate more than the pressure and the temperature. This indicates that the weakest computation is that of the velocity on the body. In the present programs, the velocity is computed by using one of the momentum equations. The energy equation has been tried instead, with no success. The latter defines the square of the modulus of the velocity by the difference between the Lagrangian and the Eulerian derivatives of pressure. Truncation errors can
occasionally make such a square become negative, so that the computa-
tion halts. Some attempts to damp the oscillations in velocity at
the wall only resulted in a general catastrophic worsening of the
computation, except perhaps, in the case of a sharp corner where
the wall region before the corner is practically disconnected from
the wall region behind the corner. The matter is being studied
further.

In the range of validity of these programs, some interesting
parametric results can be obtained, which confirm and extend the
ones available in Hayes and Probstin's book. Fig. 17 shows dif-
ferent shapes of shock waves and sonic lines for two-dimensional
elliptical bodies at different Mach numbers; Fig. 18 does the same
in the axisymmetric case. Each part of these figures deals with
a given Mach number to show the bluntness effect. Figs. 19 and
20 show the Mach number effect on the shock wave and the sonic
line for a parabolic body in the two-dimensional and the axisym-
metric case, respectively. Figs. 21 and 22 show the Mach number
effect on the shock wave and the sonic line for a circular nose
in the two-dimensional and the axisymmetric case, respectively.
FIG. 18
b. List of Cases Reported

In this report, the results for the following cases are shown:

Two-dimensional problem (program 2E):

A. Study of the mesh size effect

<table>
<thead>
<tr>
<th></th>
<th>Run No.</th>
<th>Circumferential M = 4</th>
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<tbody>
<tr>
<td>A1</td>
<td>199</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>169</td>
<td>Flat-faced body with a rounded shoulder, $M_{\infty} = 0$</td>
</tr>
<tr>
<td>A7</td>
<td>270</td>
<td></td>
</tr>
</tbody>
</table>

B. Mach number effect on a circular nose:

<table>
<thead>
<tr>
<th></th>
<th>Run No.</th>
<th>$M_{\infty}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>320</td>
<td>20</td>
</tr>
<tr>
<td>B2</td>
<td>221</td>
<td>10</td>
</tr>
<tr>
<td>B3</td>
<td>(see A5)</td>
<td>4</td>
</tr>
<tr>
<td>B4</td>
<td>222</td>
<td>3</td>
</tr>
<tr>
<td>B5</td>
<td>423</td>
<td>2</td>
</tr>
<tr>
<td>B6</td>
<td>324</td>
<td>1.7</td>
</tr>
<tr>
<td>B7</td>
<td>325</td>
<td>1.5</td>
</tr>
</tbody>
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C. Elliptical nose at $M_{\infty} = 20$

<table>
<thead>
<tr>
<th></th>
<th>Run No.</th>
<th>Bluntness parameter</th>
</tr>
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<tbody>
<tr>
<td>C1</td>
<td>(see B1)</td>
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<tr>
<td>C2</td>
<td>215</td>
<td>2</td>
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<tr>
<td>C3</td>
<td>319</td>
<td>3</td>
</tr>
<tr>
<td>C4</td>
<td>316</td>
<td>4</td>
</tr>
<tr>
<td>C5</td>
<td>317</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>318</td>
<td>6</td>
</tr>
</tbody>
</table>

D. Elliptical nose at $M_{\infty} = 10$

<table>
<thead>
<tr>
<th></th>
<th>Run No.</th>
<th>Bluntness parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>(see B2)</td>
<td>1</td>
</tr>
<tr>
<td>D2</td>
<td>230</td>
<td>2</td>
</tr>
<tr>
<td>D3</td>
<td>331</td>
<td>3</td>
</tr>
<tr>
<td>D4</td>
<td>332</td>
<td>4</td>
</tr>
<tr>
<td>D5</td>
<td>233</td>
<td>5</td>
</tr>
<tr>
<td>D6</td>
<td>234</td>
<td>6</td>
</tr>
</tbody>
</table>
E. Elliptical nose at $M_\infty = 4$

<table>
<thead>
<tr>
<th>Run</th>
<th>No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>(see A5)</td>
<td>1</td>
</tr>
<tr>
<td>E2</td>
<td>210</td>
<td>2</td>
</tr>
<tr>
<td>E3</td>
<td>211</td>
<td>3</td>
</tr>
<tr>
<td>E4</td>
<td>212</td>
<td>4</td>
</tr>
<tr>
<td>E5</td>
<td>313</td>
<td>5</td>
</tr>
</tbody>
</table>

F. Elliptical nose at $M_\infty = 2$

<table>
<thead>
<tr>
<th>Run</th>
<th>No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>(see B5)</td>
<td>1</td>
</tr>
<tr>
<td>F2</td>
<td>340</td>
<td>2</td>
</tr>
<tr>
<td>F3</td>
<td>341</td>
<td>3</td>
</tr>
</tbody>
</table>

G. Parabolic nose

<table>
<thead>
<tr>
<th>Run</th>
<th>No.</th>
<th>$M_\infty = 20$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>450</td>
<td>10</td>
</tr>
<tr>
<td>G2</td>
<td>451</td>
<td>10</td>
</tr>
<tr>
<td>G3</td>
<td>352</td>
<td>4</td>
</tr>
</tbody>
</table>

Axisymmetric problem (program 2F):

B. Mach number effect on a spherical nose

<table>
<thead>
<tr>
<th>Run</th>
<th>No.</th>
<th>$M_\infty = 20$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>120</td>
<td>10</td>
</tr>
<tr>
<td>B2</td>
<td>121</td>
<td>10</td>
</tr>
<tr>
<td>B3</td>
<td>103</td>
<td>4</td>
</tr>
<tr>
<td>B4</td>
<td>122</td>
<td>3</td>
</tr>
<tr>
<td>B5</td>
<td>223</td>
<td>2</td>
</tr>
<tr>
<td>B6</td>
<td>124</td>
<td>1.7</td>
</tr>
<tr>
<td>B7</td>
<td>125</td>
<td>1.5</td>
</tr>
</tbody>
</table>

C. Ellipsoid, at $M_\infty = 20$

<table>
<thead>
<tr>
<th>Run</th>
<th>No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>(see B1)</td>
<td>1</td>
</tr>
<tr>
<td>C2</td>
<td>115</td>
<td>2</td>
</tr>
<tr>
<td>C3</td>
<td>119</td>
<td>3</td>
</tr>
<tr>
<td>C4</td>
<td>116</td>
<td>4</td>
</tr>
<tr>
<td>C5</td>
<td>117</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>118</td>
<td>6</td>
</tr>
</tbody>
</table>
### D. Ellipsoid, at $M_\infty = 10$

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>1</td>
</tr>
<tr>
<td>131</td>
<td>2</td>
</tr>
<tr>
<td>132</td>
<td>3</td>
</tr>
<tr>
<td>133</td>
<td>4</td>
</tr>
<tr>
<td>134</td>
<td>5</td>
</tr>
</tbody>
</table>

### E. Ellipsoid, at $M_\infty = 4$

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>1</td>
</tr>
<tr>
<td>111</td>
<td>2</td>
</tr>
<tr>
<td>112</td>
<td>3</td>
</tr>
<tr>
<td>113</td>
<td>4</td>
</tr>
</tbody>
</table>

### F. Ellipsoid, at $M_\infty = 2$

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Bluntness Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>1</td>
</tr>
<tr>
<td>141</td>
<td>2</td>
</tr>
</tbody>
</table>

### G. Paraboloid

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$M_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>151</td>
<td>10</td>
</tr>
<tr>
<td>152</td>
<td>4</td>
</tr>
</tbody>
</table>

### H. Flat-faced cylinder with a rounded shoulder, $M_\infty = 10.5$

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Shoulder Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>.50</td>
</tr>
<tr>
<td>81</td>
<td>.25</td>
</tr>
<tr>
<td>82</td>
<td>.10</td>
</tr>
<tr>
<td>83</td>
<td>.05</td>
</tr>
</tbody>
</table>

The H-series of runs has been made to test the computational technique against a recently issued set of experimental data (Ref. 5 and 6). The computed pressure distributions on the body, when expressed as a function of the arc-length, fall exactly on
top of the experimental curves. The shock waves also fit exactly the experimental shapes. Some of the computed patterns are rather irregular, particularly when $\sigma$ is very small, but this should be expected, as we said in section 4. Note, for example, that the body shape assumed by the machine in case H4 is only a rough approximation to a flat-faced cylinder with a rounded shoulder, $\sigma = .05$.

6. **Acknowledgements**

The initial work on the two-dimensional and the axisymmetric problem for a perfect gas was performed at the General Applied Science Laboratories under the sponsorship of the Advanced Research Projects Agency in 1965 (Refs. 1 and 2). The extension to three-dimensional flows of a perfect gas was also performed at the General Applied Science Laboratories under the sponsorship of the Sandia Corporation, in 1966 (Ref. 4). More recently, the Sandia Corporation sponsored additional work, as a result of which the problem was reformulated in new frames of reference; the pertinent analysis, performed last year at the General Applied Science Laboratories, is not available in the open literature. The computations shown in the present report make use of the latter frames of reference, with some additional features added in the last few
months. The latter research, as well as the parametric study partially contained in the present report, has been performed at the Polytechnic Institute of Brooklyn under the sponsorship of the Office of Naval Research under Contract Nonr 839(34).

The plots have been obtained by transferring the pertinent information (as computed by the CDC 6600 machine at the Courant Institute of the New York University) to the Stromberg-Carlson 4020 plotter of the Polytechnic Institute of Brooklyn and by using an additional plotting program. I am glad to acknowledge the dedicated and efficient assistance of Mr. Martin Tillinger of the Polytechnic Institute of Brooklyn in the delicate manipulation necessary to obtain these plots.

7. References


TWO-DIMENSIONAL CASES
2 by 4 Cond. IED tests Tolerance E鸟 0.0000

Free stream Mach number = 4.00, 

TENT. STAGNATION PRESSURE = 21.70
COND. STAGNATION PRESSURE = 20.10

RELATIVE ERROR N. 0.0101

TENT. STAGNATION TEMPERATURE = 4.200
COND. STAGNATION TEMPERATURE = 4.107

RELATIVE ERROR N. 0.0041

CRITICAL PRESSURE RATIO 0.6705 (I.L. CRIT. 0.6703)
CRITICAL DENSITY RATIO 0.6705 (I.L. CRIT. 0.6703)
CRITICAL TEMPERATURE RATIO 0.6705 (I.L. CRIT. 0.6704)

STATION DISTANCE 0.0260

ACCELERATION OF STATION POINT N 1.0000

--- Diagram ---

--- Diagram ---

--- Diagram ---
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 200

FREE STREAM MACH NUMBER = 4.00, BETA = 1.40

THEOR. STAGNATION PRESSURE = 21.600
COMP. STAGNATION PRESSURE = 21.840
RELATIVE ERROR = 0.00131

THEOR. STAGNATION TEMPERATURE = 4.200
COMP. STAGNATION TEMPERATURE = 4.198
RELATIVE ERROR = 0.00007

CRITICAL PRESSURE RATIO = 0.5339 (REL. ERROR = 0.0162)
CRITICAL DENSITY RATIO = 0.6407 (REL. ERROR = 0.0163)
CRITICAL TEMPERATURE RATIO = 0.8330 (REL. ERROR = 0.0169)

STANDBY DISTANCE = 0.5191
ABSCISSA OF STAGNATION POINT = -1.00000

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 201

5 BY 8 MESH, 400 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00, DISTANCE= 1.40

THEOR. STATIONARY PRESSURE= 21.000
COMP. STATIONARY PRESSURE= 21.072
RELATIVE ERROR= 0.00020

THEOR. STATIONARY TEMPERATURE= 4.200
COMP. STATIONARY TEMPERATURE= 4.200
RELATIVE ERROR= 0.00003

CRITICAL PRESSURE RATIO=0.5234 (REL. ERROR= 0.00013)
CRITICAL DENSITY RATIO=0.6334 (REL. ERROR= 0.00033)
CRITICAL TEMPERATURE RATIO=0.0342 (REL. ERROR= 0.00183)

STANDOFF DISTANCE=0.0005
ACCURACY OF STATION POINT= -1.00000

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

HIGH Flux DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

46
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 202

7 BY 12 MESH, 500 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=4.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE=21.000
COM. STAGNATION PRESSURE=21.005
RELATIVE ERROR=0.00013

THEOR. STAGNATION TEMPERATURE=4.200
COM. STAGNATION TEMPERATURE=4.200
RELATIVE ERROR=0.00003

CRITICAL PRESSURE RATIO=0.500 (REL. ERROR=0.0000)
CRITICAL DENSITY RATIO=0.600 (REL. ERROR=0.0001)
CRITICAL TEMPERATURE RATIO=0.600 (REL. ERROR=0.0011)

STANDBY DISTANCE=0.0000
AXISSAA OF STAGNATION POINT=-1.0000

STREAKLINER3

PRESSURE DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

48
TWO DIMENSIONAL SYMMETRIC INLET BODY  RUN NO 203

10 by 10 mesh, 800 steps TOLERANCE +0.000010

FREE STREAM MACH NUMBER = 4.00  GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 21.000
COMP. STAGNATION PRESSURE = 21.072
RELATIVE ERROR = 0.00017

THEOR. STAGNATION TEMPERATURE = 4.200
COMP. STAGNATION TEMPERATURE = 4.200
RELATIVE ERROR = 0.00009

CRITICAL PRESSURE RATIO = 0.5207  (REL. ERROR = 0.0007 )
CRITICAL DENSITY RATIO = 0.6240  (REL. ERROR = 0.0001)
CRITICAL TEMPERATURE RATIO = 0.0330  (REL. ERROR = 0.0000)

STANDOFF DISTANCE = 0.440
ABSCISSA OF STAGNATION POINT = -1.00000
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOHEAT
TWO DIMENSIONAL SIMPLIFIED BLUNT BODY  RUN NO 168

3 BY 8 MESH, 400 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER: 6.00  GAMMA=1.40

THEOR. STAGNATION PRESSURE= 46.815
COMP. STAGNATION PRESSURE= 46.831
RELATIVE ERROR= 0.00004

THEOR. STAGNATION TEMPERATURE= 8.200
COMP. STAGNATION TEMPERATURE= 8.201
RELATIVE ERROR= 0.00004

CRITICAL PRESSURE RATIO=0.7115  (REL. ERROR= 0.0367 )
CRITICAL DENSITY RATIO=0.7729  (REL. ERROR= 0.2183 )
CRITICAL TEMPERATURE RATIO=0.9212  (REL. ERROR= 0.1054 )

STANDOFF DISTANCE=0.8394
ABSCISSA OF STAGNATION POINT= -1.0394

PLOT OF PRESSURE DISTRIBUTION ON THE BODY

PLOT OF MACH NUMBER DISTRIBUTION ON THE BODY

PLOT OF TEMPERATURE DISTRIBUTION ON THE BODY

52
1D DIMENSIONAL SYMMETRIC BLUNT BODY

RUN NO. 270

10 BY 10 MESH, 800 STEPS TOLERANCE=0.0000010

FREE STREAM MACH NUMBER= 0.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 48.015
COMP. STAGNATION PRESSURE= 48.790
RELATIVE ERROR= 0.00003

THEOR. STAGNATION TEMPERATURE= 6.200
COMP. STAGNATION TEMPERATURE= 6.199
RELATIVE ERROR= 0.00015

CRITICAL PRESSURE RATIO= 0.6568 (REL. ERROR= 0.1497)
CRITICAL DENSITY RATIO= 0.6577 (REL. ERROR= 0.1003)
CRITICAL TEMPERATURE RATIO= 0.6700 (REL. ERROR= 0.0449)

STANDOFF DISTANCE= 0.0777
ABSCISSA OF STAGNATION POINT= -1.00000
CONSTANT MACH NUMBER LINES

ISOBIARS

CONSTANT DENSITY LINES

ISOETHERMS
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 320

10 BY 12 MESH, 800 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00, BETA=1.40

THEOR. STAGNATION PRESSURE=515.484
COMP. STAGNATION PRESSURE=515.661
RELATIVE ERROR= 0.0034

THEOR. STAGNATION TEMPERATURE= 81.000
COMP. STAGNATION TEMPERATURE= 81.008
RELATIVE ERROR= 0.0000

CRITICAL PRESSURE RATIO= 0.5302 (REL. ERROR= 0.0038 )
CRITICAL DENSITY RATIO= 0.6354 (REL. ERROR= 0.0022 )
CRITICAL TEMPERATURE RATIO= 0.8344 (REL. ERROR= 0.0012 )

STANDOFF DISTANCE= 0.3921
ABSCISSA OF STAGNATION POINT= -1.55000

STREAMLINES

PLOT OF PRESSURE DISTRIBUTION ON THE BODY

PLOT OF MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

56
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOOTHERMS
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 221

10 BY 12 MESH 800 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00 GAMA=1.40

THEOR. STAGNATION PRESSURE=120.217
COMP. STAGNATION PRESSURE=129.227
RELATIVE ERROR=0.00016

THEOR. STAGNATION TEMPERATURE=21.000
COMP. STAGNATION TEMPERATURE=21.001
RELATIVE ERROR=0.00005

CRITICAL PRESSURE RATIO=0.5301 (REL. ERROR=0.0035)
CRITICAL DENSITY RATIO=0.6333 (REL. ERROR=0.0024)
CRITICAL TEMPERATURE RATIO=0.0342 (REL. ERROR=0.0011)

STANDEOFF DISTANCE=0.4000
ABSCISSA OF STAGNATION POINT=-1.5000

STREAMLINES

1.00
0.80
0.60
0.40
0.20
0.00
6.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0
PRESSURE DISTRIBUTION ON THE BODY

3.00
2.00
1.00
0.00
0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0
MACH NUMBER DISTRIBUTION ON THE BODY

1.00
0.80
0.60
0.40
0.20
0.00
0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0
TEMPERATURE DISTRIBUTION ON THE BODY

58
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 222

10 BY 12 MESH = 600 STEPS  TOLERANCE = 0.000010

FREE STREAK MACH NUMBER = 3.00  GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 12.081
COMP. STAGNATION PRESSURE = 12.082
RELATIVE ERROR = 0.00008

THEOR. STAGNATION TEMPERATURE = 2.800
COMP. STAGNATION TEMPERATURE = 2.800
RELATIVE ERROR = 0.00003

CRITICAL PRESSURE RATIO = 0.5297  (REL. ERROR = 0.0026 )
CRITICAL DENSITY RATIO = 0.6348  (REL. ERROR = 0.0029 )
CRITICAL TEMPERATURE RATIO = 0.8348  (REL. ERROR = 0.0017 )

STANDBF DISTANCE = 0.6940
ABSCISSA OF STAGNATION POINT = -1.50000
TWO-DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 023

10 by 12 MESH, 600 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 2.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 5.640

COMP. STAGNATION PRESSURE= 5.619

RELATIVE ERROR= 0.0034

THEOR. STAGNATION TEMPERATURE= 1.800

COMP. STAGNATION TEMPERATURE= 1.700

RELATIVE ERROR= 0.0010

CRITICAL PRESSURE RATIO=0.5774 (REL. ERROR=0.0017 )

CRITICAL DENSITY RATIO=0.6327 (REL. ERROR=0.0019 )

CRITICAL TEMPERATURE RATIO=0.0333 (REL. ERROR=0.0022 )

STANDOFF DISTANCE=1.2748

ABSCISSA OF STAGNATION POINT= -1.50000

STREAMLINES
Two Dimensional Symmetric Blunt Body

Run No 324

10 by 20 mesh, 1000 steps, tolerance = 0.000010

Free Stream Mach Number = 1.70, Gamma = 1.40

Theor. Stagnation Pressure = 4.224
Comp. Stagnation Pressure = 4.179
Relative Error = 0.01163

Theor. Stagnation Temperature = 1.570
Comp. Stagnation Temperature = 1.573
Relative Error = 0.00333

Critical Pressure Ratio = 0.5791 (Rel. Error = 0.0016)
Critical Density Ratio = 0.6344 (Rel. Error = 0.0010)
Critical Temperature Ratio = 0.0341 (Rel. Error = 0.0010)

Stagnation Point = 1.0230
Abscissa of Stagnation Point = 1.50000
CONSTANT DENSITY LINES

ISOTHERMS

PROGRAM 24, RUN NO 376, Mx 1.78

CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOTHERMS
TWO DIMENSIONAL SYMETRIC BLUNT BODY RUN NO. 229

10 BY 20 MODEL, 1153 STEPS, TOLERANCE=0.000010

FREE STREAM FROCE NUMBER = 1.56, DRAFT = 1.40

THEOR. STAGNATION PRESSURE = 3.413
COMP. STAGNATION PRESSURE = 3.310
RELATIVE ERROR = 0.0343

THEOR. STAGNATION TEMPERATURE = 1.400
COMP. STAGNATION TEMPERATURE = 1.441
RELATIVE ERROR = 0.0287

CRITICAL PRESSURE RATIO=0.5230 (REL. ERROR=0.0013)
CRITICAL DENSITY RATIO=0.6344 (REL. ERROR=0.0007)
CRITICAL TEMPERATURE RATIO=0.9399 (REL. ERROR=0.0003)

STAGNOE DISTANCE=2.5798
ASCII OF STAGNATION POINT=-1.99999
CONSTANT MACH NUMBER LINES

CONSTANT DENSITY LINES

ISOBARS

Isotherms

67
TWO DIMENSIONAL SYMMETRIC BLUNT BODY

RUN NO 219

10 BY 20 MESH: 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00 \ D\ \ GAMMA=1.40

THEOR. STAGNATION PRESSURE=515.484
COMP. STAGNATION PRESSURE=515.524
RELATIVE ERROR=0.0002

THEOR. STAGNATION TEMPERATURE=91.000
COMP. STAGNATION TEMPERATURE=91.002
RELATIVE ERROR=0.0002

CRITICAL PRESSURE RATIO=0.5242 [REL. ERROR=0.0077]
CRITICAL DENSITY RATIO=0.6391 [REL. ERROR=0.0028]
CRITICAL TEMPERATURE RATIO=0.0319 [REL. ERROR=0.0017]

STANDOFF DISTANCE=0.5280
ABSCISSA OF STAGNATION POINT=1.30000

FREE STREAM MACH NUMBER=20.00 \ D\ \ GAMMA=1.40

THEOR. STAGNATION PRESSURE=515.484
COMP. STAGNATION PRESSURE=515.524
RELATIVE ERROR=0.0002

THEOR. STAGNATION TEMPERATURE=91.000
COMP. STAGNATION TEMPERATURE=91.002
RELATIVE ERROR=0.0002

CRITICAL PRESSURE RATIO=0.5242 [REL. ERROR=0.0077]
CRITICAL DENSITY RATIO=0.6391 [REL. ERROR=0.0028]
CRITICAL TEMPERATURE RATIO=0.0319 [REL. ERROR=0.0017]

STANDOFF DISTANCE=0.5280
ABSCISSA OF STAGNATION POINT=1.30000
Two-dimensional symmetric blunt body run no 319

10 by 20 mesh, 2000 steps tolerance = 0.000010

Free stream Mach number = 20.00, Gamma = 1.40

Theor. stagnation pressure = 515.494
Comp. stagnation pressure = 515.370
Relative error = 0.00022

Theor. stagnation temperature = 91.000
Comp. stagnation temperature = 90.555
Relative error = 0.00046

Critical pressure ratio = 0.5779 (rel. error = 0.0040)
Critical density ratio = 0.6753 (rel. error = 0.0250)
Critical temperature ratio = 0.6339 (rel. error = 0.0200)

Stagnation distance = 0.042
Abscissa of stagnation point = -1.1333

Streamlines

Pressure distribution on the body

Temperature distribution on the body
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 316

10 BY 20 MESH, 2000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00  BETA=1.40

THEOR. STAGNATION PRESSURE=515.401
COM. STAGNATION PRESSURE=515.332
RELATIVE ERROR=0.00010

THEOR. STAGNATION TEMPERATURE=91.000
COM. STAGNATION TEMPERATURE=86.533
RELATIVE ERROR=0.00001

CRITICAL PRESSURE RATIO=0.5101 (REL. ERROR=0.0230)
CRITICAL DENSITY RATIO=0.0101 (REL. ERROR=0.0234)
CRITICAL TEMPERATURE RATIO=0.0337 (REL. ERROR=0.0004)

STANOFF DISTANCE=0.7200
ABSCISSA OF STAGNATION POINT=1.05000

STREAMLINE
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

Isotherms
1D DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 317

10 BY 20 MESH, 2000 STEPS TOLERANCE=0.0000001

FREE STREAM MACH NUMBER=20.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE=515.494
COMP. STAGNATION PRESSURE=515.332
RELATIVE ERROR= 0.00000

THEOR. STAGNATION TEMPERATURE= 01.000
COMP. STAGNATION TEMPERATURE= 00.993
RELATIVE ERROR= 0.00000

CRITICAL PRESSURE RATIO=0.55500 (REL. ERROR= 0.0522 )
CRITICAL DENSITY RATIO=0.6527 (REL. ERROR= 0.0287 )
CRITICAL TEMPERATURE RATIO=0.5547 (REL. ERROR= 0.0287 )

STAGNOFF DISTANCE=0.7029

ASCISSA OF STAGNATION POINT= -1.00000

<table>
<thead>
<tr>
<th>STREAM LINES</th>
</tr>
</thead>
</table>

![Graph 1](image1.png)

<table>
<thead>
<tr>
<th>PRESSURE DISTRIBUTION ON THE BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>1.00</td>
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</table>

![Graph 2](image2.png)

<table>
<thead>
<tr>
<th>MACH NUMBER DISTRIBUTION ON THE BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>1.00</td>
</tr>
</tbody>
</table>

![Graph 3](image3.png)

<table>
<thead>
<tr>
<th>TEMPERATURE DISTRIBUTION ON THE BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>0.00</td>
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74
ISOTHERMS

CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

Isotherms
TWO DIMENSIONAL SYMPHONIC BLUNT BODY  RUN NO 310

10 BY 20 MESH, 2000 STEPS  TOLERANCE=0.000016

FREE STREAM MACH NUMBER=20.00  GAMMA=1.40

THEOR. STAGNATION PRESSURE=515.404
COMP. STAGNATION PRESSURE=515.302
RELATIVE ERROR= 0.00035

THEOR. STAGNATION TEMPERATURE= 01.000
COMP. STAGNATION TEMPERATURE= 00.932
RELATIVE ERROR= 0.00010

CRITICAL PRESSURE RATIO=0.1034  (REL. ERROR= 0.1143)
CRITICAL DENSITY RATIO=0.0707  (REL. ERROR= 0.0703)
CRITICAL TEMPERATURE RATIO=0.0705  (REL. ERROR= 0.0422)

STANDOFF DISTANCE=0.7764
ABSICZA OF STAGNATION POINT= 0.00007

STRAILINES

PRESSURE DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

76
TWO DIMENSIONAL SYMMETRIC BLUNT BODY

RUN NO 233

10 BY 20 MESH. 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00. GAMMA= 1.40

THEOR. STAGNATION PRESSURE=120.217
COMP. STAGNATION PRESSURE=120.217
RELATIVE ERROR=0.00000

THEOR. STAGNATION TEMPERATURE=21.000
COMP. STAGNATION TEMPERATURE=21.000
RELATIVE ERROR=0.00000

CRITICAL PRESSURE RATIO=0.5237 (REL. ERROR=0.0037)
CRITICAL DENSITY RATIO=0.6237 (REL. ERROR=0.0037)
CRITICAL TEMPERATURE RATIO=0.5017 (REL. ERROR=0.0020)

STANEOFF DISTANCE=0.5012
ASCENDA OF STAGNATION POINT=1.30000

STREAMLINES
10 BY 20 MESH, 2000 STIPS, TOLERANCE=0.00010

FREE STREAM MACH NUMBER=10.0, DRAFT=1.40

THEOR. STAGNATION PRESSURE=123.217
COMP. STAGNATION PRESSURE=120.157
RELATIVE ERROR=0.00015

THEOR. STAGNATION TEMPERATURE= 21.600
COMP. STAGNATION TEMPERATURE= 20.500
RELATIVE ERROR=0.00004

CRITICAL PRESSURE RATIO=0.5777 (INC. ERROR=0.0003)
CRITICAL DENSITY RATIO=0.6731 (INC. ERROR=0.0000)
CRITICAL TEMPERATURE RATIO=0.6397 (INC. ERROR=0.0001)

STANDOFF DISTANCE=0.6315
ACCELERATION OF STAGNATION POINT=1.1373

STREAK LINE
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOHERMS
TWO DIMENSIONAL SYMMETRIC PLANT CODE  RUN NO 332

10 BY 20 MESH, 1000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, GAMMA= 1.40

THEORY. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.152
RELATIVE ERROR= 0.00055

THEORY. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 20.637
RELATIVE ERROR= 0.00014

CRITICAL PRESSURE RATIO= 0.5579  (REL. ERROR= 0.0003 )
CRITICAL DENSITY RATIO= 0.6631  (REL. ERROR= 0.0003 )
CRITICAL TEMPERATURE RATIO= 0.6152  (REL. ERROR= 0.0032 )

STANDOFF DISTANCE=0.7613
ASSCISA OF STAGNATION POINT= -0.37000
PROGRAM 2C. RUN NO 332. M=10.88

CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOCHROMS
1D DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 223

10 BY 20 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.073
RELATIVE ERROR= 0.00117

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 20.533
RELATIVE ERROR= 0.0032

CRITICAL PRESSURE RATIO=0.6551 (REL. ERROR= 0.0323 )
CRITICAL DENSITY RATIO=0.6254 (REL. ERROR= 0.0293 )
CRITICAL TEMPERATURE RATIO=0.6341 (REL. ERROR= 0.0293 )

STANDBOFF DISTANCE=0.7723
ABSCISSA OF STAGNATION POINT= 1.00000

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

84
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 231

18 BY 20 MESH 1000 STEPS TOLERANCE = 0.000010

FREE STREAM MACH NUMBER = 10.00, DYNAMIC = 1.40

THEORY, STATIONARY PRESSURE = 129.277
COMP. STATIONARY PRESSURE = 129.945
RELATIVE ERROR = 0.00133

THEORY, STATIONARY TEMPERATURE = 21.600
COMP. STATIONARY TEMPERATURE = 20.592
RELATIVE ERROR = 0.00330

CRITICAL PRESSURE RATIO = 0.5977 (REL. ERROR = 0.1129)
CRITICAL DENSITY RATIO = 0.6772 (REL. ERROR = 0.0119)
CRITICAL TEMPERATURE RATIO = 0.0378 (REL. ERROR = 0.0114)

STANDOFF DISTANCE = 0.7097
ASSOCIATED STATIONARY POINT = 0.02087

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY
10 BY 20 R2DM, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 21.000
COMP. STAGNATION PRESSURE= 21.000
RELATIVE ERROR= 0.000010

THEOR. STAGNATION TEMPERATURE= 4.200
COMP. STAGNATION TEMPERATURE= 4.100
RELATIVE ERROR= 0.00010

CRITICAL PRESSURE RATIO= 1.5203 (REL. ERROR= 0.0141)
CRITICAL DENSITY RATIO= 0.0274 (REL. ERROR= 0.0103)
CRITICAL TEMPERATURE RATIO= 2.0301 (REL. ERROR= 0.0029)

STANDOFF DISTANCE= 0.7643
ANALOGUE OF STAGNATION POINT= -1.32000

STAGNATION POINT: -1.32000
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

Isotherms
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 211

10 BY 20 MESH, 1000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00  GAMA= 1.40

THEOR. STAGNATION PRESSURE= 21.450
COMP. STAGNATION PRESSURE= 21.600
RELATIVE ERROR= 0.00010

THEOR. STAGNATION TEMPERATURE= 4.200
COMP. STAGNATION TEMPERATURE= 4.169
RELATIVE ERROR= 0.00014

CRITICAL PRESSURE RATIO= 0.5700  (REL. ERROR= 0.0302 )
CRITICAL DENSITY RATIO= 0.6733  (REL. ERROR= 0.0775 )
CRITICAL TEMPERATURE RATIO= 0.6050  (REL. ERROR= 0.0230 )

STANOFF DISTANCE= 0.0741
ABSCISSA OF STAGNATION POINT= -1.13333

90
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOThERMS
1-D DIMENSIONAL HYDRATIC BLUNT BODY

10 BY 20 MESH, 1000 STEPS, TOLERANCE = 0.000001

FINAL STREAM MACH NUMBER = 4.10, GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 21.000

COMP. STAGNATION PRESSURE = 21.034

RELATIVE ERROR = 0.0003

THEOR. STAGNATION TEMPERATURE = 4.200

COMP. STAGNATION TEMPERATURE = 4.153

RELATIVE ERROR = 0.0003

CRITICAL PRESSURE RATIO = 0.6229 (THEOR. ERROR = 0.0038)

CRITICAL DENSITY RATIO = 0.7131 (THEOR. ERROR = 0.0003)

CRITICAL TEMPERATURE RATIO = 0.6720 (THEOR. ERROR = 0.0003)

STAGNATION DISTANCE = 0.0015

ACCURACY OF STAGNATION POINT = 1.00000

STREAMLINES
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 313

10 BY 20 MESH, 2000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 21.626
COMP. STAGNATION PRESSURE= 21.032
RELATIVE ERROR= 0.00277

THEOR. STAGNATION TEMPERATURE= 4.298
COMP. STAGNATION TEMPERATURE= 4.109
RELATIVE ERROR= 0.00277

CRITICAL PRESSURE RATIO= 0.5439  (REL. ERROR= 0.0205 )
CRITICAL DENSITY RATIO= 0.9406  (REL. ERROR= 0.0118 )
CRITICAL TEMPERATURE RATIO= 0.8488  (REL. ERROR= 0.0184 )

STANOFF DISTANCE= 0.9718
ABSCISSA OF STAGNATION POINT= -1.00000

STREAMLINES
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 340

10 BY 20 MESH, 2000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 2.00, GAMMA= 1.4

THEOR. STAGNATION PRESSURE= 5.640
COMP. STAGNATION PRESSURE= 5.607
RELATIVE ERROR= 0.00599

THEOR. STAGNATION TEMPERATURE= 1.800
COMP. STAGNATION TEMPERATURE= 1.797
RELATIVE ERROR= 0.00171

CRITICAL PRESSURE RATIO= 0.5332 (REL. ERROR= 0.0094 )
CRITICAL DENSITY RATIO= 0.6373 (REL. ERROR= 0.0055 )
CRITICAL TEMPERATURE RATIO= 0.9335 (REL. ERROR= 0.0030 )

STANDOFF DISTANCE=1.6597
ABSCISSA OF STAGNATION POINT= 0.70000

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Diagram: Streamlines
TWO DIMENSIONAL SYMMETRIC BLUNT BODY RUN NO 341

10 BY 20 MESH, 2000 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 2.00, BETA= 1.40

THEOR. STANDBATION PRESSURE= 5.840

COMP. STANDBATION PRESSURE= 5.629

RELATIVE ERROR= 0.00202

THEOR. STANDBATION TEMPERATURE= 1.800

COMP. STANDBATION TEMPERATURE= 1.729

RELATIVE ERROR= 0.00038

CRITICAL PRESSURE RATIO=0.5290 (REL. ERROR= 0.0014 )
CRITICAL DENSITY RATIO=0.6335 (REL. ERROR= 0.0007 )
CRITICAL TEMPERATURE RATIO=0.0331 (REL. ERROR= 0.0021 )

STANDBOFF DISTANCE=1.0358

ABSCISSA OF STANDBATION POINT= -0.5333
PROGRAM 2E - RUN NO 311 - M = 2.00

Constant Mach Number Lines

Isocontours

Constant Density Lines

Isotherms
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 450

8 BY 13 MEAS.  600 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00.  BAMA= 1.40

THEOR. STAGNATION PRESSURE=515.484
COMP. STAGNATION PRESSURE=515.757
RELATIVE ERROR= 0.00053

THEOR. STAGNATION TEMPERATURE= 81.000
COMP. STAGNATION TEMPERATURE= 81.012
RELATIVE ERROR= 0.00015

CRITICAL PRESSURE RATIO= 0.5247  (REL. ERROR= 0.0000)
CRITICAL DENSITY RATIO= 0.6310  (REL. ERROR= 0.0050)
CRITICAL TEMPERAT. RATIO= 0.9318  (REL. ERROR= 0.0019)

STANDOFF DISTANCE= 0.4644
ABSCISSA OF STAGNATION POINT = 2.00000

STREAMLINES
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 451

6 BY 13 MESH, 800 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, BARR= 1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.287
RELATIVE ERROR= 0.00055

THEOR. STAGNATION TEMPERATURE=21.000
COMP. STAGNATION TEMPERATURE=21.003
RELATIVE ERROR= 0.00015

CRITICAL PRESSURE RATIO=0.5241 (REL. ERROR= 0.0070 )
CRITICAL DENSITY RATIO=0.6303 (REL. ERROR= 0.0057 )
CRITICAL TEMPERATURE RATIO=0.8315 (REL. ERROR= 0.0022 )

STANDOFF DISTANCE=0.4914
ABSCISSA OF STAGNATION POINT= -2.00000

STREAMLINES
TWO DIMENSIONAL SYMMETRIC BLUNT BODY  RUN NO 352

8 BY 13 MESH, 1400 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00  GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 21.068
COMP. STAGNATION PRESSURE= 21.079
RELATIVE ERROR= 0.00052

THEOR. STAGNATION TEMPERATURE= 4.200
COMP. STAGNATION TEMPERATURE= 4.201
RELATIVE ERROR= 0.00015

CRITICAL PRESSURE RATIO=0.5218  (REL. ERROR= 0.0123)
CRITICAL DENSITY RATIO=0.6229  (REL. ERROR= 0.0093)
CRITICAL TEMPERATURE RATIO=0.6304  (REL. ERROR= 0.0035)

STANDOFF DISTANCE=8.7139
ABSissa OF STAGNATION POINT= -2.00000

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY
CONSTANT MACH NUMBER LINES

LOCATING

CONSTANT DENSITY LINES

LOCATING
AXISYMMETRIC CASES
AXISYMMETRIC BLUNT BODY

RUN NO 120

10 BY 7 MESH, 600 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00, GAMMA=1.40

THEOR. STATION PRESSURE=515.404
COMP. STATION PRESSURE=515.556
RELATIVE ERROR= 0.00014

THEOR. STATION TEMPERATURE= 01.000
COMP. STATION TEMPERATURE= 01.003
RELATIVE ERROR= 0.00004

CRITICAL PRESSURE RATIO= 0.5311 (REL. ERROR= 0.0054 )
CRITICAL DENSITY RATIO= 0.0055 (REL. ERROR= 0.0024 )
CRITICAL TEMPERATURE RATIO= 0.0208 (REL. ERROR= 0.0035 )

STANDOFF DISTANCE= 0.1304
ABSCISSA OF STATION POINT= -1.50000

STREAKLINES
AXISYMMETRIC BLUNT BODY

RUN NO 121

10 BY 2 MESH, 600 STEPS TOLERANCE=0.0000008

FREE STREAM MACH NUMBER=10.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.240
RELATIVE ERROR= 0.00008

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 21.001
RELATIVE ERROR= 0.00005

CRITICAL PRESSURE RATIO=0.5300 (REL. ERROR= 0.00022 )
CRITICAL DENSITY RATIO=0.6140 (REL. ERROR= 0.00005 )
CRITICAL TEMPERATURE RATIO=0.6300 (REL. ERROR= 0.00005 )

STANOFF DISTANCE=0.1350

ABSCISSA OF STAGNATION POINT= 1.55008

STREAKLINES
AXISYMMETRIC BLUNT BODY

RUN NO 103

10 BY 12 MESH, 800 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00, DARAMA= 1.40

THEORETICAL STAGNATION PRESSURE= 21.00
COMPRESSIBLE STAGNATION PRESSURE= 21.072
RELATIVE ERROR= 0.00019

THEORETICAL STAGNATION TEMPERATURE= 4.200
COMPRESSIBLE STAGNATION TEMPERATURE= 4.200
RELATIVE ERROR= 0.00000

CRITICAL PRESSURE RATIO= 0.5204, REL. ERROR= 0.0021
CRITICAL DENSITY RATIO= 0.6397, REL. ERROR= 0.0012
CRITICAL TEMPERATURE RATIO= 0.6391, REL. ERROR= 0.0010

STANDOFF DISTANCE= 0.1752
ABSCISSA OF STAGNATION POINT= 1.00000

STREAKLINES
AXISYMMETRIC BLUNT BODY

RUN NO 127

10 BY 8 MESH, 600 STEPS, TOLERANCE=0.0000001

FREE STREAM MACH NUMBER=3.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE= 12.031
COMP. STAGNATION PRESSURE= 12.002
RELATIVE ERROR= 0.00005

THEOR. STAGNATION TEMPERATURE= 2.000
COMP. STAGNATION TEMPERATURE= 2.000
RELATIVE ERROR= 0.00002

CRITICAL PRESSURE RATIO= 0.0002 (REL. ERROR= 0.0005)
CRITICAL DENSITY RATIO= 0.0391 (REL. ERROR= 0.0008)
CRITICAL TEMPERATURE RATIO= 0.0381 (REL. ERROR= 0.0005)

STANCOFF DISTANCE= 0.2168
ABSCISSA OF STAGNATION POINT= 1.50000

STANNOFF DISTANCE= 0.2168
ABSCISSA OF STAGNATION POINT= 1.50000
AXISYMMETRIC BLUNT BODY  RUN #223

10 X 12 MESH, 400 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 2.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 0.140
COMP. STAGNATION PRESSURE= 0.600
RELATIVE ERROR= 0.00024

THEOR. STAGNATION TEMPERATURE= 1.000
COMP. STAGNATION TEMPERATURE= 1.000
RELATIVE ERROR= 0.00001

CRITICAL PRESSURE RATIO= 0.0031 (REL. ERROR= 0.0003)
CRITICAL DENSITY RATIO= 0.0021 (REL. ERROR= 0.0002)
CRITICAL TEMPERATURE RATIO= 0.0034 (REL. ERROR= 0.0013)

STANDOFF DISTANCE= 0.3514
ANODISSA OF STAGNATION POINT= 1.0000

STREAMLINES
AXISYMMETRIC BLUNT BODY

RUN NO 124

10 BY 15 MESH, 800 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 1.78, GAMMA= 1.40

THEOR. STAGNATION PRESSURE= 4.224
COMP. STAGNATION PRESSURE= 4.226
RELATIVE ERROR= 0.00000

THEOR. STAGNATION TEMPERATURE= 1.578
COMP. STAGNATION TEMPERATURE= 1.578
RELATIVE ERROR= 0.00000

CRITICAL PRESSURE RATIO= 0.5202 (REL. ERROR= 0.0002)
CRITICAL DENSITY RATIO= 0.6373 (REL. ERROR= 0.0002)
CRITICAL TEMPERAT. RATIO= 0.0333 (REL. ERROR= 0.0000)

STANDOFF DISTANCE= 0.4653
ABSCISSA OF STAGNATION POINT= 1.00000

PRESSURE DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

STREAKLINES
AXISYMMETRIC BLUNT BODY

10 BY 10 MESH, 200 STEPS, TOLERANCE = 0.000010

FREE STREAM MACH NUMBER = 1.50, BETA = 1.40

THEOR. STATIONARY PRESSURE = 3.413
COMP. STATIONARY PRESSURE = 3.414
RELATIVE ERROR = 0.00003

THEOR. STATIONARY TEMPERATURE = 1.450
COMP. STATIONARY TEMPERATURE = 1.450
RELATIVE ERROR = 0.00004

CRITICAL PRESSURE RATIO = 0.507 (REL. ERROR = 0.0000)
CRITICAL DENSITY RATIO = 0.0042 (REL. ERROR = 0.0003)
CRITICAL TEMPERATURE RATIO = 0.0337 (REL. ERROR = 0.0003)

STANDBY DISTANCE = 0.6210
ABSCissa OF STATIONARY POINT = 1.00000

STREAMLINES

PRESsURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

120
AXISYMMETRIC BLUNT BODY

RUN NO 115

10 BY 15 GRID, 550 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00, DAMN=1.40

THEOR. STAGNATION PRESSURE=415.484
COMP. STAGNATION PRESSURE=415.726
RELATIVE ERROR= 0.00076

THEOR. STAGNATION TEMPERATURE=81.600
COMP. STAGNATION TEMPERATURE=80.724
RELATIVE ERROR= 0.00087

CRITICAL PRESSURE RATIO=0.0313
CRITICAL DENSITY RATIO=0.0175
CRITICAL TEMPERATURE RATIO=0.0079

STANDOFF DISTANCE=0.2400
ABSCISSA OF STATIONARY POINT= -1.30000

PRESSURE DISTRIBUTION ON THE BODY

1.00
0.80
0.60
0.40
0.20
0.00

0.0 10.0 20.0 30.0 40.0 50.0

MACH NUMBER DISTRIBUTION ON THE BODY

1.00
0.80
0.60
0.40
0.20
0.00

0.0 10.0 20.0 30.0 40.0 50.0

TEMPERATURE DISTRIBUTION ON THE BODY

1.00
0.80
0.60
0.40
0.20
0.00

0.0 10.0 20.0 30.0 40.0 50.0
AXISYMMETRIC BLUNT BODY

RUN NO 119

10 BY 10 MESH 1000 STEPS TOLERANCE 0.000010

FREE STREAM MACH NUMBER = 0.000010 GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 515.404
COMP. STAGNATION PRESSURE = 515.509
RELATIVE ERROR = 0.00020

THEOR. STAGNATION TEMPERATURE = 81.000
COMP. STAGNATION TEMPERATURE = 81.005
RELATIVE ERROR = 0.00000

CRITICAL PRESSURE RATIO = 0.5414 (REL. ERROR = 0.0000)
CRITICAL DENSITY RATIO = 0.6440 (REL. ERROR = 0.0000)
CRITICAL TEMPERATURE RATIO = 0.8408 (REL. ERROR = 0.0000)

STANDOFF DISTANCE = 0.2754
ABSCISSA OF STAGNATION POINT = -1.13333
CONSTANT MACH NUMBER LINES

ISOQUANTS

CONSTANT DENSITY LINES

ISOCONTS
AXISYMMETRIC BLUNT BODY

RUN NO 116

18 BY 17 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE=515.494
COMP. STAGNATION PRESSURE=515.450
RELATIVE ERROR=0.00007

THEOR. STAGNATION TEMPERATURE=61.000
COMP. STAGNATION TEMPERATURE=60.028
RELATIVE ERROR=0.00002

CRITICAL PRESSURE RATIO=0.5437 (REL. ERROR=0.0281)
CRITICAL DENSITY RATIO=0.6489 (REL. ERROR=0.0100)
CRITICAL TEMPERATURE RATIO=0.8418 (REL. ERROR=0.0101)

STANDBY DISTANCE=0.3111
ABSCISSA OF STAGNATION POINT=-1.05000
10 BY 17 MESH: 1000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=20.00  BETA= 1.40

THEOR. STAGNATION PRESSURE=515.404
COMP. STAGNATION PRESSURE=515.323
RELATIVE ERROR= 0.00031

THEOR. STAGNATION TEMPERATURE= 81.000
COMP. STAGNATION TEMPERATURE= 80.833
RELATIVE ERROR= 0.00009

CRITICAL PRESSURE RATIO=0.5003 (REL. ERROR= 0.0533 )
CRITICAL DENSITY RATIO=0.6531 (REL. ERROR= 0.0331 )
CRITICAL TEMPERATURE RATIO=0.6304 (REL. ERROR= 0.0203 )
STANDOFF DISTANCE=0.3384
ABSCISSA OF STAGNATION POINT= -1.00000
AXISYMMETRIC BLUNT BODY

RUN NO 118

18 BY 17 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=2.00, GAMMA= 1.40

THEOR. STAGNATION PRESSURE=515.484
COMP. STAGNATION PRESSURE=515.260
RELATIVE ERROR= 0.00042

THEOR. STAGNATION TEMPERATURE= 81.000
COMP. STAGNATION TEMPERATURE= 80.090
RELATIVE ERROR= 0.00012

CRITICAL PRESSURE RATIO=0.5919 (REL. ERROR= 0.1014)
CRITICAL DENSITY RATIO=0.6708 (REL. ERROR= 0.0704)
CRITICAL TEMPERATURE RATIO=0.0579 (REL. ERROR= 0.0292)

STANDOFF DISTANCE=0.2503
ABSCISSA OF STAGNATION POINT= -0.26867

STREAMLINES

130
AXISYMMETRIC BLUNT BODY

RUN NO 130

10 BY 10 MESH; 1000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00  BETA= 1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.258
RELATIVE ERROR= 0.0023

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 21.002
RELATIVE ERROR= 0.0009

CRITICAL PRESSURE RATIO= 0.5346  (REL. ERROR= 0.0124)
CRITICAL DENSITY RATIO= 0.6399  (REL. ERROR= 0.0079)
CRITICAL TEMPERATURE RATIO= 0.8371  (REL. ERROR= 0.0049)

STANDOFF DISTANCE= 0.2772
ABSCISSA OF STAGNATION POINT= -1.30000

STREAMLINES
CONSTANT MACH NUMBER LINES

ISCORS

CONSTANT DENSITY LINES

ISOThERMS

PROGRAM 2D, RUN 103 - M=10.03
AXISYMMETRIC BLUNT BODY  

RUN NO 131

10 BY 10 MESH, 1000 STEPS  
TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, ADHMA= 1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.256
RELATIVE ERROR= 0.00530

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 21.002
RELATIVE ERROR= 0.00009

CRITICAL PRESSURE RATIO= 0.5413 (REL. ERROR= 0.0246 )
CRITICAL DENSITY RATIO= 0.6439 (REL. ERROR= 0.0157 )
CRITICAL TEMPERATURE RATIO= 0.8456 (REL. ERROR= 0.0087 )

STANDOFF DISTANCE=0.2847
ABSCISSA OF STAGNATION POINT= -1.13333

STENARIO
AXISYMMETRIC BLUNT BODY

RUN NO 132

10 BY 17 MESH, 1000 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, GAMMA= 1.43

THEOR. STAGNATION PRESSURE=129.217

COMP. STAGNATION PRESSURE=129.231

RELATIVE ERROR= 0.00013

THEOR. STAGNATION TEMPERATURE= 21.000

COMP. STAGNATION TEMPERATURE= 21.001

RELATIVE ERROR= 0.00000

CRITICAL PRESSURE RATIO=0.5439 (REL. ERROR= 0.0296 )

CRITICAL DENSITY RATIO=0.6461 (REL. ERROR= 0.0191 )

CRITICAL TEMPERATURE RATIO=0.6419 (REL. ERROR= 0.0193 )

STANDOFF DISTANCE=0.3210

ABSCISSA OF STAGNATION POINT= -1.05000

STREAMLINES
CONSTANT Mach NUMBER LINES

ISOTHERMS

CONSTANT DENSITY LINES

ISOTHERMS
AXISYMMETRIC BLUNT BODY

RUN NO 133

10 BY 17 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM RAY NUMBER=10.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.202
RELATIVE ERROR= 0.00011

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 20.909
RELATIVE ERROR= 0.00003

CRITICAL PRESSURE RATIO=0.5595 (REL. ERROR= 0.0590 )
CRITICAL DENSITY RATIO=0.6599 (REL. ERROR= 0.0279 )
CRITICAL TEMPERATURE RATIO=0.6553 (REL. ERROR= 0.0244 )

STANDOFF DISTANCE=0.3487
ABSCISSA OF STAGNATION POINT= -1.00000

- STREAMLINES -

1.00
0.80
0.60
0.40
0.20
0.00

0.0 10.0 20.0 30.0 40.0 50.0 60.0
PRESSURE DISTRIBUTION ON THE BODY

2.00
1.50
1.00
0.50
0.00

0.0 10.0 20.0 30.0 40.0 50.0 60.0
RHS NUMBER DISTRIBUTION ON THE BODY

1.00
0.80
0.60
0.40
0.20
0.00

0.0 10.0 20.0 30.0 40.0 50.0 60.0
TEMPERATURE DISTRIBUTION ON THE BODY

138
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

ISOTHERMS
AXISYMMETRIC BLUNT BODY

RUN NO 134

16 BY 16 MESH, 1000 STEPS, TOLERANCE=0.000018

FREE STREAM MACH NUMBER=0.89, GAMMA= 1.40

THEOR. STADNATION PRESSURE=128.217
COMP. STADNATION PRESSURE=128.902
RELATIVE ERROR= 0.00744

THEOR. STADNATION TEMPERATURE= 21.000
COMP. STADNATION TEMPERATURE= 20.989
RELATIVE ERROR= 0.00083

CRITICAL PRESSURE RATIO=0.8208 (REL. ERROR= 0.1881)
CRITICAL DENSITY RATIO= 0.7134 (REL. ERROR= 0.1254)
CRITICAL TEMPERATURE RATIO= 0.8793 (REL. ERROR= 0.0539)

STANDOFF DISTANCE= 0.3963
ABSCISSA OF STADNATION POINT= -0.68687

STREAMLINES
CONSTANT MACH NUMBER LINES

ISOBARS

CONSTANT DENSITY LINES

Isotherms
AXISYMMETRIC BLUNT BODY

RUN NO. 110

10 BY 10 MESH, 1000 STEPS, TOLERANCE 0.000010

FREE STREAM MACH NUMBER = 4.00, GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 21.050
COMP. STAGNATION PRESSURE = 21.070
RELATIVE ERROR = 0.0011

THEOR. STAGNATION TEMPERATURE = 4.200
COMP. STAGNATION TEMPERATURE = 4.200
RELATIVE ERROR = 0.0003

CRITICAL PRESSURE RATIO = 0.5301 (REL. ERROR = 0.0035)
CRITICAL DENSITY RATIO = 0.6331 (REL. ERROR = 0.0019)
CRITICAL TEMPERATURE RATIO = 0.8347 (REL. ERROR = 0.0018)

STANDOFF DISTANCE = 6.2869
ABSCISSA OF STAGNATION POINT = -1.30000

142
AXISYMMETRIC BLUNT BODY

RUN NO 111

10 BY 17 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER= 4.00, DABIA= 1.40
THEOR. STAGNATION PRESSURE= 21.059
COMP. STAGNATION PRESSURE= 21.070
RELATIVE ERROR= 0.00010

THEOR. STAGNATION TEMPERATURE= 4.200
COMP. STAGNATION TEMPERATURE= 4.200
RELATIVE ERROR= 0.00003

CRITICAL PRESSURE RATIO= 0.5414 (REL. ERROR= 0.0249)
CRITICAL DENSITY RATIO= 0.6437 (REL. ERROR= 0.0153)
CRITICAL TEMPERATURE RATIO= 0.6412 (REL. ERROR= 0.0094)

STANDOFF DISTANCE= 0.3402
ASSCISA OF STAGNATION POINT= 1.1333

STREAMLINES
AXISYMMETRIC BLUNT BODY

RUN NO 112

10 BY 17 MESH, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=4.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE=21.159
COMP. STAGNATION PRESSURE=21.074
RELATIVE ERROR=0.00027

THEOR. STAGNATION TEMPERATURE=4.200
COMP. STAGNATION TEMPERATURE=4.200
RELATIVE ERROR=0.00069

CRITICAL PRESSURE RATIO=0.5457 (REL. ERROR=0.0331)
CRITICAL DENSITY RATIO=0.6477 (REL. ERROR=0.0217)
CRITICAL TEMPERATURE RATIO=0.6423 (REL. ERROR=0.0111)

STANDOFF DISTANCE=0.3093
ABSCISSA OF STAGNATION POINT=-1.03500

STREAMLINES
AXISYMMETRIC BLUNT BODY

RUN NO 113

10 BY 17 MESH, 1000 STEPS, TOLERANCE = 0.000010

FREE STREAM MACH NUMBER = 4.00, GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 21.660
COMP. STAGNATION PRESSURE = 21.076
RELATIVE ERROR = 0.00039

THEOR. STAGNATION TEMPERATURE = 4.200
COMP. STAGNATION TEMPERATURE = 4.200
RELATIVE ERROR = 0.00011

CRITICAL PRESSURE RATIO = 0.5094 (REL. ERROR = 0.0009)
CRITICAL DENSITY RATIO = 0.6576 (REL. ERROR = 0.0374)
CRITICAL TEMPERATURE RATIO = 0.8038 (REL. ERROR = 0.0207)

STANDOFF DISTANCE = 0.4170
ABSCISSA OF STAGNATION POINT = 1.00000

STREAKLINES

PRESSURE DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

148
AXISYMMETRIC BLUNT BODY

RUN NO 140

10 BY 20 MESH, 2000 STEPS, TOLERANCE = 0.00001

FREE STREAM MACH NUMBER = 2.00, GAMMA = 1.40

THEOR. STAGNATION PRESSURE = 5.640
COMP. STAGNATION PRESSURE = 5.639
RELATIVE ERROR = 0.00003

THEOR. STAGNATION TEMPERATURE = 1.000
COMP. STAGNATION TEMPERATURE = 1.000
RELATIVE ERROR = 0.00011

CRITICAL PRESSURE RATIO = 0.5331 (REL. ERROR = 0.0140)
CRITICAL DENSITY RATIO = 0.6389 (REL. ERROR = 0.0034)
CRITICAL TEMPERATURE RATIO = 0.0370 (REL. ERROR = 0.0053)

STANOOFF DISTANCE = 0.5261
ABSCISSA OF STAGNATION POINT = 0.70000

150
10 BY 20 MESH, 2000 STEPS, TOLERANCE=0.000018

FREE STREAM MACH NUMBER= 2.00, OMEGA= 1.40

THEOR. STAGNATION PRESSURE= 5.640
COMP. STAGNATION PRESSURE= 5.637
RELATIVE ERROR= 0.00059

THEOR. STAGNATION TEMPERATURE= 1.000
COMP. STAGNATION TEMPERATURE= 1.000
RELATIVE ERROR= 0.00017

CRITICAL PRESSURE RATIO=0.5401 (REL. ERROR= 0.02323 )
CRITICAL DENSITY RATIO=0.6117 (REL. ERROR= 0.0123 )
CRITICAL TEMPERATURE RATIO=0.6416 (REL. ERROR= 0.0039 )

STANDOFF DISTANCE=0.6533
ABSCISSA OF STAGNATION POINT= 0.53333

STANNO〒 DISTANCED.G35
ABSOISSA OF STAGNATION FON= 0.53333

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY
AXISYMMETRIC BLUNT BODY

RUN NO 150

FREE STREAM MACH NUMBER: 20.00, GAMMA: 1.40

THOER. STATION PRESSURE: 515.484
COMP. STATION PRESSURE: 515.519
RELATIVE ERROR: 0.00007

THOER. STATION TEMPERATURE: 81.000
COMP. STATION TEMPERATURE: 81.002
RELATIVE ERROR: 0.00002

CRITICAL PRESSURE RATIO: 0.5705 (REL. ERROR: -0.0148)
CRITICAL DENSITY RATIO: 0.8209 (REL. ERROR: -0.0111)
CRITICAL TEMPERATURE RATIO: 0.8305 (REL. ERROR: -0.0038)

STANDOFF DISTANCE: 0.1435
ABSCISSA OF STATION POINT: -2.00000

(Temperature, Mach number, and pressure distribution diagrams are present.)
AXISYMMETRIC BLUNT BODY

RUN NO 151

0 BY 13 MESH, 1000 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.00, GAMMA=1.40

THEOR. STAGNATION PRESSURE=129.217
COMP. STAGNATION PRESSURE=129.253
RELATIVE ERROR= 0.0020

THEOR. STAGNATION TEMPERATURE= 21.000
COMP. STAGNATION TEMPERATURE= 21.002
RELATIVE ERROR= 0.0000

CRITICAL PRESSURE RATIO=0.5194 (REL. ERROR= 0.010 )
CRITICAL DENSITY RATIO=0.6772 (REL. ERROR= 0.0122 )
CRITICAL TEMPERATURE RATIO=0.5725 (REL. ERROR= 0.0040 )

STANDOFF DISTANCE=0.1504
ABSCissa of STAGNATION POINT= -2.0000

PRESSURE DISTRIBUTION ON THE BODY

MACH NUMBER DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY

STREAMLINES
AXISYMMETRIC BLUNT BODY

RUN NO 152

0 BY 13 MESH: 1400 STEPS TOLERANCE 0.000210

FREE STREAM MACH NUMBER = 4.00, DENSITY 1.48

THEOR. STAGNATION PRESSURE = 21.000
COMP. STAGNATION PRESSURE = 21.078
RELATIVE ERROR = 0.00038

THEOR. STAGNATION TEMPERATURE = 4.200
COMP. STAGNATION TEMPERATURE = 4.200
RELATIVE ERROR = 0.00010

CRITICAL PRESSURE RATIO = 0.5194 (REL. ERROR = 0.0168)
CRITICAL DENSITY RATIO = 0.6201 (REL. ERROR = 0.0124)
CRITICAL TEMPERATURE RATIO = 0.8203 (REL. ERROR = 0.0045)

STANOFF DISTANCE = 0.1902
ABSCISSA OF STAGNATION POINT = 2.00000

STREAMLINES
AXISYMMETRIC BLUNT BODY

RUN NO. 80

10 BY 11 MESH, 1000 STEPS, TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.59, GAMMA=1.40

THEOR. STADATION PRESSURE=147.414

COMP. STADATION PRESSURE=142.359

RELATIVE ERROR=0.00045

THEOR. STATIONATION TEMPERATURE=23.050

COMP. STATIONATION TEMPERATURE=23.047

RELATIVE ERROR=0.00013

CRITICAL PRESSURE RATIO=0.5373 (REL. ERROR=0.0171)

CRITICAL DENSITY RATIO=0.6411 (REL. ERROR=0.0113)

CRITICAL TEMPERAT. RATIO=0.6381 (REL. ERROR=0.0057)

STANDOFF DISTANCE=0.3119

ABSCissa OF STATIONATION POINT=-1.3119

STREAMLINES
AXISYMMETRIC BLUNT BODY  RUN NO 81

16 BY 16 MESH, 1000 STEPS  TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.50, GAMMA=1.40

THEOR. STAGNATION PRESSURE=142.414
COMP. STAGNATION PRESSURE=141.930
RELATIVE ERROR= 0.00340

THEOR. STAGNATION TEMPERATURE= 23.050
COMP. STAGNATION TEMPERATURE= 23.029
RELATIVE ERROR= 0.0097

CRITICAL PRESSURE RATIO=0.5774 (REL. ERROR= 0.0331)
CRITICAL DENSITY RATIO=0.6721 (REL. ERROR= 0.0362)
CRITICAL TEMPERATURE RATIO=0.0591 (REL. ERROR= 0.0350)

STANDOFF DISTANCE=0.4010
ABSCISSA OF STAGNATION POINT= 1.00000
AXISYMMETRIC BLUNT BODY

RUN NO 82

10 BY 20 POINTS, 1000 STEPS TOLERANCE=0.000010

FREE STREAM MACH NUMBER=10.59, OMEGA=1.40

THEOR. STAGNATION PRESSURE=142.414
COMP. STAGNATION PRESSURE=141.033
RELATIVE ERROR=0.0062

THEOR. STAGNATION TEMPERATURE=23.859
COMP. STAGNATION TEMPERATURE=23.623
RELATIVE ERROR=0.0016

CRITICAL PRESSURE RATIO=0.0032 (REL. ERROR=0.1597)
CRITICAL DENSITY RATIO=0.6700 (REL. ERROR=0.0704)
CRITICAL TEMPERATURE RATIO=0.6339 (REL. ERROR=0.0337)

STANDOFF DISTANCE=0.4393
ABSCISSA OF STAGNATION POINT=1.00000
AXISYMMETRIC BLUNT BODY

RUN NO. 83

10 BY 20 MESH, 1000 STEPS, TOLERANCE = 0.000010

FREE STREAM MACH NUMBER = 1.50, GAMA = 1.40

THEOR. STAGNATION PRESSURE = 142.414
COMP. STAGNATION PRESSURE = 142.03
RELATIVE ERROR = 0.00207

THEOR. STAGNATION TEMPERATURE = 29.000
COMP. STAGNATION TEMPERATURE = 29.032
RELATIVE ERROR = 0.00077

CRITICAL PRESSURE RATIO = 0.7433 (REL. ERROR = 0.0079)
CRITICAL DENSITY RATIO = 0.0034 (REL. ERROR = 0.2705)
CRITICAL TEMPERATURE RATIO = 0.0235 (REL. ERROR = 0.1152)

STANDOFF DISTANCE = 0.4618
ABSCISSA OF STAGNATION POINT = 1.00000

STREAMLINES

PRESSURE DISTRIBUTION ON THE BODY

TEMPERATURE DISTRIBUTION ON THE BODY
The results of a time-dependent computation of blunt body shock layers for two-dimensional symmetric and axisymmetric flows are presented in a systematic form for a range of values of the free stream Mach number and bodies of different shapes and variable bluntness.

A brief discussion of the relevant features of the computational technique is given. The results are presented in a graphical form; the graphs have been produced by the computer.
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<td>ROLP</td>
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