An Improved Interaction Method for Calculating Exhaust Nozzle Boattail Flows

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October 1980

Final Report for Period September 1978 - December 1979

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APPROVAL STATEMENT

This report has been reviewed and approved.

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FOR THE COMMANDER

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A turbulent boundary-layer, inviscid flow interaction method for calculating axisymmetric nozzle boattail configurations is presented. The method is applicable to flows with subsonic or supersonic free streams with Mach number in the range .5 - 1.5, including flows with shock-wave induced separation and to bodies with either high pressure exhaust plumes or solid plume simulators. The theory and some sample calculations are presented along with detailed instructions for preparation of input data, description of...
20. ABSTRACT, Concluded.

output, and instructions for operation of the computer program on an IBM 370 computer.
PREFACE

The results reported herein were developed for the Arnold Engineering Development Center, Air Force Systems Command, by Nielsen Engineering & Research, Inc., under Contract F40600-77-C-0008-P00054. The Air Force Project Manager for this contract was E. R. Thompson, AEDC/DOT. This report covers the work done during the period September 1, 1978 to December 31, 1979. The reproducibles used in the reproduction of this report were provided by the author.
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1. INTRODUCTION

The flow over the afterbody of jet aircraft is often characterized by separation which increases the drag and decreases engine performance. For subsonic flows the separation occurs in an adverse pressure gradient which causes the flow to break away from the wall and form a local area of reversed flow. The point along the wall dividing the forward and reversed flows is defined as the separation point. While an exact flow solution for the separated region can theoretically be obtained from finite difference calculations of the fully turbulent compressible Navier-Stokes equations, the complexity and expense of such calculations at the present time make that approach unrealistic for engineering requirements. Consequently, calculative techniques have been developed which consist of patching together approximate models of the flow in the various regions.

All of the methods to be discussed herein apply to axisymmetric bodies at zero angle of attack. In the method of Presz, et al. (ref. 1), the separated region is represented by a discriminating streamline which determines the effective shape of a solid body upon which an attached boundary layer is calculated. Control volume analyses locate the separation point and determine the shape of the discriminating streamline. Boundary layers and exhaust plume entrainment are modeled using integral methods. The technique is applicable to subsonic flows with Mach numbers less than that for the onset of shock induced separation, typically a free stream Mach number of about 0.9. Another approach, developed by Cosner (ref. 2), employs an integral boundary layer method for the entire body including the separated region. Empirical relations are used to extend the calculations across the separation and reattachment points for bodies with solid plume simulators. Exhaust plume entrainment is calculated by simply extending the boundary layer analysis to the plume boundary treated as a moving wall. Comparisons with data indicate the method is not successful for bodies with extensive separation. The most sophisticated approach to the problem of exhaust plume entrainment is that of Dash et al. (ref. 3) wherein finite difference methods are used for the flow calculations in all regions of the flow. Separated flow on the nozzle boattail is not considered. However, studies described by Wilmoth (ref. 4) indicate that the method correctly accounts for exhaust plume entrainment. The present author developed a method (ref. 5) which combines a finite difference inviscid flow method with integral methods for the boundary layer and exhaust plume mixing layer. The approach employed a displacement surface calculated from the viscous layer which forms an effective boundary for the inviscid flow and is compatible with the resulting inviscid pressure distribution. For separated boundary layers, the displacement surface was assumed to take the form of
A conic section. The method also included an approximate one-dimensional exhaust jet model including entrainment of the boattail boundary layer. The method was found to provide an accurate engineering prediction method for boattail flow fields with moderately underexpanded exhaust flows and for bodies with solid plume simulators for free stream Mach numbers less than that for which shock induced separation would occur on the boattail.

In this report improvements and extensions of the method of reference 5 are discussed. The improvements are the removal of the assumption that the separated displacement surface is conical and the use of a more accurate inviscid jet model based on the method of characteristics. The calculation method is extended to include shock induced separation.

2. SUBSONIC INTERACTIONS

The particular boundary layer and inviscid external flow method used in the calculations were described in references 5 and 6 and will not be described in detail here. The boundary layer method is an integral method which can be applied in a direct mode (boundary layer edge velocity, \( u_e \) prescribed) or an inverse mode (boundary layer displacement thickness, \( \delta^* \) prescribed). The inviscid flow method used is the South-Jameson (ref. 7) theory as implemented by Keller and South (ref. 8) with minor modifications to accomodate the iterative interaction procedure.

In the method described in reference 5, the first step in calculating the viscous/inviscid interaction is to calculate the inviscid flow over the basic body. The resulting distribution of the velocity at the boundary is then prescribed in the second iteration step as the boundary layer edge velocity \( u_e \) for the boundary layer calculation in the direct mode up to the separation point. The boundary layer calculation is then switched to the inverse mode and the solution is carried on into the separated flow using a prescribed distribution of the boundary layer displacement thickness \( \delta^* \). The result of the inverse calculation is a solution for the boundary layer edge velocity (the "viscous velocity") which, in general, will not agree with the "inviscid velocity" produced by the inviscid flow theory. The effective displacement surface between separation and a point downstream of reattachment or in the plume entrainment region is assumed to be conical (see fig. 1). An iterative procedure is used to find the particular cone angle \( \theta_e \) and the separation point location \( x_s \) for which the "viscous velocity" and the "inviscid velocity" will agree within an acceptable
tolerance. In the remainder of this report, this procedure will be referred to as the "Xs-θs iteration".

In the improved interaction procedure the separation point location x_s is assumed known. Also, in order to obtain a first approximation for the shape of the displacement surface an angle θ_s is assumed known. These quantities can be obtained from the method of reference 5 or several other available methods such as those evaluated by Abeyounis (ref. 9). The angle θ_s is usually estimated to be 10° as a first approximation. Thus, the new interaction procedure begins in the same manner as in reference 5. The first step is to calculate the inviscid flow over the basic body. The second step is to calculate a boundary layer displacement thickness assuming a conical displacement surface in the separated region. The next step in the new interaction procedure is the computation of the new displacement thickness distribution in which the assumption of a conical surface is dropped and the new displacement thickness is deduced from the mismatch of the viscous and inviscid velocities by

\[ \delta_{new}^* = \delta_{old}^* \frac{u_e}{u_e^*} \]

The displacement surface is prescribed in this manner for all subsequent iterations. Also, it is no longer necessary to operate the boundary layer method in a direct mode up to the separation point but the inverse method is used with the displacement surface prescribed over the entire afterbody flow region. Carter (ref. 10) has shown that this update procedure for the displacement thickness follows logically from an approximate analysis of the von Kármán momentum integral equation.

It is noted that the extension of the calculations across both the separation point and the reattachment point in the present method is accomplished in the same manner as for the method of reference 5. The approach employs an engineering approximation based on the assumptions that upstream influences are transmitted predominantly through the external inviscid flow and that violations of the boundary layer assumptions such as significant normal pressure gradients associated with separation can be neglected on the grounds that they are only important in a small neighborhood of the separation point and have negligible effect on the rest of the flow. In keeping with these assumptions, the location of the separation point is obtained independently from the boundary layer calculation and the skin friction is specified to be zero at that point keeping the boundary layer edge velocity and the displacement thickness δ∗...
continuous. By specifying the displacement thickness over the entire calculative region a smoothly converging iteration is produced. The update procedure on the displacement thickness, including a relaxation parameter, \( \omega \), can be written as

\[
\delta^*_n = \delta^*_{n-1} \left[ 1 + \omega \left( \frac{u_e}{u^*} - 1 \right) \right]
\]

where, if \( \omega = 1 \), equation (1) is obtained. It was found that overrelaxation (\( \omega > 1 \)) could be used to accelerate the convergence of the interaction process. However, with overrelaxation an oscillatory pattern was found to be produced in the convergence so that for practical calculations, underrelaxation is usually used (\( \omega < 1 \)). In the remainder of this report, this procedure will be referred to as the "\( \delta^* \)-update procedure".

It is noted that the new procedure does not provide any new information for locating the separation point, \( x_s \). Abeyounis (ref. 8) examined eight empirical and semi-empirical separation criteria and prediction methods (not including that of reference 5, the "\( x_s - \theta_s \) iteration") using experimental data from boattailed afterbodies with solid exhaust plume simulators. Abeyounis found that none of the methods accurately predicted the separation locations for all the conditions included in the data. The method of reference 5 has been found to compare favorably with the best of the criteria examined by Abeyounis. The \( x_s - \theta_s \) iteration procedure remains an option in the revised computer code.

3. SUPERSONIC INTERACTIONS

The interaction between a boundary layer and a shock wave of sufficient strength to cause separation of the boundary layer is very complex and presents formidable difficulties for developing approximate models for engineering calculations. The most detailed experimental studies of shock-wave-boundary-layer interactions in the Mach number range 1.2-1.5 have concerned normal shock waves. While the shock waves encountered on axisymmetric nozzle boattails are not necessarily normal to the surface, a similar degree of complexity of the flow to that associated with a normal shock is to be expected. Therefore, some understanding of the nature of the flow can be gained by examination of a normal-shock-boundary layer interaction. An important work for this purpose is that of Seddon (ref. 11) which discusses the
fundamental nature of normal shock and turbulent boundary layer interaction from detailed examination of velocity profiles.

An interesting feature of Seddon's work is evidence obtained that the wake hypothesis of Coles holds true over the greater part of the flow except in the immediate vicinity of the shock wave or other regions of strong pressure gradient. This is an important observation for the present work. The boundary layer method used previously for subsonic flows is based on the Coles law of the wall and law of the wake so that the work of Seddon suggests the possibility of extending the method to flows with shock waves.

In developing the calculative technique to be described here, it was found that straightforward application of the calculative techniques used in reference 5 and discussed in the previous section was not possible. Calculations using those techniques were found to be unstable. A new calculative technique was derived which employs Prandtl-Meyer theory and the semiempirical approach of Mager (ref. 12).

In order to produce a stable calculation, it was found to be necessary to eliminate from iterative calculations the boundary layer upstream of the separation point. Thus, for supersonic interactions, the first two steps of the calculation are the same as for subsonic interactions, that is, calculation of the inviscid flow over the basic body followed by a calculation of the boundary layer. The separation point is determined from the inviscid pressure distribution by an approximate method and the first boundary layer calculation is made assuming a conical separated displacement surface as in the method of reference 5. In subsequent iterations, the starting point for the boundary layer calculations is the separation point. Thus, the boundary layer upstream of the separation point is calculated only once and is assumed to be the same for all subsequent iterations. Downstream of the separation point the theory for prescribed displacement thickness is modified by replacing the arbitrarily specified $\delta^*$ distribution with an equation employing the Prandtl-Meyer function.

\[
\frac{d\delta^*}{dx} = \tan \phi - \frac{d\theta_w}{dx} \tag{3}
\]

where

\[
\phi = - \sqrt{\frac{y+1}{y-1}} \tan^{-1} \left[ \sqrt{\frac{y-1}{y+1} \left( \frac{M_e^2 - 1}{M_e^2} \right)} \right] + \tan^{-1} \left( \sqrt{\frac{M_e^2}{e - 1}} \right) + \phi_c \tag{4}
\]
with

\[ \phi_c = \phi_s + \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1}\left[ \sqrt{\frac{\gamma - 1}{\gamma + 1}} \left( \frac{M_2 s - 1}{e_s} \right) \right] + \tan^{-1}\left( \sqrt{\frac{M_2 s - 1}{e_s}} \right) \]

(5)

\[ \phi_s = \tan^{-1}\left( \frac{d\phi^*}{dx} + \frac{dr_w}{dx} \right) \]

(6)

\[ M_e = \frac{u_e}{a_e} \cos \phi \]

(7)

In the implementation of this theory the Mach number \( M_e \) in the Prandtl-Meyer function is evaluated using the velocity component \( u_e \) as calculated from the boundary layer theory for the current iteration with the tangential angle, \( \phi \), evaluated from equation (3) at the previous step of the current boundary layer integration.

The separation point used in supersonic cases is not so easily predicted as for subsonic flows. In the present method, two options are available for predicting the separation point. In one option the separation point is determined from the inviscid solution on the basic body at the first iteration. This option depends somewhat on the arbitrary spacing of the calculative mesh of the external inviscid flow in that the separation position is placed at the inviscid mesh point previous to the point at which the maximum Mach number is calculated on the boattail. In the second option, the user of the method is allowed to input any arbitrary separation point location. With the separation point known, calculation requires an initial value for the angle of the displacement surface after separation. This is determined from the theory of Mager. This theory employs the following equations:

\[ \frac{p_s}{p_i} = 1 + 0.225 \gamma M_1^2 \left[ 1 + \frac{1}{2} (\gamma - 1) M_1^2 \right] \]

(8)

\[ \left( \frac{p_f}{p_i} \right)_V = \frac{p_s}{p_i} \left[ 1 + 0.18 \gamma M_1^2 e_f \left[ 1 + 0.275 (\gamma - 1) M_1^2 \right] \right] \]

(9)

\[ \left( \frac{p_f}{p_i} \right)_I = \left[ 2 \gamma M_1^2 \sin^2 \theta_s - (\gamma - 1) \right] / (\gamma + 1) \]

(10)
\[ \tan \theta_f = \left\{ \left[ \frac{1}{2} (\gamma + 1) M_i^2 / (M_i^2 \sin^2 \theta_s - 1) - 1 \right] \tan \theta_s \right\}^{-1} \]  

The required angle \( \theta_f \) is determined by an iterative procedure as follows. The value of \( M_i \) is the maximum Mach number ahead of the shock, obtained from the inviscid solution. Then \( p_s / p_i \) is determined from equation (8), and the first approximation to \( p_f / p_i \) is determined from equation (9) with \( \theta_f \) approximated by

\[ \theta_f = \left\{ \sqrt{M_i^2 - 1} / \gamma M_i^2 \right\} \left[ (p_f / p_i) - 1 \right] \]  

so that

\[ \frac{p_f}{p_i} = \frac{p_s}{p_i} \left\{ (1 + G) / \left[ 1 + (p_s / p_i) G \right] \right\} \]  

where

\[ G = 0.18 - \sqrt{M_i^2 - 1} / \left[ 1 + 0.275 (\gamma - 1) M_i^2 \right] \]  

Then \( \theta_s \) is computed from the oblique shock relation, equation (10), and \( \theta_f \) from equation (11). Substituting \( \theta_f \) into equation (9) and calculating a new \( \theta_s \) from equation (10) allows a second value of \( \theta_f \) to be determined from equation (11). The second value of \( \theta_f \) is used as the initial value of the turning angle of the displacement surface following Mager's advice that further iteration will not improve the accuracy.

With the Prandtl-Meyer equation replacing the arbitrarily specified \( \delta^* \) distribution, there are three equations for the three unknowns, \( u_e, \delta_i, \) and \( \delta^* \) of the boundary layer theory. However, the overall flow problem is not closed since the calculation of the flow in the limited region of separation does not necessarily satisfy the boundary conditions on the flow at downstream infinity. In order to provide final closure of the problem, the Prandtl-Meyer analysis stops at the reattachment point and the calculation method returns to the \( u_e \) prescribed procedure as in the theory of reference 5. In this procedure the value of \( u_e \) that was obtained from the boundary-layer-Prandtl-Meyer theory is faired into the inviscid \( u_e \) solution obtained from the previous iteration. The result of this procedure is as in the subsonic case, two velocity distributions, one from the boundary-layer-Prandtl-Meyer theory and one from
the external inviscid-flow theory. In order to cause these velocity distributions to agree as closely as possible, another parameter must be adjusted. The parameter selected for this purpose is the boundary layer edge velocity at the separation point $U_{es}$. Because of the approximations inherent in the present model, the velocity at the separation point for the boundary-layer calculation cannot be forced to be equal to the velocity at that point in the inviscid flow for any arbitrary iteration step. Thus, the value of the initial velocity for the boundary-layer calculation is iterated until the mean squared error between the boundary-layer velocity and the inviscid velocity is minimized as for the subsonic flows discussed previously.

Due to the approximate nature of the model, it is generally not possible to cause the boundary layer and inviscid solutions to agree as closely as for subsonic cases. While it is typically possible in subsonic cases to achieve agreement to an rms error of less than one percent, an error of four-to-five percent is more typical of supersonic cases calculated to date. However, as will be shown subsequently, the pressure coefficient distribution determined from the boundary layer velocity solution compares very well with measured values.

4. EXHAUST PLUME ENTRAINMENT MODEL

The effect of an exhaust jet plume on the flow on an after-body has been found to consist of two separate effects. First is the effect of the shape of the plume. Second is the effect of the entrainment of external air into the plume boundary. The two effects oppose each other since the entrainment of low-speed external air by the high-speed jet tends to decrease the effective expansion of the jet boundary.

The shape effect of the jet plume is accounted for by the expansion of the inviscid jet core flow. The entrainment effect is determined by calculating a jet mixing displacement thickness and defining an effective body shape using that surface.

The basis of the new exhaust plume entrainment model is the technique developed by Peters, et al. (ref. 13) in which an integral method for the exhaust plume mixing layer is coupled with a method of characteristics inviscid jet calculation. The modifications to Peters' technique for the present calculation method include use of a prescribed external pressure distribution, calculation of integrals in the integral mixing layer method across the mixing layer only, that is, omitting the
external inviscid flow from the integrals, and determination of derivatives of flow quantities at the inner boundary of the mixing layer by numerical differences rather than by solution of a set of simultaneous equations. The boundary of the jet is taken to be the midpoint of the mixing layer and the displacement thickness of the mixing layer is calculated in a manner analogous to that for a boundary layer (see fig. 2). The entrainment of the boundary layer is thus accounted for to a first approximation by using the displacement surface of the jet as the effective boundary upon which to calculate a boundary layer. The boundary layer of the boattail is then simply extended onto this approximate surface as though the jet were a solid surface. Entrainment is accounted for by the fact that the displacement surface of the mixing layer velocity profile is a negative quantity relative to the jet boundary.

4.1 INTEGRAL EQUATIONS

The basic equations of the entrainment in the coordinates shown in figure 2 are:

Continuity

\[
(\rho u_r)_x + \left\{ \rho r \left[ v - u(r_w)_x \right] \right\}_r = 0 \]  \hspace{1cm} (15)

Axial Momentum

\[
\rho u u_x + \rho_0 \left[ v - u(r_w)_x \right] u_r = -\rho p_x + (\rho u u_r)_r \]  \hspace{1cm} (16)

The energy equation is represented by the approximation

\[
S = \left[ T_t/T_{te} - 1 \right] = \left[ T_{ti}/T_{te} - 1 \right] \left[ u - u_e \right]/\left[ u_i - u_e \right] \]  \hspace{1cm} (17)

where

\[
r_w = r_i + \frac{1}{2} b \hspace{1cm} \text{(see figure 2)} \]  \hspace{1cm} (18)

Integrating across the mixing/entrainment layer and using the continuity equation to eliminate the radial velocities yields
\[ \int_{r_i}^{r_w} r \left[ \rho (2u - u_w) u_x + u (u - u_w) \rho_x \right] dr \]
\[ + \frac{1}{2} (r_w^2 - r_i^2) (p_e)_x - r_w \beta_w (u_r)_w \]
\[ + r_i \rho_i \left[ v_i - u_i (r_w)_x \right] (u_w - u_i) = 0 \]  \hspace{1cm} (19)

and
\[ \int_{r_i}^{r_e} r \left[ \rho (2u - u_e) u_x + u (u - u_e) \rho_x \right] dr + \frac{1}{2} (r_e^2 - r_i^2) (p_e)_x \]
\[ + r_i \rho_i \left[ v_i - u_i (r_w)_x \right] (u_e - u_i) = 0 \]  \hspace{1cm} (20)

The results of the solution of these equations are used to define a displacement thickness
\[ \delta^* = \int_{r_w}^{r_{i+b}} \left[ 1 - \frac{\rho u}{\rho e} \right] \frac{r}{r_w} \, dr \]  \hspace{1cm} (21)

As a first approximation, it is assumed that the effective boundary of the jet is defined by
\[ r_b = r_w + \delta^* = r_i + \frac{1}{2} b + \delta^* \]

The boundary \( r_b \) is then used as an effective solid boundary on which a boundary layer is computed in the usual manner.

4.2 ENTRAINMENT LAYER VELOCITY PROFILES

The velocity profiles of the plume mixing layer are represented by
4.3 DENSITY PROFILES

The mixing/entrainment zone density profiles are determined in terms of the temperature profiles for isentropic flow

\[ \frac{\rho_e}{\rho} = \frac{T}{T_e} = (1 + m_e)(S + 1) - M_e \left( \frac{u}{u_e} \right)^2 \]  

(23)

where \( m_e = \frac{1}{2} (\gamma - 1) M_e^2 \)

4.4 TURBULENT EDDY VISCOSITY

The term \( r \omega w_B(w_u) w \) in equation (19) represents the turbulent shear stress at the half radius surface. The factor \( \beta_w \) is the eddy viscosity factor. The model for the eddy viscosity used in this work is the same as that used by Peters, et al. (ref. 13).

4.5 EQUATIONS SOLVED

Evaluation of the integrals of equations (19) and (20) with the profiles of equations (22) and (23) results in a set of two ordinary differential equations of the form

\[ A_{i1} \frac{dr_i}{dx} + A_{i2} \frac{db}{dx} + A_{i3} \frac{dp_e}{dx} = B_i \]  

(24)

with \( i = 1 \) and 2, where \( A_{ij} \) and \( B_i \) are functions of \( r_i \), \( b \), \( u_e \), and \( u_i \).

The equations (24) are numerically integrated using a simple first-order predictor-corrector method as described in reference 5.

Many terms appearing in the coefficients of equation (24) depend on the flow conditions at the inner mixing zone boundary. In order to solve the equations, the following quantities must
be evaluated at $r_i$, $\partial u/\partial x$, $\partial u/\partial r$, $\partial p/\partial x$, $\partial p/\partial r$. To provide these parameters, the inviscid jet core flow is computed using the irrotational method of characteristics simultaneously with the numerical solution of equations (24) in a manner similar to that of reference 13. This calculation is carried out until the inner mixing layer radius, $r_i$, becomes zero, or for a specified distance downstream of the nozzle. Downstream of that point, the jet boundary is assumed to be cylindrical.

5. RESULTS

In this section, the theory is compared with experimental results on axisymmetric boattail-sting and boattail-exhaust plume configurations.

5.1 CIRCULAR ARC BOATTAILS WITH SOLID PLUME SIMULATORS

Wind tunnel studies of the configuration shown in figure 3 were described in reference 14. The configuration is a cone-cylinder, with a circular arc boattail. Three of the boattails are examined here to illustrate the capabilities of the calculative method. The first example is for a boattail (configuration 1 in fig. 3) for which extensive separation is evident experimentally. Surface static pressure distributions were measured along the boattail and along the sting for free-stream Mach numbers from 0.4 to 1.2. Boundary-layer transition was tripped at $x/D = .167$. Calculations were made for Mach numbers of 0.6, 0.8, and 0.9.

In figure 4 is shown a typical variation of the rms error

$$s = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( u_{e_v} - u_{e_I} \right)^2 / N \right]^{1/2}$$

between the viscous and inviscid solutions for configuration 1 in subsonic flow. During the first four iterations a conical displacement surface was used to generate an approximate shape, and then the new procedure [eq. (2)] was used with $\omega = .5$. Large oscillations in the error occur in the first four iterations, followed by a smoothly convergent sequence. When the error is reduced to a value of the order of one percent, oscillations again appear, although of smaller amplitude. The error appears to approach an asymptotic nonzero value. The
value of the minimum error depends on a number of factors, including the coarseness of the calculation mesh used for the external inviscid flow and the smoothness of the boundary. No consistent relationship was found between the value of the minimum error and the location of the separation point.

In figure 5 is shown the effect of the new interaction model on the calculated pressure distribution for the model with the circular arc boattail of configuration 1 and cylindrical plume simulator. The separation point used for the calculations was the value predicted using the \( x_s - \theta_s \) iteration method of reference 5. The pressure coefficients shown were calculated from the viscous velocity, \( u_{ev} \). The new \( \delta^* \) update iteration procedure using equation (2) with \( \omega = 0.5 \) results in small adjustments to the shape and in turn to the pressure distribution. In figure 6 is shown other comparisons between the new theory and data from reference 14 for Mach numbers of 0.4, 0.6, 0.8, and 0.9 on the same boattail as in figure 5. The location of separation was predicted in each case as the location where

\[
H_i = \delta^*_i / \theta_i = 1.2
\]

for the first and second boundary layer iterations. The calculated pressure coefficients were determined from the average of the viscous and inviscid velocity distributions, \( u_{ev} \) and \( u_{ei} \). The comparisons for \( M_0 = 0.4, 0.6, \) and 0.8 are excellent. The comparison for \( M_0 = 0.9 \) is good although the expansion of the flow at the beginning of the boattail is slightly underpredicted. The difference for \( M_0 = 0.9 \) is probably due to the fact that a weak shock occurs which is almost of sufficient strength to cause separation. Attempts to calculate the flows using the theory for shock-induced separation were unsuccessful, but the improved subsonic theory predicts the pressure distribution well.

In figure 7 is shown the results of calculations for two cases of shock-induced separation on the same body as for the results shown in figures 5 and 6. The separation point in each case was determined by the procedure described previously. That is, \( x_s \) was derived to be the location of the inviscid calculative point previous to the point at which the maximum Mach number is calculated on the boattail at the first iteration. The pressure coefficients were determined from the viscous velocity distributions, \( u_{ev} \), for which the best agreement with the inviscid velocity was obtained. The results for a Mach number of 1.15 are very good with the predicted shock location and plateau pressure agreeing very closely with the data. For a Mach number of 1.3, the predicted shock location is very good while the predicted plateau pressure is in fair agreement with the data.
The afterbody drag on the model of figures 5, 6, and 7 is shown in figure 8. The predicted drag is slightly high for low subsonic Mach numbers but is well predicted for high subsonic Mach numbers and underpredicted for transonic Mach numbers. The prediction is excellent for the low subsonic Mach number of 1.15, but is slightly low at the higher Mach number of 1.3.

A comparison with data on configuration 2 is shown in figure 9. The boattail of configuration 2 is slightly longer than that of configuration 1 resulting in a shorter region of separated flow. The predicted pressure distribution is in excellent agreement with the data.

5.2 CIRCULAR ARC BOATTAILS WITH HIGH PRESSURE EXHAUST JETS

Four cases with real exhaust jets are shown in figure 10. The configuration 1 afterbody, was used with a sonic nozzle and jet total pressure to free-stream static pressure ratios of 2.0, 3.0, 4.0, and 5.0. The data shown are for a free-stream Mach number of 0.8. The calculations were made for a nozzle Mach number of 1.01 and pressure ratios of 2.1, 3.0, 4.0, and 5.0, respectively. These adjustments were necessary for two reasons. First, the present method of characteristics jet theory cannot calculate for a nozzle Mach number of exactly 1.0. Second, the external static pressure at the end of the boattail tends to be slightly higher than the free-stream pressure, $P_0$, so that in order to achieve a supersonic flow in the jet as required by the method of characteristics, a slightly higher pressure ratio was necessary for the lowest pressure than was used in the experiment. The separation point locations shown in figure 9 were determined by the same criterion used in the previous comparisons shown in figure 6. Good comparisons with the experimental data are calculated for all four pressure ratios although the comparison appears to improve with increasing nozzle pressure.

The predicted afterbody drag for the body with an exhaust jet is compared with experimental values in figure 11. The new theory appears to underpredict the drag for low pressure ratios and overpredict the drag for high pressure ratios. The comparison could probably be improved by using a different separation location in the calculations.

5.3 SUMMARY OF RESULTS

The calculative method developed previously was improved by removing the restriction that the separation flow region have a conical shape and by extending the Mach number range to include
flows with shock-induced separation. Also, an improved exhaust jet calculative method was incorporated based on a simultaneous solution of the method of characteristics for the inviscid jet core flow and an integral method for the jet mixing boundary.

The results of sample calculations indicate that for subsonic flows, the conical displacement surface is a very good approximation and relaxing the requirement of a conical surface yields only a small adjustment to calculated pressure distributions while providing a substantial increase in computational speed and reduction in cost.

Calculations for supersonic flows indicate the theory produces a good approximation for the pressure distribution and consequently for the afterbody drag for Mach numbers up to 1.3.

6.0 COMPUTER PROGRAM ORGANIZATION

In this section, the general organization of the programs will be described. Specific information on data required for input and data developed for output will be described in sections 7, 8, and 9. Sample Job Control Card decks for a typical IBM 370 installation are presented in section 10.

The overall program consists of a mainline program (program 1) and three main subprograms each consisting of several subroutines. The first main subprogram is the inviscid-flow program (program 2). It is a modified version of the program described in reference 8. The second main subprogram is the boundary-layer program (program 3). It is based on the integral theory described in reference 5. The third subprogram is the inviscid exhaust plume, mixing layer program (program 4). The mainline program controls the iteration between the other three programs. Either of the first two subprograms may be used separately, without iterating by appropriate choice of the input parameters.

Both the viscous-flow programs and the inviscid-flow programs require some punched card input and may require some input data from disc or tape data files. The data files must be identified by specific Logical Unit numbers. The general relationship of the programs and the various data files are shown in figure 12. The specific Logical Unit numbers required for input and output are listed in Table I. Two Logical Unit numbers are associated with each data file shown in figure 12. One unit is used for input, the other for output.

Program 2 requires initially data from cards describing the free-stream conditions, the computational mesh and the body
shape. Alternately, the program can accept the input body shape from data file 1. It can also accept an initial solution for the perturbation velocity potential from another data file (data file 2). Program 2 produces printed output lists of the appropriate flow field quantities, quantities describing the configurations and the computational mesh and several data files. Data file 2 is rewritten using the new solution for the potential. A third file (data file 3) is written containing the distribution of the axial velocity component at the inviscid boundary for use by the viscous flow program.

Program 3 requires initially the free-stream conditions and gas constants as well as parameters describing the shape of the surface over which the boundary layer is flowing. On the first iteration of a viscous-inviscid interaction, the surface shape is the same as that for program 2. On subsequent iterations, the body shape for the boundary-layer program remains the same, except when it is modified by the calculation of a new plume shape, while that for the inviscid flow is modified by the addition of the boundary layer. Program 3 can also accept data from data files as optional input. The boundary-layer-edge velocity distribution, $u_e$, can be input from data file 3, produced by program 2. The distribution of the body shape augmented by the displacement thickness can be input from data file 4. That file differs from data file 1 because it contains the raw data for $\delta^* + \xi_w$ versus $x$ as calculated by the boundary-layer program while data file 1 contains the shape interpolated to the $x$ stations of the original input shape. If program 3 is being used separately from program 2 (i.e., without iterating), two additional options are available for card input. Either the boundary-layer-edge velocity, $u_e$, can be input as mentioned previously, or the displacement thickness, $\delta^*$, may be input. These options are described more fully in sections 8.1 and 8.2.

Program 3 produces as output lists of the boundary layer and flow quantities as they are calculated along the body. In addition, program 3 produces an updated version of data file 4 and the augmented body shape (data file 1) required by program 2. Data file 4 also contains a list of the velocity ratio $u_e/u_{e0}$ corresponding to the boundary layer.

Program 3 can be used in a two-dimensional boundary layer mode if desired. However, calculation of a viscous-inviscid interaction or exhaust plume entrainment can only be done for axisymmetric cases with the present inviscid program.

All card input pertaining to programs 2 and 3 is input through an input subroutine called by program 1. Program 1 also produces a file of the quantities needed to restart and continue the calculation if the calculation should terminate before all iterations are completed. These data are stored on data file 5.
Detailed instructions regarding restarting are presented in sections 10.2.3 and 11.2.

7. INPUT TO THE PROGRAMS

The data required by the programs generally fall into three categories: (1) geometrical data; (2) flow field data; and (3) control parameters. The control parameters are indices for specifying options and iteration counters. It will be noted by comparison with reference 8 that a number of input quantities required for the inviscid-flow program have been eliminated in the present version. This has been done by incorporating the calculations required to obtain some of the quantities into the present code or by simply defining fixed values which have been found to be successful. Specifically, a value of 1.4 is used for the initial value of the subsonic relaxation factor, a value of 0.1 is used for the initial value of the supersonic relaxation factor and a value of 1.3 is used for the exponent in the normal coordinate stretching function. Also, it is assumed that the computational grid has equal step sizes in both coordinate directions at the nose of the body. Finally, the number of relaxation steps allowed in the inviscid program is fixed at 20 for the first four interaction iterations and is changed to 40 and 80 after four and eight iterations, respectively.

The general requirement of the input data is that the tabular lists of the various distributions required represent smooth curves. This is especially true of the list of body shape coordinates. The inviscid program uses cubic splines to fit the input coordinates, so those coordinates must accurately represent a smooth curve with continuous second derivatives.

7.1 TABULAR FORM

The input data required for calculating transonic viscous, inviscid-flow interactions consist of several punched cards containing parameters describing the free-stream flow conditions, the computational mesh for the inviscid calculation, initial values for the viscous flow calculation, and certain options that are available in the program. A dictionary of the input data is presented in the next section. Table II shows the input variables as they are to be punched on the data cards. More detailed explanation of the requirements for the inviscid-flow program (program 2) are presented in reference 8 and are not repeated herein.
7.2 DICTIONARY OF INPUT VARIABLES

The variables required for input on punched cards are defined in this section in the order in which they are required. Additional details on the format of the punched data are given in Table II. The first three cards of any input data deck contain a description of the case being calculated. Any or all of these three cards may be blank, but all three are required. The remaining variables in Table II are as follows:

NRSTRT  Integer indicating whether calculation is being restarted to continue a previous calculation. Only valid for interaction calculations (LPROG = 0, and LITER = TRUE. See below).

\[ \begin{array}{ll}
= 0 & \text{Start from zero. Input all quantities on cards or data files as required.} \\
> 0 & \text{Restart. Input data file 5 (Logical Unit 11) containing data from previous iteration plus all other input data files plus other card data as indicated in Table II.}
\end{array} \]

N3  Integer indicating whether restart is to begin with new values of \( \chi_5 \) and \( \theta_5 \) (see section 11.2 and Table III).

ILIM  Integer number of seconds corresponding to estimated length of calculation. When the time from the beginning of the calculation is within 10 seconds of this limit, the final restart files will be written. This assures that the job will not terminate while writing such files.

LPROG  Integer indicating level of calculation.

\[ \begin{array}{ll}
= -1 & \text{Inviscid flow only.} \\
= 0 & \text{Viscous-Inviscid interaction.} \\
= 1 & \text{Boundary layer only.}
\end{array} \]

N1  Integer iteration counter for inner viscous-inviscid iteration

N2  Integer iteration counter for \( \chi_5-\theta_5 \) iteration presently limited to a maximum of 20.

IBL  Integer indicating how interaction calculations are to begin.
= 3 Start with inviscid flow.

= 0 Start with boundary layer.

IUNIT

Integer indicating which value of the gas constant, RGAS, the energy conversion factor, XJ, the acceleration of gravity, GC, and the constants in Sutherland's temperature-viscosity relation are to be used. The choice depends on whether air is the gas being calculated and the units of the input quantities.

= 1 Input units must be pounds, feet, seconds, and °R.

= 2 Input units must be pounds, inches, seconds, and °R.

= 3 Input units must be newtons, meters, seconds, and °K.

For another gas, or other units, put in anything for IUNIT and put in nonzero values of VISC, RGAS, XJ, GC, and SCON. Any units are allowed. The basic rule is that all input quantities must be consistent with regard to units.

MIT

Number of relaxation cycles allowed for the inviscid-flow program (program 2). If a value of zero is input, a value of 20 is used. Otherwise, the input value is used.

GAM

Ratio of specific heats of the external inviscid flow.

AMINF

Free-stream Mach number.

IXY

Integer number of values of coordinate pairs, XO,YO, to be input for inviscid body shape. If IXY = 0, the required shape must be input from data file 1 (Logical Unit 14). Maximum value is 200.

XO,YO

Axial and radial coordinates of body shape for inviscid-flow calculation, 2 per card.

The next series of variables, items 7 and 8 in Table II, are for the inviscid-flow program (program 2). Detailed information on how these data are to be obtained is contained in reference 1.

IMAX

Number of grid lines in the tangential direction; I = 1 is the forward stagnation line, I = IMAX is the rear stagnation line for closed bodies and downstream
infinity for open bodies. For each grid refinement
IMAX is increased such that \( \text{IMAX}_{\text{NEW}} = 2(\text{IMAX}_{\text{OLD}}) - 1 \).
The present limit on IMAX is 81. Instructions for
changing this limit appear as comments in the program
listing (subroutine ONE0). The grid refinement option
is generally not used for viscous-inviscid interaction
calculations.

JMAX
Number of grid lines in the normal direction; \( J = 1 \)
Corresponds to an infinite distance from the body and
\( J = \text{JMAX} \) is on the body. The same formula and limit
that apply to IMAX also apply to JMAX.

MHALF
Number of grid refinements to be done. For inter-
action calculations a value of zero should be used
with a grid fine enough for adequate resolution.

KLOSE
Body type.

\[ \begin{align*}
= 0 & \quad \text{Open body (i.e., one with a sting or wake).} \\
= 1 & \quad \text{Closed body.}
\end{align*} \]

LREADP
Integer indicating whether initial estimate of poten-
tial distribution is to be input from data file 2
(Logical Unit 13).

\[ \begin{align*}
= 0 & \quad \text{No.} \\
= 1 & \quad \text{Yes.}
\end{align*} \]

If any one, or all of the next four input quantities are input
as zero, the pre-programmed values are used.

DNDZO
Step size of the normal coordinate at the body. The
pre-programmed value is 7 percent of the maximum body
diameter.

XIXM
Value of the computational coordinate, \( X \), at the
matching point of the two stretching functions used in
the finite-difference scheme (see ref. 3), for open
bodies only. Since \( X \) varies from zero to one, XIXM
is the fraction of the total number of grid points
which will be in the first stretching region (ahead of
\( x_m \)). The pre-programmed value is 0.75.

XM
Axial location, \( x_m \) (in physical coordinates), of the
junction (or matching point) between the two tangential
stretching functions, for open bodies only, see refer-
ence 8. Must be less than \( XO(IXY) \). This parameter is
used to concentrate computational mesh points in a certain region. The usual approach for interaction calculations (the preprogrammed value) is to let $x_m$ be equal to the length of the body to the beginning of the sting, or plume, XBT.

**DSDXIM**  
Step size of the tangential coordinate at the junction between the two tangential stretching functions. The preprogrammed value is 8 percent of the length of the afterbody (XBT−XZNEW).

**XBT**  
Length of the body.

**DMAX**  
Maximum body diameter.

**XZNEW**  
Length of forebody. Also, this is the axial location at which boundary-layer calculations will begin after four iterations have been calculated. The usual procedure is to start the boundary-layer calculations close to the nose of a long body at XZ (see item 17 in Table II) and then after four iterations move the starting point to XZNEW (XZNEW > XZ). In subsequent iterations, the boundary layer does not change for $X < XZNEW$. For long slender bodies with boattails, XZNEW should be the beginning of the boattail.

**PLUMIN**  
Logical variable indicating whether an exhaust plume is being calculated.

**GAMAP**  
Ratio of specific heats of exhaust gas.

**PTPPFS**  
Ratio of nozzle total pressure to free-stream static pressure.

**AMP**  
Nozzle exit Mach number.

**THTAP**  
Nozzle exit divergence angle.

**TTP**  
Nozzle total temperature.

**GMP**  
Ratio of gas constant of air to that of the exhaust gas.

**XJ**  
Energy conversion factor. If one of the preprogrammed values is acceptable, put in a value of 0.0. The value used will then be determined by the value of IUNIT on item number 3 as follows:
The remaining input variables are related to the boundary-layer program alone or to the viscous-inviscid interaction method.

**IUNIT**

<table>
<thead>
<tr>
<th>IUNIT</th>
<th>XJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>778.0</td>
</tr>
<tr>
<td>2</td>
<td>9336.0</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**GC**
Gravity constant. If one of the preprogrammed values is acceptable, put in a value of 0.0. The value used will then be determined by the value of IUNIT on item number 3 as follows.

<table>
<thead>
<tr>
<th>IUNIT</th>
<th>GC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.2</td>
</tr>
<tr>
<td>2</td>
<td>386.4</td>
</tr>
<tr>
<td>3</td>
<td>9.81</td>
</tr>
</tbody>
</table>

**LSEP**
Logical variable indicating whether the location of separation (XSEP) is known (TRUE) or not (FALSE).

**LITER**
Logical variable indicating whether the conical separated interaction procedure is to be used. If LITER = TRUE, the calculation procedure is the same as that described in reference 5 for bodies with solid plume simulators until a solution is reached. When the $x_8$-$\theta_8$ iteration terminates, the calculation then begins the $\delta^*$-update procedure described in section 2 of this report. If LITER = FALSE, the calculation follows the procedure described in section 2 or 3 of this report, depending on the value of the next input variable, LNSHK.

**LNSHK**
Logical variable indicating whether the shock-induced separation procedure is to be used. If LNSHK = TRUE, the calculation procedure for subsonic flow (no shock) is used even if supersonic flow with a shock wave occurs. This parameter is used to override the shock-separated flow procedure for transonic flows where weak shock waves occur and the supersonic procedure does not yield a good result. If LNSHK = FALSE, the supersonic procedure will be followed automatically if a shock wave with Mach number greater than 1.25 is found on the boattail on the first iteration.

**XSEP**
Axial location of separation. Put in only if LSEP = TRUE.
DTHET  Angle of $\delta^*$ surface with the boattail tangent at $x_S$. Put in only if LSEP = TRUE. A value of 0.0 will cause the program to use value of 10.0 (degrees).

IOPT  Integer indicating the mode of the calculation.
= 1 $u_e$ is to be input.
= 2 $\delta^*$ is to be input.

Put in a value of 1 for starting an interaction calculation.

K  Integer indicating whether flow is axisymmetric.
= 0 Two dimensional.
= 1 Axisymmetric.

LVAR1  Integer indicator for method of input of $u_e$ when IOPT = 1.
= 0 Input $u_e$ (dimensional) on cards.
= 1 Input $u_e/u_{e_0}$ on cards.
= 2 Input $u_e/u_{e_0}$ from data file 3 on Logical Unit 12.

LSHAPE  Integer indicating option for calculating all initial conditions (I.C.) except $u_e$ (see section 8.4).
= 0 Input initial values per LIC.
= 1 Calculate I.C. for flat plate.
= 2 Calculate I.C. for cylinder.
= 3 Calculate I.C. for cone.

LIC  Integer indicating initial condition options for IOPT = 1 and LSHAPE = 0.
= 1 Put in CFCl and DELTAl.
= 2 Put in CFCl and DELST1.

LDSTAR  Integer indicating whether a file of $\delta^* + r_w$ is to be input.
= 0  No input.
= 1  File of \( \delta^* + r_W \) versus \( x \) is required on Logical 
Unit 15 (data file 4).

**LSHPBL**  Integer indicating whether body shape is to be input 
for boundary-layer calculations.

= 0  XRL and RL are assumed to be the same as XO and 
YO. This is usually the case when starting an 
interaction calculation.

= 1  XRL and RL will be required.

**NOTE:** The next three variables, NVAR, XVAR, VAR, are only 
required on cards if LPROG = 1 and LVARI = 0 or 1.

**NVAR**  Integer indicating the number of values to be input for 
the prescribed variable \((u_e \text{ or } \delta^*)\). Maximum value is 
100.

**XVAR, VAR**  Axial location and value of prescribed variable as 
follows:

- \( \text{IOPT} = 1 \) and \( \text{LVARI} = 0 \), \( \text{VAR} = u_e \)
- \( \text{IOPT} = 1 \), and \( \text{LVARI} = 1 \), \( \text{VAR} = u_e/u_{e_0} \)
- \( \text{IOPT} = 2 \), \( \text{VAR} = \delta^* \)

**EL**  Reference length. Needed if input data lengths are 
nondimensionalized. If lengths are dimensional, put 
in \( \text{EL} = 1.0 \).

**PT**  Total pressure, \( p_t \text{(lb/ft}^2) \), \( \text{(lb/in}^2 \text{)}, \text{or (newton/m}^2 \text{)} \).

**TT**  Total temperature, \( T_t \text{ (°R) or (°K)} \).

**TWONTT**  Ratio of body surface temperature to total temperature, 
\( T_w/T_t \).

**VISC**  Constant \( \lambda \) in Sutherland's formula for viscosity.

\[
\mu = \lambda \frac{T^{3/2}}{T + T_s}
\]

If one of the programmed values is acceptable, put in 
a value of 0.0. The value used will then be deter-
mimed by the value of IUNIT on item number 3 as 
follows:
IUNIT  VISC
1  \(2.27 \times 10^{-8}\) lb sec/ft\(^2\) (°R)\(^{1/2}\)
2  \(1.5764 \times 10^{-10}\) lb sec/in\(^2\) (°R)\(^{1/2}\)
3  \(1.4582 \times 10^{-6}\) Newton sec/m\(^2\) (°K)\(^{1/2}\)

**RGAS**
Gas constant. If one of the programmed values is acceptable, put in a value of 0.0. The value used will be determined by the value of IUNIT as follows:

<table>
<thead>
<tr>
<th>IUNIT</th>
<th>RGAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1716.0 ft(^2)/sec(^2) °R</td>
</tr>
<tr>
<td>2</td>
<td>247104.0 in(^2)/sec(^2) °R</td>
</tr>
<tr>
<td>3</td>
<td>286.96 m(^2)/sec(^2) °K</td>
</tr>
</tbody>
</table>

**SCON**
Constant \(T_s\), in Sutherland's viscosity law (see definition for VISC). If one of the programmed values is acceptable, put in a value of 0.0. The value used will be determined by the value of IUNIT as follows:

<table>
<thead>
<tr>
<th>IUNIT</th>
<th>SCON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>198.6 °R</td>
</tr>
<tr>
<td>2</td>
<td>198.6 °R</td>
</tr>
<tr>
<td>3</td>
<td>110.333 °K</td>
</tr>
</tbody>
</table>

**DFACT**
Relaxation factor for adding \(\delta^*\) to body in the \(x_8-\theta_8\) iteration scheme. Usual value is 1.0. If a value of 0.0 is put in, a value of 1.0 will be used.

**XZ**
Axial location of beginning of boundary-layer calculation.

**RLEN**
Axial location of end of boundary-layer calculation. Usually at least one maximum diameter larger than XBT.

**XT**
Axial location of transition from laminar to turbulent boundary-layer flow.

**DXP**
Axial interval at which velocity profiles are to be printed. If a value of 0.0 is put in, no profiles are printed. In any case, profiles will not be printed more often than the output step size for individual output quantities (see section 9.1).

**HLIM**
Limit value of \(H_i = \delta_i^*/\theta_i\) to indicate separation as discussed in reference 5. Input of a blank or a value...
of 0.0 will cause a value of 1.2 to be used. To move the value of $x_s$ forward, decrease HLIM. To move $x_s$ downstream, increase HLIM. A value greater than 4.0 will allow the calculation to proceed to a separation singularity if one should occur. The calculation will terminate at that point. See section 5 for a discussion of the use of HLIM in sample calculations.

CFCl Value of skin-friction coefficient at initial boundary-layer station (see section 8.4).

DELTA1 Value of boundary-layer thickness, $\delta$ (compressible), at initial boundary-layer station (see section 8.4).

DELST1 Value of boundary-layer displacement thickness, $\delta^*$, at initial boundary-layer station (see section 8.4).

UEL Value of boundary-layer-edge velocity $u_e$ at initial boundary-layer station.

DUEDX Value of boundary-layer-edge velocity gradient at initial boundary-layer station.

NR Integer number of values of XRP and RL to be input for body shape. If NSHPBL = 0, this is assumed to be the same as IXY. Maximum value is 200.

XRP,RL Axial and radial coordinates of body shape for boundary-layer calculation. If LSHPBL = 0, these are assumed to be the same as XO and YO, respectively. For two-dimensional configurations, these represent the x and y coordinates of a surface measured from a reference plane.

8. PROGRAM OPTIONS

Several optional modes of calculation are available through the input parameters. A description of the options and the corresponding values of the pertinent parameters follows.

8.1 BOUNDARY-LAYER OPTION

To use only the boundary-layer program, put in the three card description, then all values on the fourth input data card, Item 2 in Table II, should be zero. Then the first value on the fifth input data card should be:
LPROG=1 (see Table II, Item 3)

Of the remaining variables shown on item number 3 in Table II, only IUNIT is required. The remaining cards would be those corresponding to item 4 and items 13 to 21 as described in Table II. With this option, the user has the choice of specifying either the free-stream velocity, \( U_e \), or the displacement thickness, \( \delta^* \), through the variables NVAR, XVAR, and VAR on items 14 and 15. The boundary-layer calculation can be restarted at any station by inputting the value of the variables at that station as listed in the output. The calculated list of \( \delta^* + r_w \) and \( U_e/U_{eo} \) will be written on Logical Unit 10 (data file 4) when the calculation terminates.

Another method is also available for calculating the boundary layer alone. The boundary-layer step of a viscous-inviscid iteration can be executed separately. The appropriate values on the fifth card would be:

\[
\begin{align*}
\text{LPROG} & = 0 \\
\text{N1} & = 1 \\
\text{N2} & = 21 \\
\text{IBL} & = 0 \\
\text{IUNIT} & = 1, 2, \text{ or } 3
\end{align*}
\]

This option requires LITER = TRUE and input of all other quantities as though the iterative sequence were to be completed. With the values just described, only the boundary layer will be calculated and then the run will be terminated. If it is desired to continue the iteration, simply make N2 less than 21. The free-stream velocity distribution must be provided on Logical Unit 12 for this case. All other optional inputs are the user’s choice.

8.2 INVISCID-FLOW OPTION

To use only the inviscid-flow program, put in the three card description, then all values on the fourth card should be zero. Then put in LPROG = -1 on the fifth card (item number 3 in Table II). Of the remaining values on that card, only IUNIT is required and that quantity is required only if PLUMIN is TRUE. After the first five cards only the data for items 4 to 9 or 10 as described in Table II and section 7.2 are required for this option.

8.3 VISCID-INVISCID ITERATION OPTION

To use both the boundary-layer and the inviscid-flow programs iteratively, put in LPROG = 0 and all other quantities as
appropriate. Such iterations can be started with only the body shape and free-stream flow quantities known. The \(x_{S-S}\) iteration procedure (\text{LITER} = \text{TRUE}) may be restarted to continue a prematurely terminated iteration. Several options are available to the user for restarting an unfinished iteration. See section 11.2 for an example of restarting. The simplest option is to put in \(\text{NRSTRT} = 1\) as the first value on the fourth input data card and to provide the required input data files on Logical Units 11, 12, 13, 14, and 15 (see fig. 12 and Table I). The only other data required for restarting are the three-card description of the case. The calculation then proceeds from where the previous iteration stopped. Another method of restarting, which is valid for all iteration procedures, would be to omit the restart file and put in \(\text{NRSTRT} = 0\). The user can then vary any of the other input quantities, using the data files or punched cards as desired. Note that the \(x_{S-S}\) calculation terminates when \(N_2\) reaches a value of 21. The value of \(N_1\) increases continuously throughout the calculation while the value of \(N_2\) is reset to 1 each time the \(x_{S-S}\) cycle finds a minimum error without satisfying the convergence criterion.

8.4 BOUNDARY-LAYER INITIAL CONDITIONS

Initial values of boundary-layer quantities can be obtained in several ways. The user can obtain values of the skin-friction coefficient, \(C_f\), and either the boundary-layer thickness, \(\delta\), or the displacement thickness, \(\delta^*\). These are shown on item 18 in Table II. The appropriate values \(\text{LSHAPE} = 0\) and \(\text{LIC} = 1\) or 2 are punched on the card corresponding to item 13. For the case when no other source of this information is available, formulas have been included in the program based on the Blasius solution for laminar boundary layers and based on one-seventh power law velocity profiles for turbulent flows. These formulas are only available if \(u_e\) is being specified (\(\text{IOPT} = 1\)). The basic formulas calculate \(C_f\) and \(\delta\) in the transform plane (incompressible, two-dimensional). The formulas are as follows:

**Laminar Flow**

\[
C_{fi} = \frac{0.664}{\sqrt{\frac{u_e}{v_{e_0}}} x} \tag{26}
\]

\[
\delta_i = \frac{5x}{\sqrt{\frac{u_e}{v_{e_0}}} x} \tag{27}
\]
Turbulent Flow

\[ C_f = 0.0592 \left( \frac{U_e}{v_e} \right)^{-0.2} \tag{28} \]

\[ \delta_i = 0.37 \left( \frac{U_e}{v_e} \right)^{-0.2} \tag{29} \]

These formulas provide initial values for boundary layers on flat plates. They are chosen by inputting \( \text{LSHAPE} = 1 \). For other geometries, the value of the \( x \) coordinate is transformed. Thus, \( \text{LSHAPE} = 2 \) chooses the values for a circular cylinder where

\[ x = \frac{r_w^2}{x_a} \tag{30} \]

where \( x_a \) is the axial coordinate and \( \text{LSHAPE} = 3 \) chooses the values for a cone, where

\[ x = \frac{1}{3} \left( \frac{r_w^2}{x_a} \right) \tag{31} \]

These formulas have been found to be quite adequate for calculating flows over long bodies. Small initial errors in the calculated boundary layer become negligible in a few boundary-layer thicknesses.

8.5 OPTIONS FOR DETERMINING THE SEPARATION POINT

The logical variables \( \text{LSEP}, \text{LNSHK}, \) and \( \text{LITER} \) and the input quantity \( \text{HLIM} \) are used to select a particular method of specifying \( x_s \). The options are summarized as follows:
The entire $x_S-\theta_S$ iteration procedure is a prediction method for $x_S$. The options which require input of $x_S$ or HLIM for that mode are used to obtain a first approximation for starting the $x_S-\theta_S$ iteration. In addition, those options can be used with the $\delta^*$-update procedure to provide a fixed value of $x_S$. Shock separated cases have the two options discussed in section 3.

9. PROGRAM OUTPUT

9.1 STANDARD OUTPUT

The complete program output is presented in the following list. Options for reducing the amount of printed output as discussed in reference 5 for the previous version of the program have been omitted from the present version of the program.

1. Three-line title or description
2. List of all values of integers on first and second data cards
3. List of body geometry input
4. List of other input values for inviscid flow
5. List of input indices for boundary-layer calculation
6. List of body shape data for boundary layer
7. List of other boundary-layer input quantities
8. Plume velocity and shape distributions. These lists are printed at the beginning and after the 4th iteration.

9. Computed geometric parameters in normal direction for inviscid flow

J - normal grid index
AN - normal coordinate
G - stretching function derivatives (refs. 7 and 8)
GH - stretching function derivatives at half intervals

10. Computed geometric parameters in tangential direction

I - tangential grid index
S - arc length along reference surface
X - axial coordinate
Y - radial coordinate
THET - angle of reference coordinate surface, θ. For closed bodies, θ is the same as the body angle, θ_B. For open bodies, θ = θ_B on the forebody and θ = 0 on the afterbody.

THETB - body angle, θ_B.
AK - surface curvature on closed bodies. For open bodies AK is the surface curvature on the forebody and AK = -(d^2r_w/dx^2) on the afterbody.

F - derivative of the tangential stretch function (refs. 7 and 8)

11. Inviscid relaxation iteration history

IT - iteration number
DPMAX - maximum φ correction, max |φ_{ij}^{IT} - φ_{ij}^{IT-1}|
ID, JD - I and J location of DPMAX
RMAX - maximum residual, max |R_{ij}|, where R_{ij} is the right-hand side of the difference equation
IR,JR - I and J location of RMAX
ISUB,ISUP - indicates if maximum residual occurred at a subsonic or supersonic point
RAVG - average value of the residual
RF1 - relaxation factor for subsonic points
QF3 - relaxation factor for supersonic points
NS - number of supersonic points
SEC/CY - time for iteration cycle

12. Tabulated values of surface pressure coefficient, $C_p$, Mach number, and axial velocity on the body along with a rough plot of $C_p$ along the body. This plot is distorted in the axial direction because it is for equal spacing in the computational space. The asterisks show the level of sonic $C_p$. The inviscid velocity distribution is used to calculate $C_p$ unless otherwise indicated. For example, the label "(AVERAGE OF INVISCID AND VISCOUS SOLUTIONS)" indicates that $C_p$ is derived from $1/2(U_{ev} + U_{ei})$.

13. Drag coefficients by trapezoidal integration of the $C_p$'s on the real body. The displacement surface is removed for calculation of the drag.

14. Coordinates x and y of the sonic line

15. Boundary-layer reference velocity, $u_{e_0}$, unit Reynolds number, $Re_0/L$ and viscosity, $\nu_{e_0}$. This is only printed on the first step ($N_l = 1$).

16. List of boundary-layer quantities with profiles at intervals governed by DXP.

- $X$ - axial distance from the nose, x
- $UTAU$ - friction velocity, $u_T$
- $UE/UZ$ - boundary-layer-edge velocity ratio, $u_e/u_{e_0}$
- $DSTPR$ - augmented body radius, $\delta^* + r_w$
- $HTR$ - transformed shape factor, $\delta_i^*/\theta_i$
**17. Quantities showing status of iteration**

- **XMAX** - location of maximum difference between $u_{ev}$ and $u_{el}$
- **UBCHK** - maximum value of $(u_{ev} - u_{el})/u_{e}$ (percent)
- **DRMS** - value of rms error (percent)

These quantities are printed each cycle during the iteration procedures described in section 2 and 3 of this report.

**18. Quantities showing status of $x_{S}-\theta_{S}$ iteration**

- **XSEP** - the current value of $x_{S}$
- **DTHET** - the current value of $\theta_{S}$
- **DRMS** - the current value of the rms error (percent)

If the calculation proceeds to a normal completion, a message will be printed indicating the iteration number at which the minimum error occurred and the value of other pertinent parameters for that iteration. The drag value and inviscid flow and boundary-layer data representing the solution will be found in the output list under the indicated iteration number.
9.2 SPECIAL OUTPUT MESSAGES

Several special messages are contained in the output to call attention to specific conditions that may occur. The messages are listed in this section with instructions about what to do when they are encountered.

(1) DIVERGENCE.RMAX EXCEEDS RCHEK,---------

This message is printed by the inviscid-flow program if the relaxation procedure diverges. Check all input to verify that it is correct. If no obvious errors appear, the difficulty is probably either in the choice of parameters for the computational mesh, or the smoothness of the data defining the body shape.

(2) RF1 DECREASED TO ___ BECAUSE 10-CYCLE AVG FOR RMAX INCREASED.

This message refers to the subsonic relaxation factor in the inviscid-flow program. The initial value is 1.4. The value is automatically reduced by 10 percent if: (1) the maximum residual, averaged over 10 cycles, is greater than that for the previous 10 cycles, and (2) the last maximum residual occurred at a subsonic point.

(3) QF3 INCREASED TO ___ BECAUSE 10-CYCLE AVG FOR RMAX INCREASED.

This message refers to the supersonic damping factor in the inviscid-flow program. The initial value is 0.1. The value is automatically increased if: (1) the maximum correction, averaged over 10 cycles, is greater than that for the previous 10 cycles, and (2) the last maximum residual is at a supersonic point.

(4) INPUT FROM TAPE13 HAS INCOMPATIBLE DIMENSIONS

This message is printed if the dimensions of the $ij$ solution read from Logical Unit 13 (data file 2 in figure 12) are not the same as the values of IMAX and JMAX put on item number 7 in Table II.

(5) METHOD FOR CALCULATING UTAU IN DERIV DOES NOT CONVERGE

This message refers to the iteration used to solve for $U_T$ when $S^*$ is prescribed in the boundary-layer calculation. The only known cause of the iteration failing to converge is an error in the input data (see ref. 5 for details).

(6) DELTAI HAS BECOME NEGATIVE STOP INTEGRATION, PRINT PROFILE AT PREVIOUS STEP
This message refers to the transformed boundary-layer thickness, $\delta_i$. The error condition may occur due to the initial integration step size $DXZ$ being too large. Another possible cause might be a too sudden change in the body shape, or in the prescribed $u_e$ or $\delta^*$ distribution.

(7) **DELTA HAS BECOME NEGATIVE**  
STOP INTEGRATION, PRINT VALUES AT PREVIOUS STEP

This message is not expected to occur in the finished program. If it does, check the input data carefully.

(8) **METHOD FOR CALCULATING INITIAL VALUE OF DELI DOES NOT CONVERGE**

When initial values of $C_f$, $\delta$, or $\delta^*$ are known, the calculation must solve an integral equation for the initial value of the transformed thickness, $\delta_i$. This is done by iteration in a similar manner as for $U_e$ described in message (5). If the iteration does not converge, it is usually due to errors in the input quantities.

(9) **RESULTS OF ITERATION**

This message is printed at the end of each step of the $x_s\theta_s$ cycle. It is followed by the current value of $x_s$, $XSEP$, the current value of $\theta_s$, $DTHET$, and the value of the rms error, $DRMS$.

(10) ***FINAL RESULTS***  
BEST SOLUTION WAS ITERATION NO.___

This message is printed whenever the smallest root-mean-squared error has been found.

(11) **SKIN FRICTION HAS BECOME NEGATIVE IN AN INCORRECT MANNER.**  
CHECK ALL INPUT CAREFULLY

This message will be printed if the skin-friction coefficient changes sign. It may indicate that the initial estimate of the separation point location was too far downstream. It has usually been observed to occur when strong shocks are present, or when too few relaxation steps, MIT were used initially.

(12) **ATTACHED BOUNDARY LAYER SOLUTION TERMINATED AFTER ___ ITERATIONS**

This message will be printed if the viscous-inviscid interaction converges and no separation occurred or the separation point for the next iteration would have been downstream of the end of the body.
10. PROGRAM OPERATING PROCEDURE

In this section, the construction of card decks for operation of the computer programs is described. First, a general description of the operations required is given. Then the specific Job Control cards needed for operation on an IBM 370 computer are listed. The same card decks should be applicable at any 370 installation with minor modifications.

10.1 GENERAL JOB CONTROL SEQUENCE

The following list is the general Job Control procedure that would be required to run the programs for a complete viscid-inviscid interaction calculation. The reader is referred to figure 16 and Table I.

1. Create partitioned data sets for restart files (files 1-5 in fig. 12).
2. Define units 2, 3, 8, 9, and 10. These unit numbers are needed for output.
3. Define units 11, 12, 13, 14, and 15 if NRSTRT = 1 in the input data. These unit numbers correspond to the input files. They contain data created in a previous run.

For starting an initial calculation, the partitioned data sets would be created in a separate operation. Then, since no data would be on file, only units 2, 3, 8, 9, and 10 need to be defined. For restarting an iterative calculation, all data files would exist, so units 11 to 15 must also be defined.

To execute the boundary-layer program alone, unit 10 must be defined in order to output the \( \delta^* + r_w \) and \( u_e/u_{eo} \) list. Unit 12 must be defined when LVAR1 = 2, and unit 15 must be defined when LDSTAR = 1.

To execute the inviscid program alone, units 2 and 8 must be defined. Unit 13 is also required when LREADP = 1, and unit 14 is required when IXY = 0.

10.2 JOB CONTROL EXAMPLES

In this section, specific examples of Job Control cards used for the operations discussed previously are presented. In the examples, the computer program is referred to as "ITER" with
the source code names "SITER" and the load module or binary version named "BITER". The account ID used in the examples is WYL.XM.K01. Logical units 5 and 6 are the standard input/output file numbers. It is not necessary to specifically define these unit numbers in the JCL deck. An estimated core memory size of 256K will be adequate for all cases except when the restart procedure is being used. Then the estimate should be increased to 512K.

10.2.1 Creating Partitioned Data Sets

Partitioned data sets for use as input/output disk files must be created before the normal program operation can proceed. The following procedure is suggested:

- Use IBM Utility Program IEFBR14.
- Use default values for DCB (DSORG=PO,RECFM=VS).
- On 3330 disk, use SPACE in tracks as follows (refer to fig. 12 and Table I for explanation of file numbers):
  - VELBOD (File 3): SPACE = (TRK,(2,1,i0))
  - RESTRT (File 5): SPACE = (TRK,(10,2,10))
  - PHI (File 2): SPACE = (TRK,(20,4,10))
  - XOFILE (File 1): SPACE = (TRK,(4,1,10))
  - DSFILE (File 4): SPACE = (TRK,(6,1,10))

Example of creating a partitioned data set called VELBOD:

//EXEC PGM=IEFBR14
//A DD DSN=WYL.XM.K01.VELBOD,VOL=volume,
//   UNIT=3330,DISP=(,CATLG),
//   SPACE=(TRK,(2,1,i0))

10.2.2 Starting an Iteration Sequence

To start an iteration sequence, unit numbers, 2, 3, 8, 9, and 10 must be defined. When LITER = TRUE in the input data set, the following sequence of cards should be used:
In the example presented in section 11.1, LITER = FALSE and the restart procedure is not available. However, the JCL cards corresponding to unit numbers 2, 3, 8, 9, and 10 must still be defined as follows:

//GO.FT02F001 DD DUMMY
//GO.FT03F001 DD DUMMY
//GO.FT08F001 DD DUMMY
//GO.FT09F001 DD DUMMY
//GO.FT10F001 DD DUMMY

10.2.3 Restarting an Iteration Sequence

The specific cards used to perform a restart of the calculation started in the previous section (when LITER = TRUE) are:
 These cards were used with the example discussed in section 11.2. The input data cards required for restarting are summarized in Table III.
10.2.4 Executing the Boundary-Layer Program Alone

The specific cards used to perform the calculations discussed in section 11.3 are listed in this section. In the example shown here, all input is assumed to be from cards, but the output list of $\delta^* + r_w$ and $u_e/u_{e_0}$ is to be saved on unit 10. Unit 12 would be required for input if $LVARI = 2$, and unit 15 would be required if $LDSTAR = 1$. The cards used in the example in section 11.3 are:

```
// EXEC FORTGO,PROG=ITER,VOL=volume
// LIB='SYL.XM.K01.BITER'
//GO.FT10F001 DD DSN=~L.XM.K01.DSFILE(RUNI),
// DISP=OLD
//GO.SYSIN DD *
```

Input data cards

/*

10.2.5 Executing the Inviscid Program Alone

The cards used to perform the calculations discussed in section 11.4 are listed in this section. In this example, the velocity potential, $\phi$, is input from unit 13, and the new solution for $\phi$ is output on unit 8. The calculated velocity on the body is output on unit 2. Input from unit 13 corresponds to $LREADP = 1$ in the card input data. In addition, unit 14 would be required for input of the body shape if $IXY = 0$ in the card input data. The specific cards used in the example are:

```
// EXEC FORTGO,PROG=ITER,VOL=volume,
// LIB='WYL.XM.K01.BITER'
//GO.PT02F001 DD DSN=WYL.XM.K01.VELBOD(RUN2),
// DISP=OLD
//GO.PT08F001 DD DSN=WYL.XM.K01.PHI(RUN2),
// DISP=OLD
//GO.PT13F001 DD DSN=WYL.XM.K01.PHI(RUN1),
// DISP=OLD,LABEL=(,,,IN)
//GO.SYSIN DD *
```
In this section, several example calculations are presented to aid in program checkout. An example is presented of a complete viscid-inviscid interaction using the δ*-update procedure described in section 2. An example is also presented of the use of the boundary-layer program alone for a two-dimensional geometry. That example also demonstrates the two options for boundary conditions, having \( u_0 \) specified in the beginning of the calculation, and \( \delta^* \) specified in the second part. Input data for another sample case are also presented to demonstrate the use of the program to calculate the inviscid flow alone.

### 11.1 Axisymmetric Interaction

A list of the punched card input data for a sample calculation on the boattailed body shown in figure 3a and b is presented in figure 13. The case being calculated is for a free-stream Mach number of 0.8. The body corresponds to the ogive-cylinder body with a circular-arc boattail described in reference 14. The JCL card deck for this case has been presented in section 10.2.2. The running time for the complete calculation is about 3.0 minutes on the IBM 370/165. The calculations shown were made by an IBM 3033 computer in 1.04 minutes. Small numerical differences will occur when the program is run on a different machine.

Selected output for the sample case is shown in figure 14. A total of 14 iterations were performed, with the minimum error of 0.74 percent occurring on the 13th iteration.

The complete list of output for this case consisted of a total of approximately 5000 lines. Output steps 1-7 as listed in section 9.1 have been omitted from this presentation since they simply verify the input data. The output pages shown are those corresponding to steps 8-18 of the set described in section 9.1. Finally, figure 14 concludes with the inviscid solution and boundary-layer solutions corresponding to the best result, iteration number 13, and the final page, from iteration 14 showing the final messages.
11.2 EXAMPLE OF RESTARTING AN INTERACTION CALCULATION

For a case where the \( x_0 - \delta_0 \) iteration is being used, the calculation may terminate prematurely. The punched card input data for restarting such a case is presented in figure 15. The JCL card deck for this calculation was presented in section 10.2.3. Note that the iterative calculations cannot be restarted at any arbitrary iteration using the restart file, unit 11. That file and the other output files contain only the data that were output just prior to the termination. It will be recalled that this restart procedure is only available when the input quantity \( \text{LITER} = \text{TRUE} \).

11.3 TWO-DIMENSIONAL BOUNDARY LAYER

A list of the punched card input data for a sample calculation on the two-dimensional configuration shown in figure 16 is presented in figure 17. Note that two sets of input are presented for this case, giving an example of the options of prescribed \( u_e \) and prescribed \( \delta^* \). The data for \( u_e \) and \( \delta^* \) were obtained from the experimental results of reference 15 which indicate separation occurring in an adverse pressure gradient region downstream of a shock wave. The output for the complete boundary-layer calculation are presented in figure 18. No external data files were used for input for this case. The JCL card deck for this case was presented in section 10.2.4.

11.4 AXISYMMETRIC INVISCID FLOW

The punched card input data for a sample calculation of the inviscid flow alone are presented in figure 19. The output for this case is shown in figure 20.
REFERENCES


REFERENCES (Concluded)


Figure 1.- Effective body shape for separated flow.
Figure 2. - Schematic of exhaust plume entrainment quantities.
All dimensions are referenced to the maximum diameter.

(a) Forebody.

(b) Boattail configuration 1.

(c) Boattail configuration 2.

(d) Boattail configuration 3.

Figure 3.—Body with circular arc boattail (ref. 14).
Figure 4.- Typical variation of rms error of a separated flow.
Figure 5. - Effect of new interaction model on separated flow predictions.
Figure 6.—Comparison of improved subsonic theory and data for a circular arc boattail with a cylindrical plume simulator (ref. 14).
Figure 7. Comparison of theory with data for supersonic flows.
Figure 8.- Afterbody drag on a circular arc boattail with a cylindrical plume simulator.
Figure 9.— Comparison between theory and data for configuration 2; $M_o = 0.8$. 

---

$C_p$ vs. $x/D$ for configuration 2 with $M_o = 0.8$. The figure shows a comparison between theoretical and experimental data, with markers indicating the data points and a smooth line representing the theory. The x-axis represents $x/D$ ranging from 0 to 1.6, and the y-axis represents $C_p$ ranging from -0.4 to 0.4. The markers are labeled as 'Data', and the line is labeled as 'Theory'. The figure includes a note that specifies the configuration and Mach number.
Figure 10.- Comparison between the theory and data for a boattail with a high pressure air jet; \( M_o = 0.8 \).
Figure 10. Concluded.
Figure 11.— Afterbody drag on a boattail with high pressure air jets.
Figure 12.- General relationship of programs and data files.
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
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</thead>
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</table>

98  
0.0  
0.1  0.025013  
0.2  0.050026  
0.3  0.075038  
0.4  0.100051  
0.5  0.125064  
0.6  0.150077  
0.7  0.175090  
0.8  0.200102  
0.9  0.225115  
1.0  0.250128  
1.1  0.275141  
1.2  0.300154  
1.3  0.325166  
1.4  0.350179  
1.5  0.375192  
1.6  0.400205  
1.7  0.425218  
1.8  0.450230  
1.9  0.475242  
2.0  0.499760  
2.1  0.498366  
2.2  0.500000  
2.3  0.500000  
2.5  0.500000  
3.0  0.500000  
3.5  0.500000  
4.0  0.500000  
5.0  0.500000  
6.0  0.500000  
7.0  0.500000  
7.5  0.500000  
8.0  0.500000  
8.025  0.499781  
8.05  0.499125  
8.075  0.498030  
8.1  0.496496  
8.125  0.494521  
8.15  0.492104  
8.175  0.489241  
8.2  0.485931  
8.225  0.482171  

(a) First 49 cards.

Figure 13.— Input data for viscous-inviscid interaction calculation.
<table>
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<th>Value</th>
<th>Probability</th>
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(c) Remaining 15 cards.

Figure 13.— Concluded.
INITIAL VALUES FOR PLUME

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I  XPE(I)  YPE(I)
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2 10.0000  1400.016

(a) Plume initial conditions.

Figure 14.- Selected output for viscid-inviscid interaction calculation.
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(b) Initial plume solution.

Figure 14.—Continued.
--- NORMAL COORD. STRETCH FOR ALT= 1.300 ---

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(c) Computed geometric parameters in normal direction for inviscid flow.

Figure 14.- Continued.
(d) Computed tangential geometric parameters.

Figure 14.—Continued.
(d) Concluded.

Figure 14. — Continued.
### Iteration No. 1

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(e) Inviscid iteration results from first inviscid solution.

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(e) First boundary layer calculation (incomplete).

Figure 14.— Continued.
Figure 14.—Continued.

(g) Solution after 4 iterations.

Figure 14.—Continued.
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(g) Continued.

Figure 14.—Continued.
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AFTERBODY DRAG COEFFICIENT = 0.04598

STATUS OF ITERATION

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DRMS & = 2.0226
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(g) Concluded.

Figure 14.- Continued.
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(h) Plume solution after 4 iterations.
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TIME TO CALCULATE PLUME = 1.42 SECS

(h) Concluded.

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(i) Best fit boundary layer solution.

Figure 14. - Continued.
ITERATION NO. 13 (AVERAGE OF INVISCO AND VISCOS SOLUTIONS)

PLOT OF CP AT EQUAL XI-INCREMENTS

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(j) Best fit C_p plot.

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(j) Concluded.

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Total Body Drag Coefficient = 0.05315
After Body Drag Coefficient = 0.02622

Status of Iteration

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XMAX   =  9.9845
UECK  =  3.0180
DRMS  =  1.1709
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**** Iteration for Boundary Layer/Inviscid Flow Equilibrium Converged ****

**** Final Results ****

Best Solution was Iteration No. 13

```
XSEP   =  6.5125
DRMS   =  0.7365
```

(k) Final page of output.

Figure 14.- Concluded.
NASA CONFIGURATION 1
(BLANK CARD)
RESTARTING ITERATION SCHEME AFTER 10600 ITERATIONS FOR RUN

$1 \ 0 \ 600$

Figure 15.- Sample input data for restart.
Figure 16.- Two-dimensional configuration for boundary-layer calculation.
ALGER TEST CASE

TWO-DIMENSIONAL BOUNDARY LAYER CALCULATION

SPECIFYING VELOCITY DISTRIBUTION FROM X=0

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22

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</table>

Figure 17.- Input data for two-dimensional boundary-layer calculation.

[a] Input for case with $J_e$ specified.
**ALBER TEST CASE**

**TWO-DIMENSIONAL BOUNDARY LAYER CALCULATION**

**SPECIFYING DELST DISTRIBUTION FROM X=10.75**

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</tbody>
</table>

(b) Input data for case with $\delta^*$ specified.

Figure 17.- Concluded.
Figure 18.- Output from two-dimensional boundary-layer calculation.
<table>
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<tr>
<th>A1</th>
<th>UTAU</th>
<th>UPITA</th>
<th>GELT</th>
<th>THETA</th>
<th>CX</th>
<th>UC/UX</th>
<th>DL3</th>
<th>FX</th>
<th>HTN</th>
</tr>
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<td>1.0000001</td>
<td>1.0000001</td>
<td>1.0000001</td>
<td>1.0000001</td>
<td>1.0000001</td>
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<td>1.0000001</td>
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<td>1.0000001</td>
<td>1.0000001</td>
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<td>1.0000001</td>
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<td>1.0000001</td>
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<td>1.0000001</td>
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<td>1.0000001</td>
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</tbody>
</table>

(b) Output from case with \( \varepsilon^* \) specified.

Figure 18.- Concluded.
NASA DATA COMPARISON - CONFIGURATION 1
JET SIMULATED WITH A SOLID STING
BOATTAIL L/D = 0.8

<table>
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<tr>
<th>x</th>
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<td>0.030026</td>
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(a) First 50 cards.

Figure 19.- Input data for inviscid calculation.
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<tr>
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<td>0.255000</td>
</tr>
</tbody>
</table>

(b) Next 50 cards.

Figure 19.—Continued.
10.5  0.255000
10.8  0.255000
11.2  0.255000
11.6  0.255000
12.0  0.255000

(c) Remaining 7 cards.

FIGURE 19.—Concluded.
### Normal coordinates. Stretch for \( \text{ALF} = 1.300 \)

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<th>AN</th>
<th>G</th>
<th>GH</th>
</tr>
</thead>
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<td>0.7725E-04</td>
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<td>2</td>
<td>0.1617E+03</td>
<td>0.1545E-03</td>
<td>0.4607E-03</td>
</tr>
<tr>
<td>3</td>
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<td>0.7662E-03</td>
<td>0.1365E-02</td>
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<tr>
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<td>0.1955E-02</td>
<td>0.2960E-02</td>
</tr>
<tr>
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<td>0.3336E-02</td>
<td>0.5143E-02</td>
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<td>0.1720E+02</td>
<td>0.6620E-02</td>
<td>0.1013E-02</td>
</tr>
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<td>7</td>
<td>0.1303E+02</td>
<td>0.9905E-02</td>
<td>0.1207E-01</td>
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<tr>
<td>8</td>
<td>0.1022E+02</td>
<td>0.1425E-01</td>
<td>0.1607E-01</td>
</tr>
<tr>
<td>9</td>
<td>0.6215E+01</td>
<td>0.1981E-01</td>
<td>0.2065E-01</td>
</tr>
<tr>
<td>10</td>
<td>0.6729E+01</td>
<td>0.2579E-01</td>
<td>0.2476E-01</td>
</tr>
<tr>
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<td>0.5655E+01</td>
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<td>0.3735E-01</td>
</tr>
<tr>
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<td>0.4643E-01</td>
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<td>0.6215E-01</td>
<td>0.6576E-01</td>
</tr>
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<td>0.6106E-01</td>
</tr>
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<td>0.7535E-01</td>
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<td>0.1026E+00</td>
<td>0.1116E+00</td>
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<td>0.1822E+01</td>
<td>0.1195E+00</td>
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(a) Normal coordinates.

Figure 22. - Output for inviscid calculation.
(b) Tangential coordinates.

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(b) Concluded.

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(c) Iteration history.

Figure 20.— Continued.
**Iteration No. 1**

**Plot of CP at Equal XI-Increments**

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</tbody>
</table>

(d) Tabulated solution and plot of $C_p$. Figure 20.—Continued.
TOTAL BODY DRAG COEFFICIENT= 0.07332

AFTERBODT DRAG COEFFICIENT= 0.04289

(d) Concluded.
Figure 20.- Continued.
ITERATION NO. 1

NO. OF SONIC PTS. ON EACH CONSTANT-J LINE, STARTING WITH J=JMAX (BODY SURFACE) AT LEFT

\[
\begin{array}{cccccccccccccccccc}
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

\( N = 4 \)

\( X_S(K), K=1,...,N \)

0.205E+01 0.207E+01 0.810E+01 0.638E+01

\( Y_S(K), K=1,...,N \)

0.495E+00 0.495E+00 0.495E+00 0.447E+00

(e) Sonic point distribution.

Figure 20.- Concluded.
<table>
<thead>
<tr>
<th>Data File (fig. 12)</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>3</td>
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</tbody>
</table>
TABLE II. BASIC INPUT DATA

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Variables</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TITLE (three cards)</td>
<td>20A4</td>
</tr>
<tr>
<td>2</td>
<td>NRSTRT,N3,ILIM</td>
<td>3I5</td>
</tr>
<tr>
<td></td>
<td>If NRSTRT $\neq$ 0 and N3 $\neq$ 0, skip to item 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If NRSTRT $\neq$ 0 and N3 $\neq$ 0 stop. No further input is necessary</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>LPROG,N1,N2,IBL,IUNIT,MIT</td>
<td>6I5</td>
</tr>
<tr>
<td>4</td>
<td>GAM,AMINF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If LPROG = 1 skip to item 13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>IXY</td>
<td>I5</td>
</tr>
<tr>
<td></td>
<td>If IXY = 0, skip next card</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>XO,YO (IXY cards)</td>
<td>2F10.0</td>
</tr>
<tr>
<td>7</td>
<td>IMAX,JMAX,MHALF,KLOSE,LREADP</td>
<td>5I5</td>
</tr>
<tr>
<td>8</td>
<td>DNDZO,XIXM,XM,DSDXIM,XBT,DMAX,XZNEW</td>
<td>7F10.0</td>
</tr>
<tr>
<td>9</td>
<td>PLUMIN</td>
<td>L5</td>
</tr>
<tr>
<td></td>
<td>If PLUMIN = FALSE, skip next card</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>GAMAP,PTPPFS,AMP,THETAP,TTP,GMP,XJ,GC</td>
<td>7F10.0</td>
</tr>
<tr>
<td></td>
<td>If LPROG = -1, skip remaining cards</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>LSEP,LITER,LNSHK</td>
<td>L5</td>
</tr>
<tr>
<td></td>
<td>If LSEP = FALSE, skip next card</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>XSEP,DTHET</td>
<td>2F10.0</td>
</tr>
<tr>
<td></td>
<td>If NRSTRT $\neq$ 0 stop. No further input is necessary</td>
<td></td>
</tr>
</tbody>
</table>
TABLE II. CONCLUDED

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Variables</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>IOPT,K,LVAR1,LSHAPE,LIC,LDSTAR,LSHPBL</td>
<td>7I5</td>
</tr>
<tr>
<td></td>
<td>If LPROG ≠ 1 or if LPROG = 1 and both IOPT = 1 and LVAR1 = 2, skip items 14 and 15</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>NVAR</td>
<td>I5</td>
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<tr>
<td>15</td>
<td>XVAR,VAR</td>
<td>2F10.0</td>
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<tr>
<td>16</td>
<td>EL,PT,TT,TWONTT,VISC,RGAS,SCON,DFACT</td>
<td>8F10.0</td>
</tr>
<tr>
<td>17</td>
<td>XZ,RLEN,XT,DXP,HLIM</td>
<td>5F10.0</td>
</tr>
<tr>
<td></td>
<td>If LSHAPE ≠ 0, skip next card</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If LIC = 1, input CFC1 and DELTA1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If LIC = 2, input CFC1 and DELST1</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>CFC1,DELTA1 (or DELST1)</td>
<td>2F10.0</td>
</tr>
<tr>
<td></td>
<td>If IOPT = 1, skip next card</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>UE1,DUEDX</td>
<td>2F10.0</td>
</tr>
<tr>
<td></td>
<td>If LSHPBL = 0 and LPROG = 0, skip items 20 and 21</td>
<td></td>
</tr>
<tr>
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<td>NR</td>
<td>I5</td>
</tr>
<tr>
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<td>XRP,RL</td>
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TABLE III. SUMMARY OF INPUT DATA FOR RESTARTING

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<td>1</td>
<td>TITLE (Three cards)</td>
<td>20A4</td>
</tr>
<tr>
<td>2</td>
<td>NRSTRT, N3, ILIM</td>
<td>5I5</td>
</tr>
<tr>
<td></td>
<td>If N3 = 0 stop. No further cards are necessary</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>XSEP, THETS</td>
<td>2F10.0</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

\( A_{nj} \) coefficients in eq. (24)
\( a \) speed of sound
\( B_n \) term in eq. (24)
\( b \) width of mixing layer (fig. 2)
\( C_f \) skin fiction coefficient
\( D \) maximum body diameter
\( G \) quantity defined in eq. (14)
\( H_i \) transformed shape factor, \( \frac{\delta_i^*}{\theta_i} \)
\( M \) Mach number
\( m \) \( \frac{\gamma - 1}{2} \) \( \rho^2 \)
\( p \) pressure
\( r \) radius
\( S \) \( \frac{T_e}{T_{te}} - 1 \)
\( s \) root-mean-square error, eq. (25)
\( T \) temperature
\( u, v \) \( x, r \) velocity components
\( x, r \) physical coordinates defined in figure 2
\( x_s \) location of separation point (fig. 1)
\( \beta \) eddy viscosity factor, \( \tau/\mu(\partial u/\partial y) \)
\( \gamma \) ratio of specific heats
\( \delta_i \) transformed boundary-layer thickness
\( \delta^* \) displacement thickness
\( \delta_i^* \) transformed displacement thickness, \( \int_0^1 (1 - u/u_e)dy \)
\( \theta_s \) half-angle of conical displacement surface
LIST OF SYMBOLS (Concluded)

\( \theta_i \) transformed momentum thickness, \( \int \frac{u}{u_e} \left[ 1 - \frac{u}{u_e} \right] dy \)

\( u \) molecular viscosity

\( v \) \( u/\rho \)

\( \rho \) density

\( \tau \) shear stress

\( \phi \) angle in eqs. (4)-(7)

\( \omega \) underrelaxation factor [eq. (2)]

Subscripts

\( e \) refers to boundary-layer-edge

\( f \) refers to conditions after a shock wave

\( i \) refers to conditions preceding a shock wave, or conditions at the inner edge of an exhaust jet mixing layer

\( I \) refers to inviscid flow

\( j \) refers to conditions in exhaust nozzle

\( o \) refers to the undisturbed free stream

\( s \) refers to separation point

\( t \) denotes stagnation point

\( V \) refers to viscous flow

\( w \) refers to conditions on a solid surface

Special notation

\( ( \ )_x \) refers to differentiation with respect to \( x \)