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Supersonic Nozzle Contour Design Using the Method of Characteristics with Boundary Layer Corrections

A Thesis

Presented for the

Master of Science

Degree

University of Tennessee, Knoxville

John P. Grubb

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ABSTRACT

This paper describes the method used to design a two dimensional convergent/divergent nozzle using the method of characteristics. The principle of conservation of mass was used in the subsonic region and "Pucketts" Method of Characteristics, in the supersonic region. The inviscid contour was then corrected by the displacement thickness of the boundary layer. A laminar or turbulent boundary layer was calculated using the compressible von Karman Momentum Integral. A sample problem is attached with several recommendations for improvement. A listing of the computer code is also included in the report.

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NOMENCLATURE

A	Cross sectional area of nozzle, ft
Bi	Y-intercept of characteristics, i = 1 to 2
C	Constant used in Coles wake parameter CAPPIE
CAPPIE	Coles wake parameter in the skin friction law
CF	Coefficient of skin friction
Ci,Di	Curve fit constants, i = 0 to 6
CHAR+	Angle of the right running characteristic with respect to the horizontal, degrees
CHAR-	Angle of the left running characteristic with respect to the horizontal, degrees
CP	Specific heat of the median at constant pressure, lbf-ft/lbm-deg R
DEL	Compressible boundary-layer thickness, ft
DEL*	Compressible boundary-layer displacement thickness, ft
DELi	Incompressible boundary-layer thickness, ft
DELi*	Incompressible boundary-layer displacement thickness, ft
DELANG	Angle between the nozzle wall segments, degree
DELX	Length of the nozzle wall segments, ft
FLOW	Angle of the direction of flow in the nozzle with respect to the horizontal, degree
f(LAM)	Thwaites boundary layer function

GAM	Ratio of specific heats
H	Ratio of compressible displacement thickness to compressible momentum thickness used in Thwaites boundary layer equations
Hi	Ratio of incompressible displacement thickness to incompressible momentum thickness used in Thwaites boundary layer equations
HEIGHT	Height of a cross section of the nozzle, ft
HEIGHT*	Height of the throat, ft
k	Constant used in Coles wake parameter CAPPIE
LAM	Velocity gradient parameter used in Thwaites equations
M	Mach number
MAXANG	Maximum expansion angle of the nozzle approximately equal to one-half the Prandtl-Meyer expansion angle, degree
MDOT	Mass flow rate, slugs/sec
MU	Angle of the characteristic with respect to the flow, degree
MUINF	Dynamic viscosity in the free-stream of the nozzle, lbf-sec/ft^2
N	Shape factor of the velocity profile associated with a turbulent boundary layer
NORMX	Axial distance, X, normalized by the length of the supersonic nozzle

NU	Prandtl-Meyer expansion angle used in the calculation of the inviscid flow properties, degree
NUINF	Kinematic viscosity in the free-stream of the nozzle, ft^2/sec
NUMSEG	Number of straight-line segments in the nozzle wall contour
PIE	Trigonometric constant = 3.141593
PR	Prandtl number
PT	Total pressure in the free-stream, psf
RHO	Local density in the boundary layer, slugs/ft^3
RHOINF	Density in the nozzle free-stream, slugs/ft^3
R	Universal gas constant, lbf-ft/lbm-deg R
RED	Reynolds number based on compressible boundary layer thickness, DEL
RET	Reynolds number based on incompressible momentum thickness, THETAi
Si	Incompressible Thwaites skin friction parameter
SLOPE	Angle of the inviscid wall contour with respect to the horizontal, degree
T	Local static temperature in the boundary layer, deg R
TAW	Adiabatic wall temperature, deg R

THETA	Compressible momentum thickness of the boundary layer, ft
THETAi	Incompressible momentum thickness of the boundary layer, ft
TINF	Static temperature in the free-stream of the nozzle, deg R
TT	Total temperature in the free-stream of the nozzle, deg R
U	Local velocity in the boundary layer, ft/sec
UINF	Velocity in the free-stream of the nozzle, ft/sec
X	Distance along the nozzle in the axial direction, ft
X1,X2	Known axial location of a characteristic, ft
Y	Vertical distance perpendicular to the nozzle centerline, upward being positive, ft
y	Perpendicular (normal) distance from the wall, used in association with the bounadry layer, ft
Y1,Y2	Known vertical location of a characteristic, ft

CHAPTER I

INTRODUCTION

Background

Convergent/divergent (supersonic) nozzles will play an increasingly important role in the various aspects of modern flight development. Currently, supersonic nozzles are used as a part of the propulsion system of rockets, jets, and the other space vehicles. In the future, two-dimensional supersonic nozzles will be used inside supersonic ram (SCRAM) jet engines as a means to mix the fuel and air prior to the combustion section. In order to promote the mixing of the fuel and air, the boundary layer inside the fuel nozzle should be turbulent.

Supersonic nozzles will also be utilized in the future to cool parts of a vehicle traveling at hypersonic speeds. Future interceptor missiles will view their targets through window. To keep this window from failing in the extreme thermal enviroment produced at hypersonic speeds, a two-dimensional jet blowing cooler air over the window will be required upstream of the window. The window will stay cool as long as the free-stream air does not penetrate to the surface. To prevent the mixing of the free-stream flow and the surface flow, it is preferred to keep the boundary layer inside the window cooling jet laminar, thus

maximizing the cooling efficiency.

In a supersonic nozzle, the minimum constriction between the convergent nozzle and the divergent nozzle is called the throat. At the throat of a convergent/divergent nozzle, the local Mach number is one. Elementary analytical aerodynamics relates the area ratio, the ratio between the throat area and the exit area, required to produce a particular exit Mach number, but no consideration is given to the design of the wall contour needed to produce a shock free nozzle.

This thesis describes a procedure that can be used to design a two-dimensional (slot) nozzle using the Method of Characteristics with either a laminar or turbulent boundary layer correction. Contained in the report is a discussion of the assumptions used to calculate the convergent nozzle contour, a description of the Method of Characteristics used to calculate the divergent nozzle contour, considerations (assumptions) used to define the inviscid contour, a description of the boundary layer calculation, an examination of a sample case, and a listing of the computer program.

The user friendly program was designed to run on any personal computer using G-W Basic version 3.2. The program was developed to solve for the wall contour of nozzles with very small exit heights. However, a Mach 1.8 supersonic wind tunnel has been built using this program which had an 8 in. square test section. All indications

showed uniform flow was present.

Comparison of Two- and Three- Dimensional Nozzles

Many applications require the use of a two-dimensional (slot) nozzle that can not be accomplished using three-dimensional (axisymmetric) nozzles. The first nozzles built were two-dimensional since they were easier to compute and simpler to manufacture. When utilizing a nozzle with flexible walls, multi-Mach numbers can be acquired with the same nozzle. The variable Mach number capability is achieved by varying the nozzle exit to throat area ratio (geometry) of the nozzle. With axisymmetric nozzles, only one Mach number can be obtained per nozzle, since the area ratio can not be changed in a nozzle with a fixed geometry.

As the free-stream Mach number increases, the static temperature decreases which increases the possibility of condensing water vapor, or liquefying the air. To prevent air liquefication, the total temperature in the stilling chamber can be raised. For Mach numbers above five, the high total temperature required to prevent liquefacation induces dimensional instabilities in a two-dimensional nozzle. The instabilities are attributed to the uncooled tunnel walls expanding, and is particularly noticed at the throat. Hence, two-dimensional nozzles are usually not used for Mach numbers greater than five.

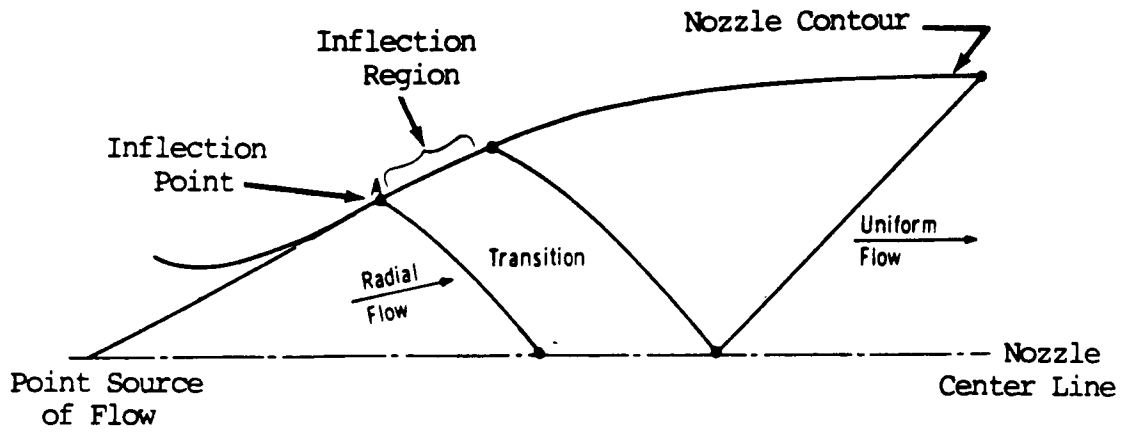
In addition to the reduced susceptibility to dimensional instabilities, axisymmetric nozzles have a much more uniform boundary layer then two-dimensional nozzles because of the smaller transverse pressure gradients. The smaller pressure gradient would allow a laminar boundary layer to exist longer in the nozzle, thus creating a "quieter" test section. One downfall of the axisymmetric nozzle however, is that small disturbances tend to be focused on the nozzle center line, which is usually where the test model is located in a wind tunnel.

Evolution of Nozzle Design

The foundation of designing a two-dimensional convergent/divergent (supersonic) nozzle using the Method of Characteristics was formulated by Prandtl and Busemann (Ref 1). Foelsch's assumption (Ref 2) that the flow near the inflection point was produced from a single source and expanded radially (Fig 1) greatly simplified the calculations. The inflection point is the point in the nozzle contour where the radius of curvature changes sign, and expansion of the flow is a maximum. Foelsch's assumption is the basis on which the present program is founded.

The next improvement came from converting the inflection point into an inflection region called the transition region (Fig 1). Multiple free-stream Mach

numbers can be obtained using a tunnel with a flexible plate for the nozzle wall, with the transition region defined as the region of constant curvature. The 40- by 40-inch supersonic Wind Tunnel in the von Karman Gas Dynamics Facility at the Arnold Engineering Development Center was designed in this fashion using the method of reference 3.

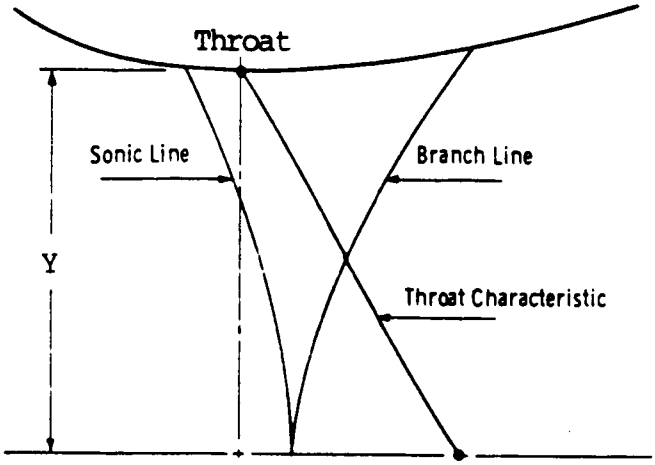


Ref 5, Fig 2

Figure 1. Nozzle with radial Flow and a Transition Region to produce a Continuous Curvature

The next advance in the development of nozzle design came with a new approximation for the flow entering the divergent nozzle. The classical assumption was that the sonic line, the line where the local Mach number is one, was a straight line propagating from the nozzle throat, as

is used in the present program. The method of reference 4 assumed a curved (or conical surface for 3-dimensional) sonic line originating upstream of the throat (Fig 2). Such an assumption eliminates the discontinuities in the nozzle contour which had previously produced sharp changes in axial Mach number.



Ref 5, Fig 4

Figure 2. Nozzle Throat Region

The present state of the art methods are those of reference 5, which eliminate the gap between the sonic line at the throat and the first characteristic from the throat wall (Fig 2). Eliminating this gap allows the radius of curvature at the throat to be as large as 5 times the throat radius, thus producing a gentler expansion of the flow.

CHAPTER II

METHOD OF SOLUTION

General

This paper will discuss a program intended to compute the wall contour of a supersonic nozzle given throat height, which will control the exit height, maximum expansion angle, which will control the exit Mach number, and total pressure and temperature to calculate the boundary layer thickness. The three main sections in the program calculate the convergent section, the divergent section, and the boundary layer.

Convergent Section of the Nozzle

The convergent section of a nozzle is used to accelerate the flow from low speed to high subsonic speed. The highest speed obtainable in this section of the nozzle is that of the speed of sound, Mach one. The convergent section was designed using the conservation of mass. Given the equation for mass flow:

$$MDOT = \frac{PT*A*M}{\sqrt{\frac{R*TT}{GAM}}\left\{1+\frac{(GAM-1)}{2}M^2\right\}^{\frac{GAM+1}{2(GAM-1)}}} \qquad (1)$$

This equation can be rearranged, knowing that for a two-dimension nozzle, area is the height of the nozzle multiplied by a unit width:

$$\frac{MDOT\sqrt{\frac{R*TT}{GAM}}}{PT} = \frac{HEIGHT \quad M}{\left\{1+\frac{(GAM-1)}{2} M^2\right\}^{\frac{GAM+1}{2(GAM-1)}}} = \text{constant} \qquad (2)$$

If the throat height is known, the height at any axial station can be calculated by:

$$HEIGHT = \frac{HEIGHT*}{M} \left\{\frac{1+\frac{(GAM-1)}{2} M^2}{1+\frac{(GAM-1)}{2}}\right\}^{\frac{GAM+1}{2(GAM-1)}} \qquad (3)$$

For a given throat height, HEIGHT*, there are two unknowns in the above equation, height and Mach number. For a nozzle to have uniform flow, the Mach number distribution should be well behaved. Therefore, the Mach number was assumed, and the height calculated. The alternative method of assuming a height distribution and calculating the Mach number distribution would produce a good looking contour, but perhaps an unacceptable Mach number distribution.

The assumed distribution of Mach number in the convergent part of the nozzle is shown in figure 3. This Mach number distribution was obtained from knowing the contour of an axisymmetric Mach 8 hypersonic wind tunnel with a 50 inch exit diameter.

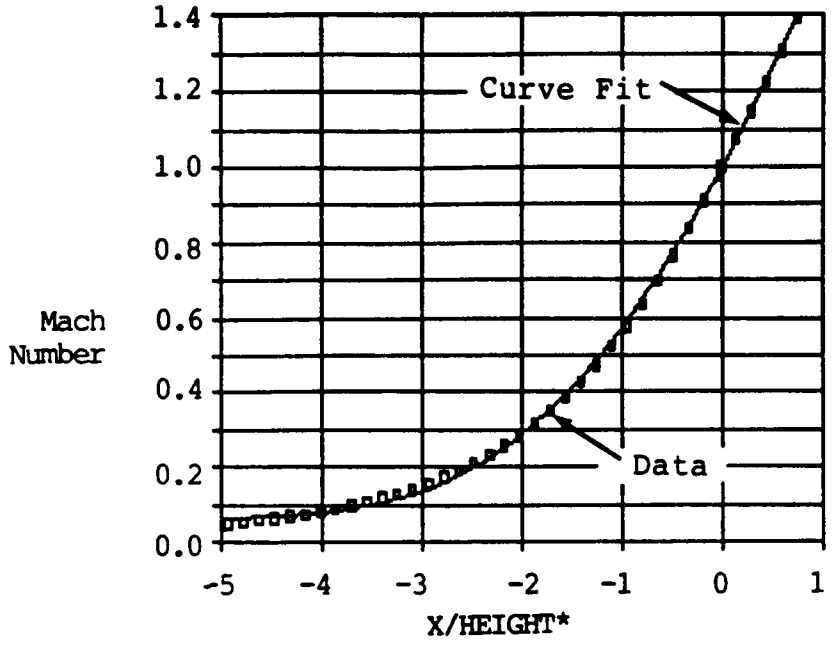


Figure 3. Distribution of Subsonic Mach number Obtained from a Mach 8 Nozzle

Several other nozzles with exit Mach numbers ranging from Mach 2 to Mach 6 were compared to the Mach 8 nozzle (Fig 4). These nozzles all had throat diameters significantly smaller than the Mach 8 nozzle of figure 3. The Mach number distribution of the Mach 8 nozzle was chosen as an average contour of the 5 nozzles.

The axial distance (upstream of the throat) was normalized by the throat height. This will cause nozzles with larger throats to have correspondingly longer

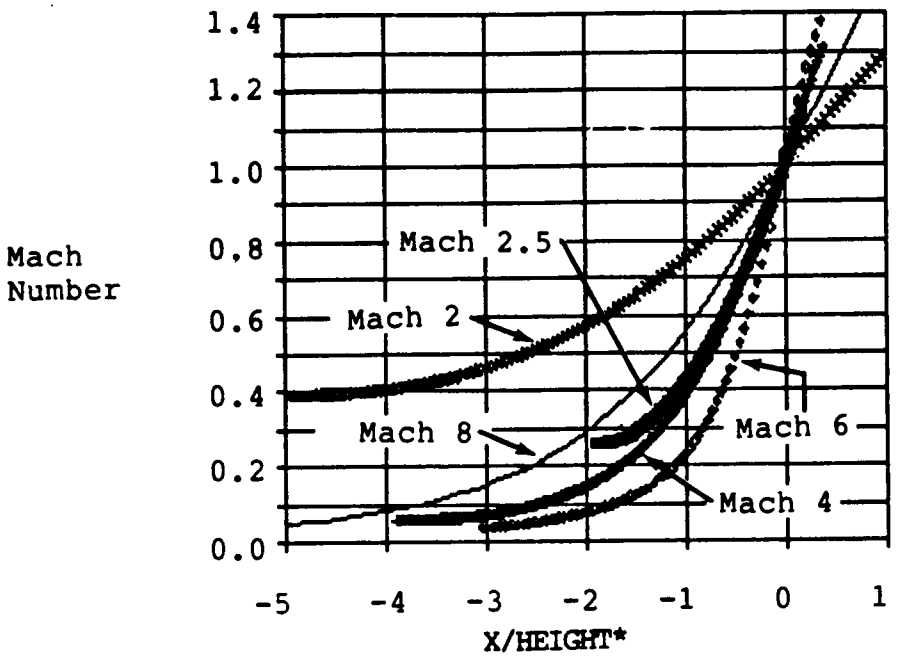


Figure 4. Comparison of Subsonic Mach number Distribution From Several Wind Tunnels

compression sections. The Mach number distribution was fitted with a sixth order polynomial as:

$$M = \sum Ci \left\{ \frac{X}{HEIGHT^*} \right\}^i \qquad (4)$$

C0 =	0.995345 E+0	C4 =	-1.466458 E-3
C1 =	0.491046 E+0	C5 =	8.861818 E-5
C2 =	5.802925 E-2	C6 =	1.535031 E-5
C3 =	-8.186715 E-3		

The program calculates the contour of the convergent or subsonic section of the nozzle as follows: a normalized

axial distance is chosen, and the Mach number at the normalized axial station is calculated using equation (4). Then the height at that station can be determined using equation (3).

Divergent Section of the Nozzle

The Method of Characteristics is used for computing the nozzle wall contour in the divergent section of the nozzle. The method can be derived from the mass, momentum and energy equations assuming a two-dimensional, inviscid, and irrotational flow. The initial observation is that discontinuities in the velocity derivative can exist across lines or characteristics. These characteristics are the same as the Prandtl-Meyer Mach lines. Across the characteristics, the compatibility of the flow angle and the Prandtl-Meyer function must exist as:

$$\begin{aligned} \text{FLOW} + \text{NU} &= \text{constant} \\ \text{FLOW} - \text{NU} &= \text{constant} \end{aligned} \qquad (5)$$

Another way to view the Method of Characteristics is that disturbances in supersonic flow occur across Mach lines or characteristics. The angle that the characteristic makes with the horizontal is the sum of the angle of the characteristic to the flow, and the angle of the flow to the horizontal. Once the angle of the characteristic with respect to the horizontal is known, by

assuming each characteristics cancels out at the wall (i.e., the wall angle is the same as the characteristic angle), the wall contour can be determined.

There are two processes in designing the inviscid contour of a nozzle using the Method of Characteristics: calculation of the various flow parameters (flow angle, Mach number, characteristic angle, etc.), and the calculation of the contour. Each of these segments will be evaluated separately.

Flow Field Parameters

Using the Method of Characteristics to solve a two-dimensional flow can be accomplished using the "Puckett a-b" method (Ref 6). Three angles are required to characterize the flow in the nozzle: the flow angle (FLOW), the Prandtl-Meyer function (NU), and the characteristic angle (MU). As shown in figure 5, the contour of the nozzle has been separated into trapezoid regions, each with an a,b combination. The figure has been drawn with an incremental nozzle angle of 2 deg up to a maximum deflection of 6 deg. The "a" represents the angle of the left running characteristic, and the "b" represents the angle of the right running characteristic.

The a,b combination is obtained from the incremental nozzle angle, DELANG. This angle is calculated from the

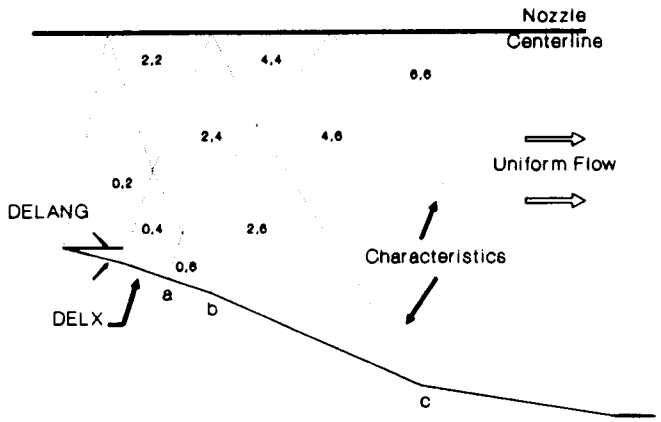


Figure 5. Puckett Nozzle Nomenclature

maximum expansion angle (MAXANG) and the number of segments the nozzle wall is divided into (NUMSEG).

$$DELANG = \frac{MAXANG}{NUMSEG} \tag{6}$$

The Mach number distribution in the Y direction entering the divergent section is assumed to be uniform and equal to one. When the nozzle is broken up in this manner, the angles FLOW and NU are calculated from the previous and current trapezoids as:

$$FLOW = 0.5[(a-b)_1 - (a-b)_2] \tag{7}$$

$$NU = 0.5[(a+b)_1 + (a+b)_2] \tag{8}$$

Once NU is determined, the Mach number can be found from the Prandtl-Meyer function (Ref 7, Eqts 171a). The Mach number is iterated until the change in the Prandtl-

Meyer angle is less then 0.1%. The angle between the flow and the characteristic, MU, is based on the average Mach number across the characteristic (Fig 6) as:

$$MU = \sin^{-1}\left\{\frac{2}{M_1 + M_2}\right\} \tag{9}$$

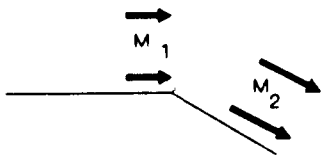


Figure 6. Typical Expansion Fan

The angle that the characteristic makes with the horizontal (or nozzle center line) is a function of the characteristic angle (with respect to the flow) and the flow angle (with respect to the horizontal). This is the angle required to determine the wall contour, or local slope, and is calculated as:

$$CHAR+ = FLOW + MU \tag{10}$$

$$CHAR- = FLOW - MU \tag{11}$$

Inviscid Nozzle Wall Contour

The nozzle wall contour is found by knowing the X-Y coordinates of the nozzle wall and the angle of the characteristic with respect to the horizontal, CHAR+ and CHAR-. The points on the wall prior to the inflection point (Fig 5, Point b) can be determined by knowing the incremental nozzle angle and incremental nozzle distance.

$$X = X1 + DELX \cos(DELANG) \quad (12)$$

$$Y = Y1 + DELX \sin(DELANG) \quad (13)$$

When describing a point on the nozzle center line (Fig 7a), the Y coordinate is set to zero, and X is calculated as:

$$X = X1 - \frac{Y1}{\tan(CHAR+)} \quad (14)$$

The intermediate points in the nozzle or the points on the nozzle wall downstream of the inflection point are obtained from the intersection of two straight lines (Fig. 7b) as:

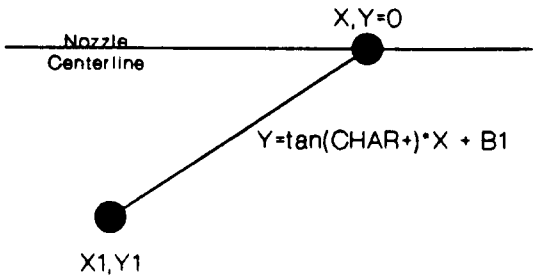
$$X = \frac{B1 - B2}{\tan(CHAR-) - \tan(CHAR+)} \quad (15)$$

$$Y = X * \tan(CHAR+) + B1 \quad (16)$$

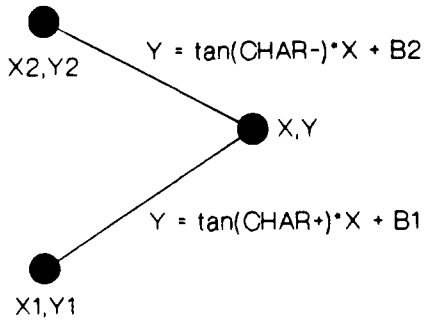
where:

$$B1 = Y1 - X1 * \tan(CHAR-) \quad (17)$$

$$B2 = Y2 - X2 * \tan(CHAR+) \quad (18)$$



a. Centerline Points



b. Intermediate Points

Figure 7. Determination of Wall Geometry

Laminar Boundary-Layer Corrections

Thwaites Method

One method to calculate the laminar boundary layer in a variable pressure gradient is to use Thwaites equation (Ref 8). Thwaites incompressible viscous equation:

$$UINF \frac{d}{dX}\left\{\frac{LAM\ dX}{dUINF}\right\} = 2[Si-LAM(2+Hi)] = f(LAM) = 0.45-6LAM \quad (19)$$

can be solved using a single parameter, LAM, where:

$$LAM = \frac{THETAi^2}{NUINF}\frac{dUINF}{dX} \quad (20)$$

The value of the incompressible momentum thickness, THETAi, can be obtained from the integral

$$THETAi^2 = \frac{0.45\ NUINF}{UINF^6}\int_0^{00} UINF^5\, dX \quad (21)$$

The variation of Hi and Si used in the program are curve fits of Thwaites shape and shear functions from reference 8 (Table 4.8) and are shown in figures 8-9, and calculated as:

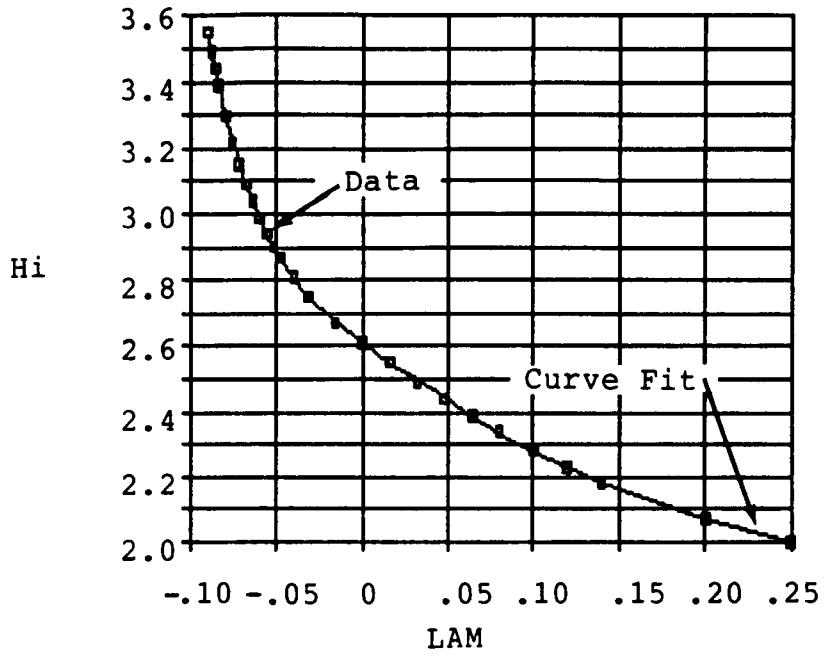


Figure 8. Thwaites Ratio of Boundary Layer Displacement and Momentum Thickness

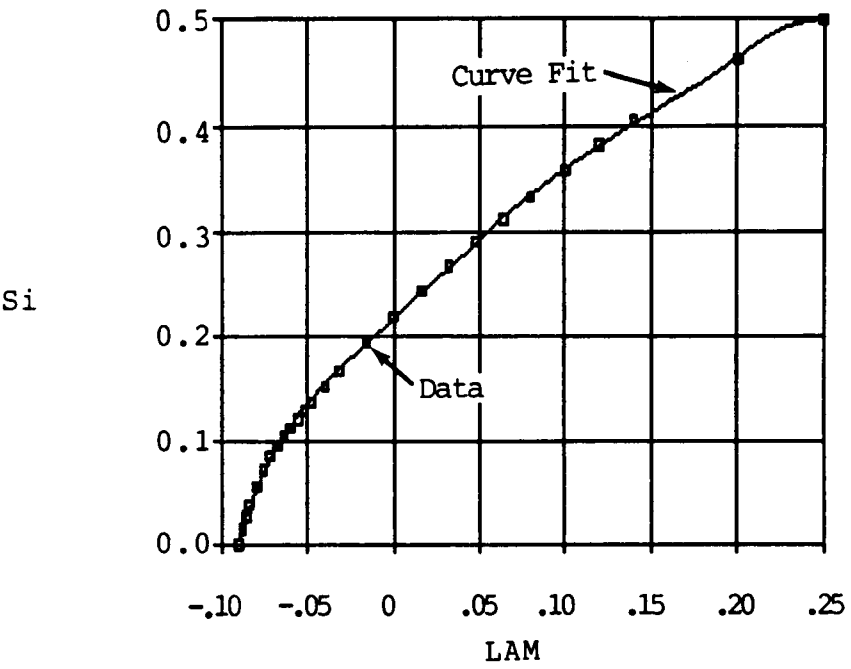


Figure 9. Variation of Thwaites Skin Friction Parameter

$$Hi = \sum Ci\ (LAM)^{i} \tag{22}$$

$$Si = \sum Di\ (LAM)^{i} \tag{23}$$

C0 =	2.608267E+0	D0 =	2.176646E-1
C1 =	-3.700521E+0	D1 =	1.504052E+0
C2 =	1.209578E+1	D2 =	7.109906E-1
C3 =	-2.764393E+2	D3 =	1.604095E+1
C4 =	3.148932E+3	D4 =	-6.391872E+2
C5 =	-1.410558E+4	D5 =	4.043900E+3
C6 =	2.193374E+4	D6 =	-7.541629E+3

In the computer program, the running sum of the edge velocity to the fifth power is obtained, and the incompressible momentum thickness, THETAi, is calculated as:

$$THETAi = \left\{ \frac{0.45\ NUINF}{UINF^{6}} \sum UINF^{5}\ DELX \right\}^{1/2} \tag{24}$$

Next, the incompressible values of LAM and Hi are calculated. The incompressible values are corrected for compressibility effects using a compressiblity transformation suggested by Mann and Whitten (Ref 9) in the form of:

$$H = Hi\ \frac{TAW}{TT}\left\{1+ \frac{(GAM-1)}{2}\ M^{2}\right\}+ \frac{(GAM-1)}{2}\ M^{2} \tag{25}$$

$$THETA = THETAi\left\{\frac{TT}{TINF}\right\}^{3} \tag{26}$$

$$\text{where } TAW = TINF + \frac{\sqrt{PR}\ UINF^{2}}{2Cp} \tag{27}$$

Finally, the compressible displacement thickness, DEL*, is calculated by:

$$DEL^* = H * THETA \tag{28}$$

Laminar Momentum-Integral Equation

The laminar boundary layer in a variable pressure gradient can also be calculated using the compressible von Karman Momentum Integral Equation, as described in reference 8 for two dimensional flow as:

$$\frac{dTHETA}{dX} + \frac{THETA}{UINF}\frac{dUINF}{dX}\left\{2 + \frac{DEL^*}{THETA} - M^2\right\} = \frac{CF}{2} \tag{29}$$

where:

$$DEL^* = \int_0^{\infty}\left\{1 - \frac{RHO}{RHOINF}\frac{U}{UINF}\right\}dy \tag{30}$$

$$THETA = \int_0^{\infty}\frac{RHO}{RHOINF}\frac{U}{UINF}\left\{1 - \frac{U}{UINF}\right\}dy \tag{31}$$

In the present analysis, the velocity profile, U/UINF, is assumed to obey a sine distribution shown in figure 10 as:

$$\frac{U}{UINF} = SIN\left\{\frac{y}{DEL}\frac{PIE}{2}\right\} \tag{32}$$

and the derivative of the velocity profile is:

$$\frac{dU}{dy} = \frac{UINF}{DEL}\frac{PIE}{2} \tag{33}$$

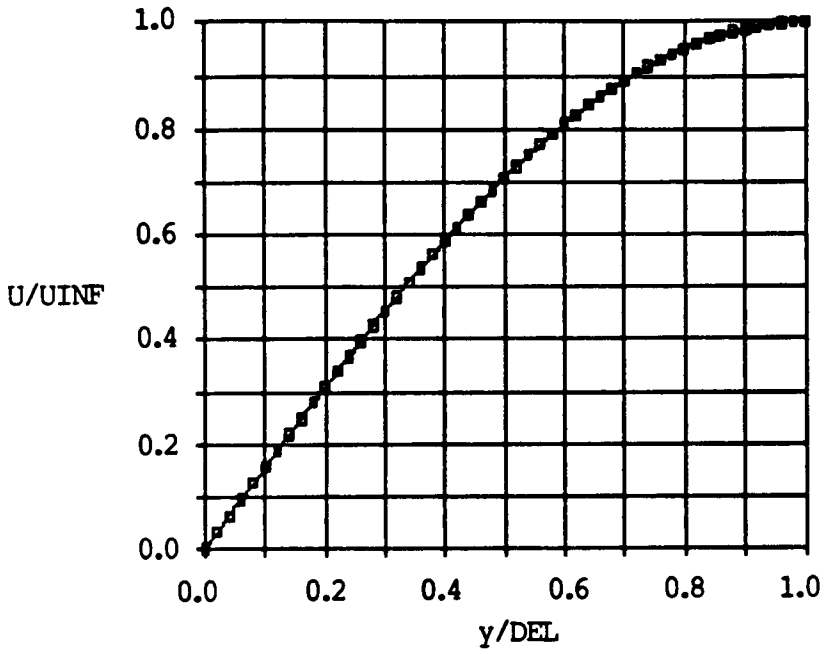


Figure 10. Laminar Boundary Layer Velocity Profile

The coefficient of friction at the wall, CF, is assumed as:

$$CF = \frac{MUINF}{0.5\ RHOINF * UINF^2} \frac{dU}{dy} \qquad (34)$$

In the computer program, the initial boundary layer thickness, DEL, is assumed, and the integration of DEL* and THETA are obtained using a ten point trapezoidal method. After CF is computed, the compressible von Karman Momentum Integral is calculated. Finally, DEL is iterated until both sides of the compressible momentum integral converge to within 0.1%.

Turbulent Boundary-Layer Corrections

The compressible von Karman Momentum Integral Equation (Eqts 29) can also be approximated assuming a turbulent boundary layer. The solution of the compressible momentum integral equation was obtained from Sivells (Ref 5) as follows. The skin friction coefficient (Fig 11) was taken from reference 10 as

$$CF = \frac{0.0773}{[\log(RET) + 4.561][\log(RET) - 0.546]} \qquad (35)$$

The shear layer parameter, CAPPIE, can be calculated using Coles' law of the wall and law of the wake (Ref 11) as

$$k\sqrt{\frac{2}{CF}} = \ln(RED) + 0.5 \ln\frac{CF}{2} + k*C + 2\,CAPPIE \qquad (36)$$

where k = 0.41 and C = 5.0

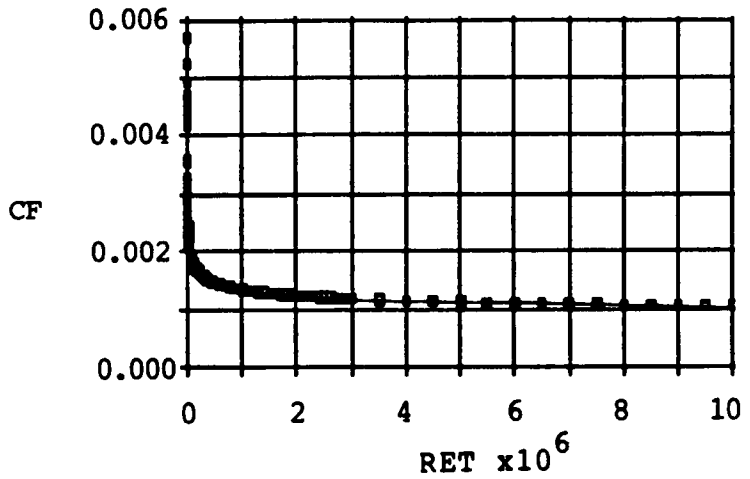


Figure 11. Variation of Turbulent Skin Friction versus Reynolds number based on THETA

The incompressible displacement and momentum thickness can be calculated "from the logarithmic velocity profile by neglecting the laminar sublayer, representing the wake function by a sine^2 distribution, and integrating to obtain" (Ref 5)

$$\frac{DELi^*}{DEL} = \frac{(1 + CAPPIE)}{k} \frac{CF}{2} \tag{37}$$

$$\frac{THETAi}{DEL} = \frac{DELi^*}{DEL} - \frac{CF}{2k} (2+3.179\ CAPPIE + 1.5\ CAPPIE^2) \tag{38}$$

The power of the velocity profile, N, (Fig 12) is evaluated through the use of the incompressible kinematic momentum thickness as:

$$N = 0.5 \left\{ \frac{DEL}{THETAi} - 3 + \left[\frac{DEL}{THETAi} \left\{ \frac{DEL}{THETAi} - 6 \right\} + 1 \right]^{\frac{1}{2}} \right\} \tag{39}$$

Thus the turbulent velocity profile (Fig 13) used in the calculation of the displacement and momentum thickness is

$$\frac{U}{UINF} = \left\{ \frac{y}{DEL} \right\}^{\frac{1}{N}} \tag{40}$$

The one other unknown in the displacement and momentum integrals is the density ratio, RHO/RHOINF. This ratio is defined as:

$$\frac{RHO}{RHOINF} = \frac{TINF}{T} \tag{41}$$

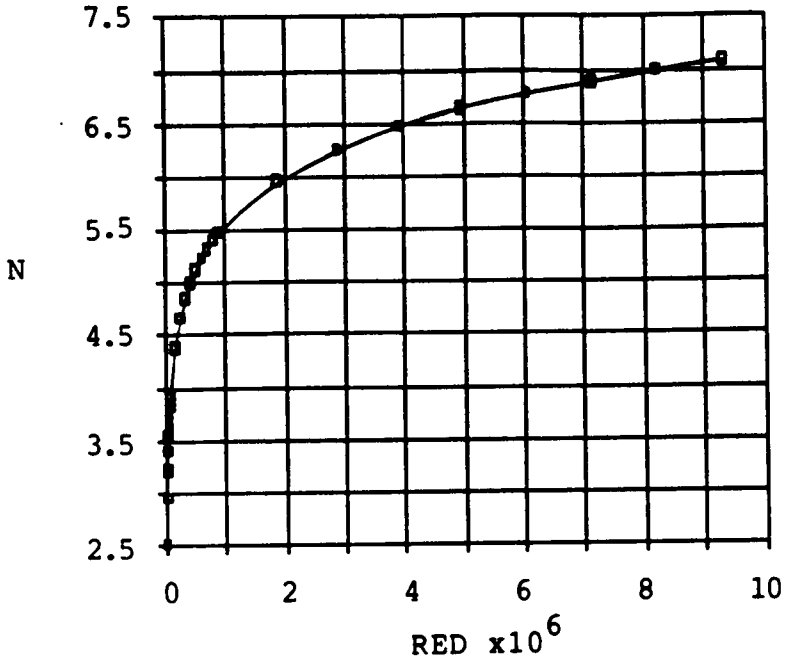


Figure 12. Exponent of the Turbulent Velocity Profile with Reynolds number based on Delta

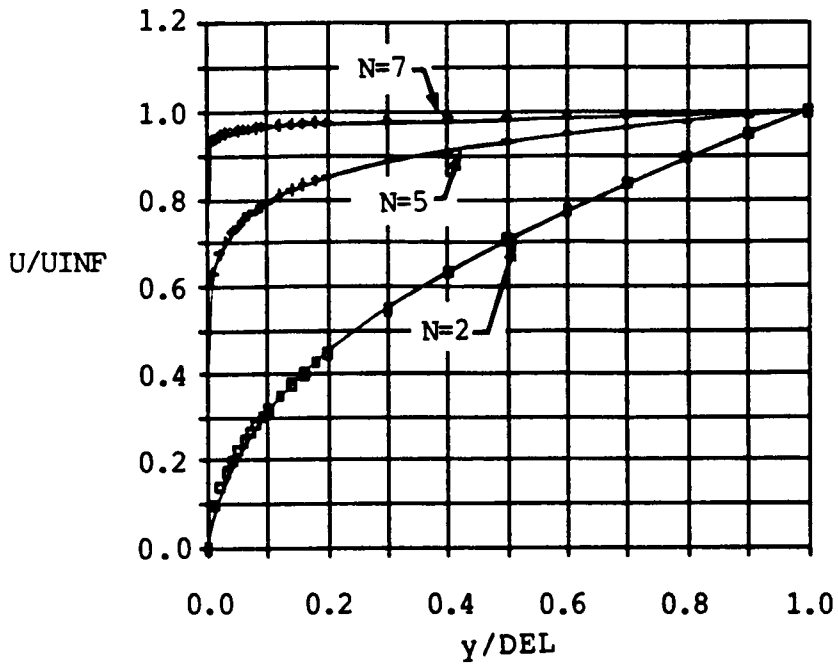


Figure 13. Turbulent Velocity Profile

The static temperature through the boundary layer is approximated by Crocco's quadratic temperature distribution (Ref 4) and assuming an adiabatic wall as:

$$T = TAW + [TINF - TAW] \left\{ \frac{U}{UINF} \right\}^2 \qquad (42)$$

An iteration process is used to solve the compressible von Karman Momentum Integral Equation. DEL is assumed, and CF is calculated. For the first iteration, N is assumed to be 2. U/UINF is then calculated, and DEL* and THETA are then integrated using a ten point trapezoidal method, and N is calculated. DEL (and N) are iterated until both sides of the compressible von Karman Momentum Integral Equation converge to within 0.1%.

Correction of Inviscid contour for Boundary Layer

The inviscid contour was corrected for viscous effects by adding the product of the boundary layer displacement thickness and the secant of the wall slope to the inviscid contour as:

$$Y = Y1 + \frac{DEL^*}{\cos(SLOPE)} \qquad (43)$$

In this fashion, the axial location of each point will remain unchanged.

CHAPTER III

PROGRAM DESCRIPTION

Discussion of Program

There are two assumptions built into the calculation of the inviscid contour concerning 1) the reflections of the characteristics and 2) the length of the incremental nozzle wall segments (DELX). The current program uses the assumption that the expansion waves do not reflect from the nozzle wall. This constraint means the compression part of the nozzle will start at the inflection point, the point at which the throat characteristic contacts the nozzle wall (Point "b" on Fig 5).

The inflection point is a dividing line in the nozzle. Upstream of the inflection point, the length of the incremental nozzle segments have a direct effect on the contour. However, downstream of the inflection point, the contour has already been set and is dependent on the intersection of the characteristics and the nozzle wall (i.e., the length of nozzle segments has little effect).

The assumption of no reflected characteristics has an effect on the maximum wall slope. Since the slope of the wall is dependent on the free-stream Mach number (one-half the Prandtl-Meyer angle), the maximum angle the flow expands could become quite large and result in separating

the flow.

The second consideration, the determination of incremental body length (DELX), is made to maximize the length of the nozzle. The incremental body length was determined by making the length of the last segment in the expansion region (determined through input) equal to the length of the first segment in the compression region (calculated by computer). From figure 5, this corresponds to line segment ab equaling line segment bc. The iteration of DELX continues until the difference of the two line segments is less then 5%.

Several types of boundary layer calculations have been incorporated into the program. Two methods can be used to calculate the compressible laminar boundary layers, Thwaites Method and the von Karman Momentum Integral. With the von Karman Momentum Integral, a sine velocity profile has been assumed. The turbulent boundary layer calculation also solves the compressible von Karman Momentum Integral using a velocity profile with a variable power. The turbulent boundary layer calculation will be initiated after the Reynolds number (based on X) exceeds six million. The critical Reynolds number is based on the power of the velocity profile, N. When the Reynolds number is less then six million, the calculation of N is approximately one, which would indicate a laminar boundary layer. The high critical Reynolds number could be due to the favorable pressure gradients found in supersonic nozzles allowing a

laminar boundary layer to exist farther along the nozzle wall.

The boundary layer correction consists of adding the vertical component (with respect to the nozzle coordinates) of the boundary-layer displacement-thickness to the inviscid contour. In effect, the vertical coordinates of the nozzle wall contour will be increased by the boundary-layer displacement-thickness. In using the vertical component of displacement-thickness, the axial location of each point in the original inviscid contour will remain unchanged.

Several parameters in the program are iterated until a specified condition is met. For instance, in the supersonic nozzle, Mach number is iterated until a particular Prandtl-Meyer expansion angle (NU) is reached. This iteration is accomplished using a modified Newton-Raphson Iteration. In the Newton-Raphson method, the derivative of the function is known, and the slope is used to "predict" the required Mach number needed to reach the known expansion angle. In general, however,the slope of the function can not be determined. The current program calculates a linear slope from two previous calculations, and proceeds to "predict" the required Mach number to obtain the known expansion angle.

Running the Program

This user friendly program requires a minimum amount of effort to execute on virtually any small personal computer. The program was written in the Basic language, and was executed on G-W Basic version 3.2. The execution of the program will generate the following files, all with the same "parent" name:

file.INT - Initial input file
file.SUB - Contains inviscid subsonic contour
file.SFF - Contains supersonic flow field
file.GEO - Contains inviscid supersonic geometry
file.PRF - Contains complete inviscid geometry
file.BLC - Contains boundary layer calculations
file.FIN - Contains final contour

If running the program for the first time, an input file will be created "file.INT". Required inputs are: PT, TT, throat height, maximum turning angle, number of divisions in the contour, type of boundary layer, and wall temperature if not adiabatic. Each subsequent run only requires the name of the "parent" file, and all the necessary inputs will be read from the input file (file.INT).

If editing of the data is required (for instance, "smoothing" the boundary layer contour), the program can be ended prematurely, and restarted at a later date using the "new" data.

To obtain a particular exit Mach number and exit height, it was found expedient to run the program in this order:

1. Use NACA 1135 tables (Ref 7) to determine the Prandtl-Meyer expansion angle for the desired exit Mach number. The expansion angle that should be placed in the program is 1/2 the expansion angle (NU) of the desired exit Mach number. Set the number of incremental nozzle segments so that the incremental nozzle angle is approximately 1 degree. Run the program setting the initial file to optimize the length of the incremental nozzle segments (DELX).

2. Run the convergent and supersonic flow field subroutines (1 and 2) of the program.

3. Evaluate the exit Mach number. Change the maximum expansion angle by editing the input file "file.INT" as appropriate. Re-run the flow field subroutine (2) of the program. Repeat this step as necessary.

4. When the desired exit Mach number has been calculated, run the supersonic geometry subroutine (3) of the program.

5. Edit the input file and turn off the optimization of the incremental body segments, and input the calculated value of the optimum body segment (DELX).

6. Evaluate the exit height of the nozzle, and modify the throat height as appropriate. Re-run the supersonic geometry subroutine (3) of the program. Note, this will not change the exit Mach number previously calculated. Repeat this step until the desired exit height is obtained.

7. After the inviscid subsonic and supersonic contours have been calculated, combine the two contours using subroutine 4 of the program.

8. When the complete inviscid contour has been determined, calculate the boundary layer using one of the three methods provided.

9. After assuring the credibility of the boundary layer calculation, add the boundary layer to the inviscid contour by executing subroutine 6 of the program. The final contour of the nozzle will be placed in the file "file.FIN".

CHAPTER IV

RESULTS AND DISCUSSION

A sample contour was run as part of the program verification. A supersonic nozzle with an exit Mach number of 2.0 and an exit height of 0.375 inches were the design requirements used in running the program. In the first iteration of the program, only the maximum expansion angle was changed until an exit Mach number of 2 was obtained. Then the throat height was adjusted to obtain the required exit height.

A contour with similar requirements was designed using the method of reference 5 and correcting for a laminar boundary layer computed with the GRAPES program. These program results will be referred to as "theory" and will be compared to the current program results.

The two contours, with a laminar boundary layer correction applied, are shown in figure 14. Both nozzles have a nominal exit height of 0.375 inches, and the appropriate throat height for an exit Mach number of 2. However, the length of the nozzle from the current program is approximately 1/2 that of theory.

Various lengths of incremental nozzle segments, DELX, were used in an attempt to increase the length of the nozzle. A comparison of the characteristics and nozzle length is shown using a very short DELX (Fig 15a) or the

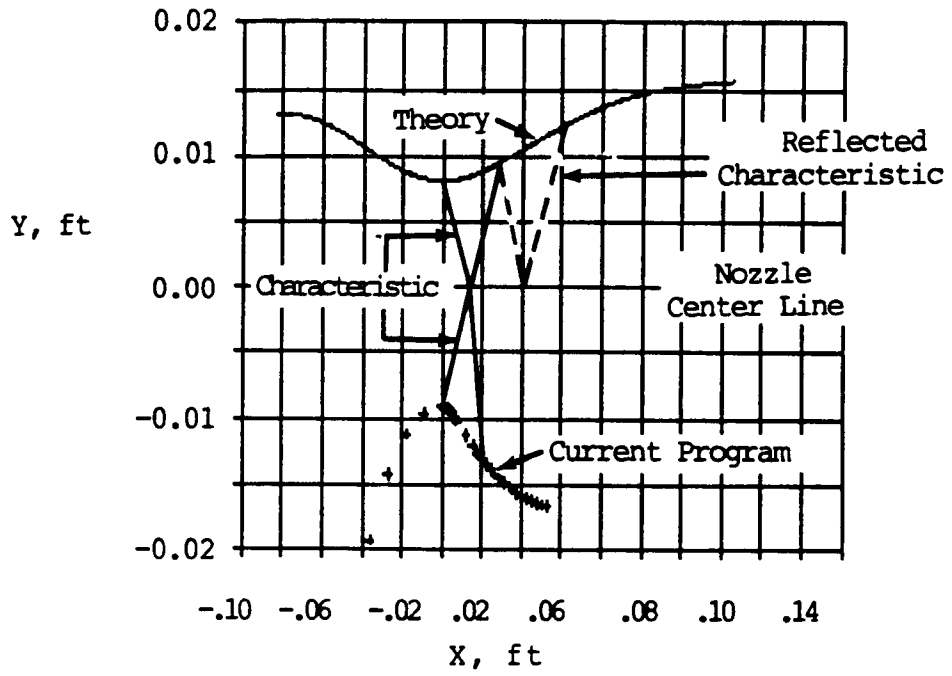
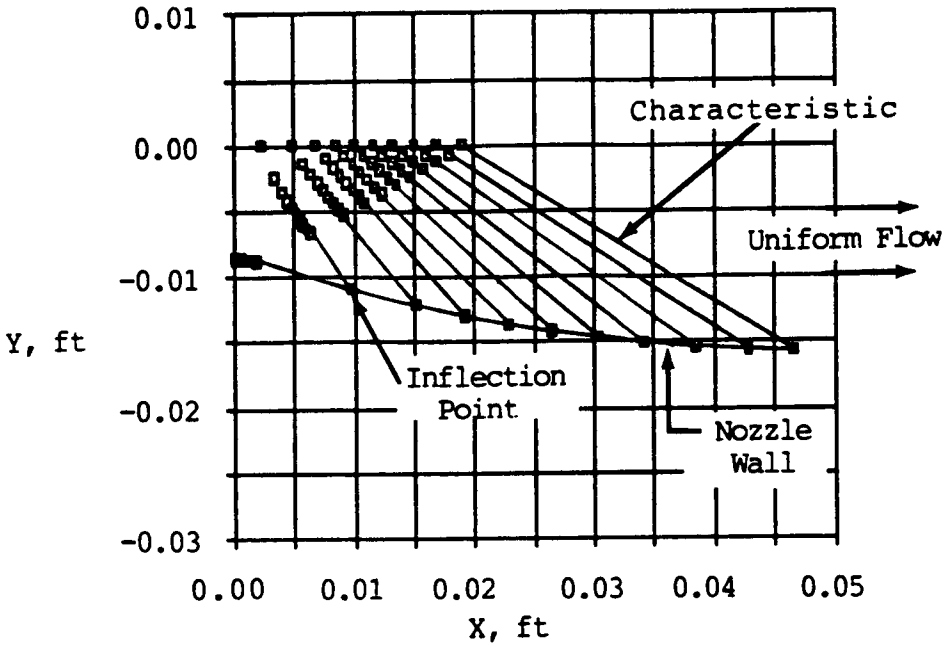


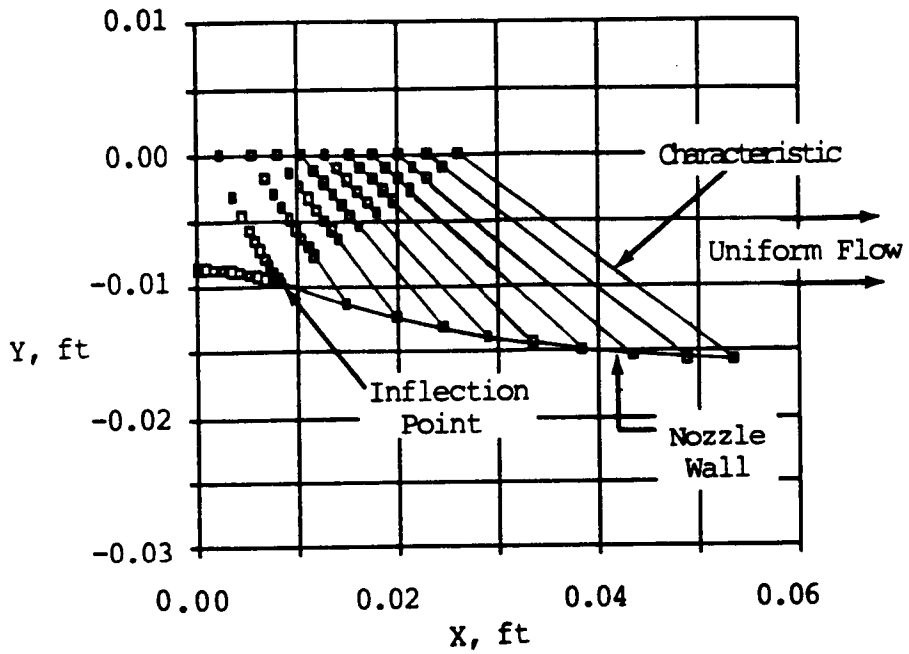
Figure 14. Comparison of Two Mach 2 Nozzle Contours

"optimum" DELX as set by the program (Fig 15b). Increasing DELX will decrease the curvature at the throat, thus increasing the size of the nozzle. As shown in figure 15, increasing DELX by a factor of 4 increases the overall nozzle length 13 percent. A larger DELX than that in figure 15b would cause the characteristic to pass through the wall of the nozzle, which is not permitted.

The difference between the two programs is the ability of the theory's program to reflect characteristics from the nozzle wall back to the nozzle center line (Fig 14). By allowing multi-reflections, the slope of the nozzle wall can be held to a set value. This region of constant curvature defines the transistion region of the nozzle (Fig 1). In the current program all of the "absorption" of the



a. DELX = 0.0002 ft



b. DELX = 0.0008 ft

Figure 15. Influence of the Length of Body Segment

characteristic occurs at the intersection of the wall and the first (throat) characteristic. This intersection defines the inflection point of the nozzle (Fig 1). The characteristics shown in figure 14 are not to scale.

The assumption of no reflected characteristics places a constraint on the maximum allowable Mach number due to separation. A good rule of thumb says the maximum expansion angle should be less than 12 degrees. This criteria would limit the current program to a maximum free-stream Mach number of 2.

Although the two contours appear very different, when the axial distance is normalized with the length of the supersonic region (Fig 16), the two contours look nominally the same. Since the normalized contours look similar, it is believed that both programs produce shock free nozzles. The transistion region (Fig 1) can also be seen in figure 14 as a region of constant wall angle. The current program does not have a region of "constant curvature", and thus, the slope of the wall in the current program is constantly changing.

The comparison of the boundary layer displacement thickness (Fig 17) for a laminar boundary layer is shown using theory (Ref 5), the laminar von Karman Momentum Integral and a modified compressible Thwaites method. The modified Thwaites curve is a product of the compressible shape factor (H) and the incompressible

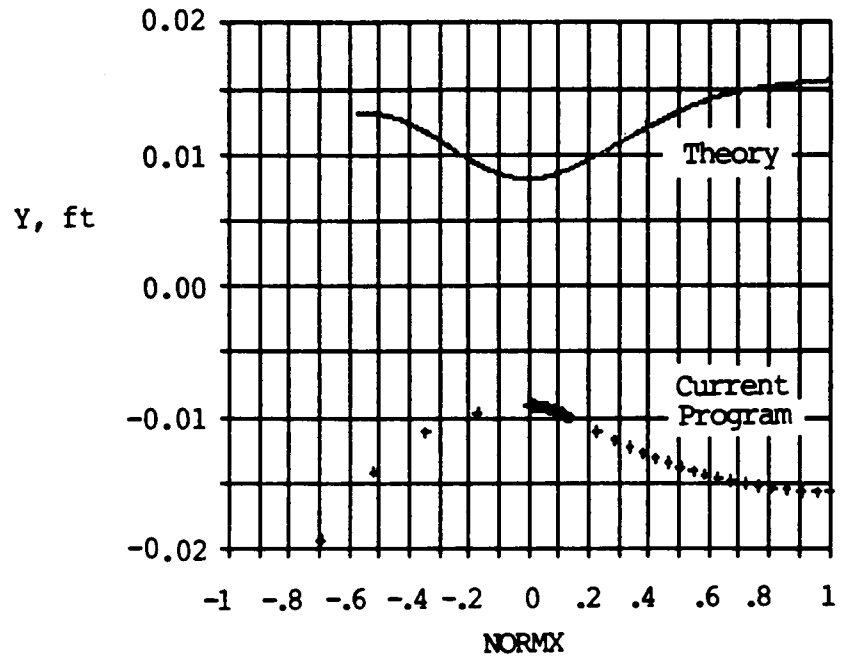


Figure 16. Normalized Nozzle Contours

momentum thickness (THETAi). The incompressible momentum thickness was used in the definition of DEL* since the transformation to the compressible THETA was a factor of 5 greater than its incompressible counterpart (THETAi). As shown, the distribution using the modified Thwaites method matches the von Karman Integral. Because of the agreement between the von Karman Integral to the present approach for calculating the Thwaites displacement thickness, DEL*, the modified Thwaites method has been adopted. Both methods of calculating the displacement thickness compare very well to the theoretical results of reference 5.

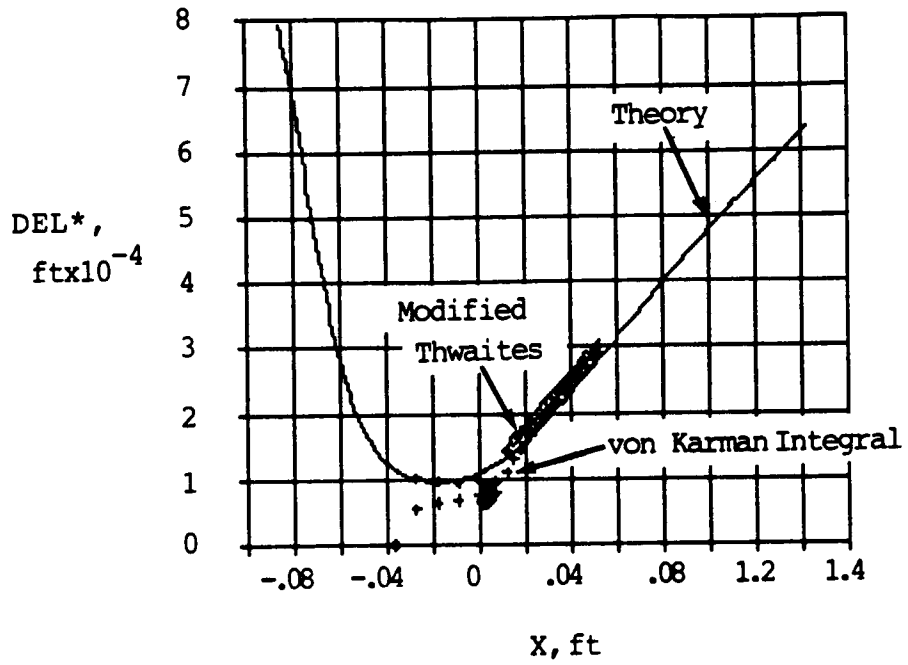


Figure 17. Distribution of Displacement Thickness

An interesting effect of the distribution of displacement thickness due to the initial state of the flow entering the subsonic convergent nozzle can be seen in figure 17. The theory is based on fully developed pipe flow entering the nozzle, while the current program assumes flow with no boundary layer entering the nozzle. Ironically, these two very different initial conditions theoretically produce the same nominal distribution of displacement thickness through the nozzle.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A computer program has been developed that calculates the contour of a convergent/divergent nozzle using the Method of Characteristics. The inviscid nozzle wall contour can also be corrected using the displacement thickness of a laminar and/or turbulent boundary layer. The following conclusions can be made:

1. The computer program calculates the wall contour of the convergent and divergent sections of a two-dimensional supersonic nozzle with boundary layer corrections on virtually any small personal computer.

2. The inviscid wall contour can be corrected by assuming that a laminar or laminar/turbulent boundary layer exists on the wall of the nozzle.

3. The calculation of the displacement thickness of a laminar boundary layer using the von Karman Momentun Integral compared well to other "theoretical" results.

4. The resulting wall contour will be the longest nozzle possible for a given free-stream Mach number and throat height with no multi-reflecting characteristics from the wall to the nozzle center line. A shorter nozzle can be calculated by using a shorter incremental wall distance, DELX, than the one computed in the program.

In the future, to decrease design limitations (allow for a free-stream Mach number greater than 2), and improve program usage, the program could be modified in the following areas:

1. By allowing multi reflections of the characteristics, predictions of nozzles with higher free-stream Mach numbers would be possible without the probability of flow separation.

2. Many applications require a given nozzle length, as well as an exit Mach number and exit area. In the current program, the length of the nozzle can be varied slightly by changing DELX. The capability of specifying a longer nozzle length could be easily incorporated into the above modification of multi-reflecting characteristics.

3. Currently, the user has to iterate the maximum expansion angle and throat height to achieve the design specifications of exit Mach number and exit nozzle height. Having the program iterate these two parameters would save the user hours of frustration.

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REFERENCES

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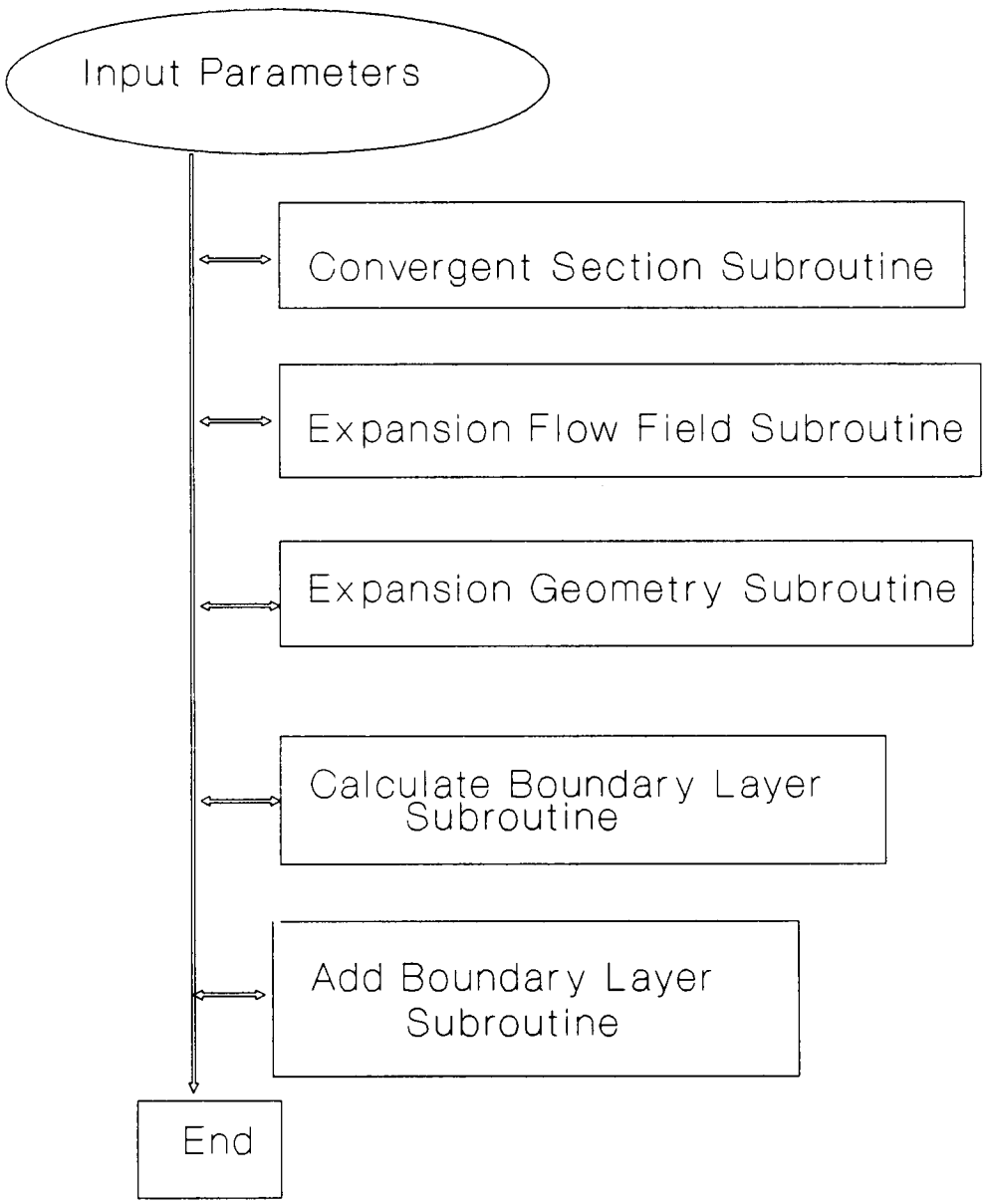
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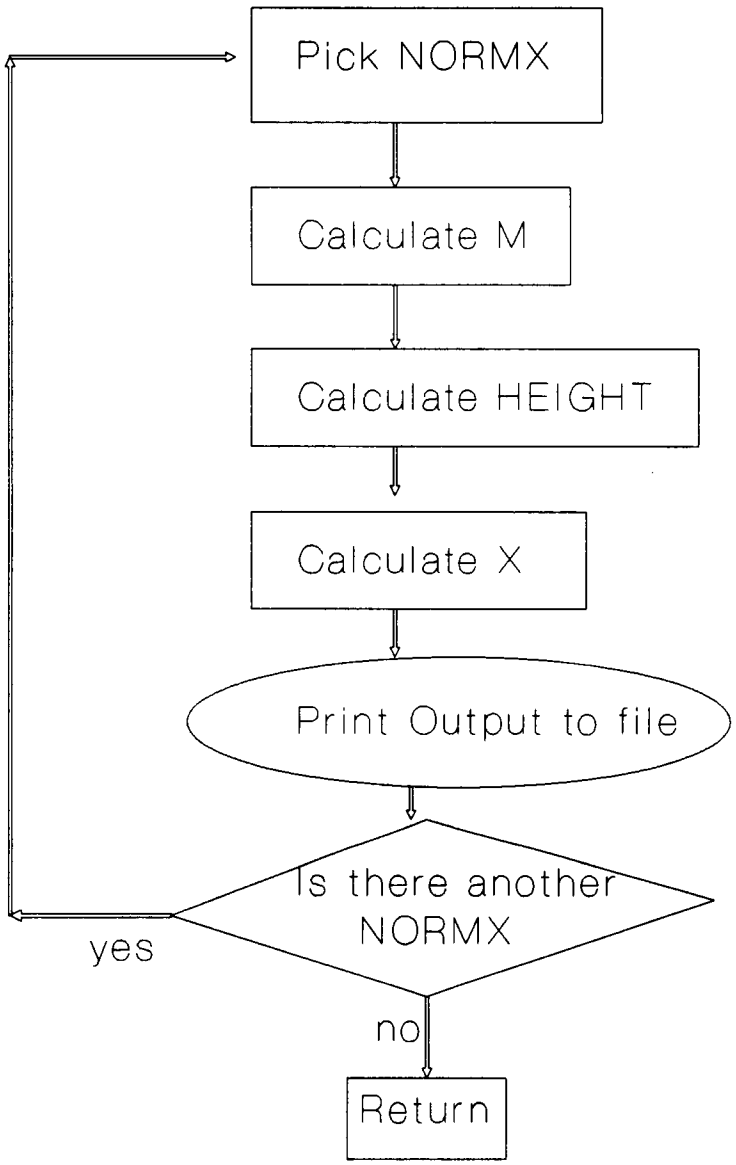
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APPENDIX: PROGRAM LISTINGS

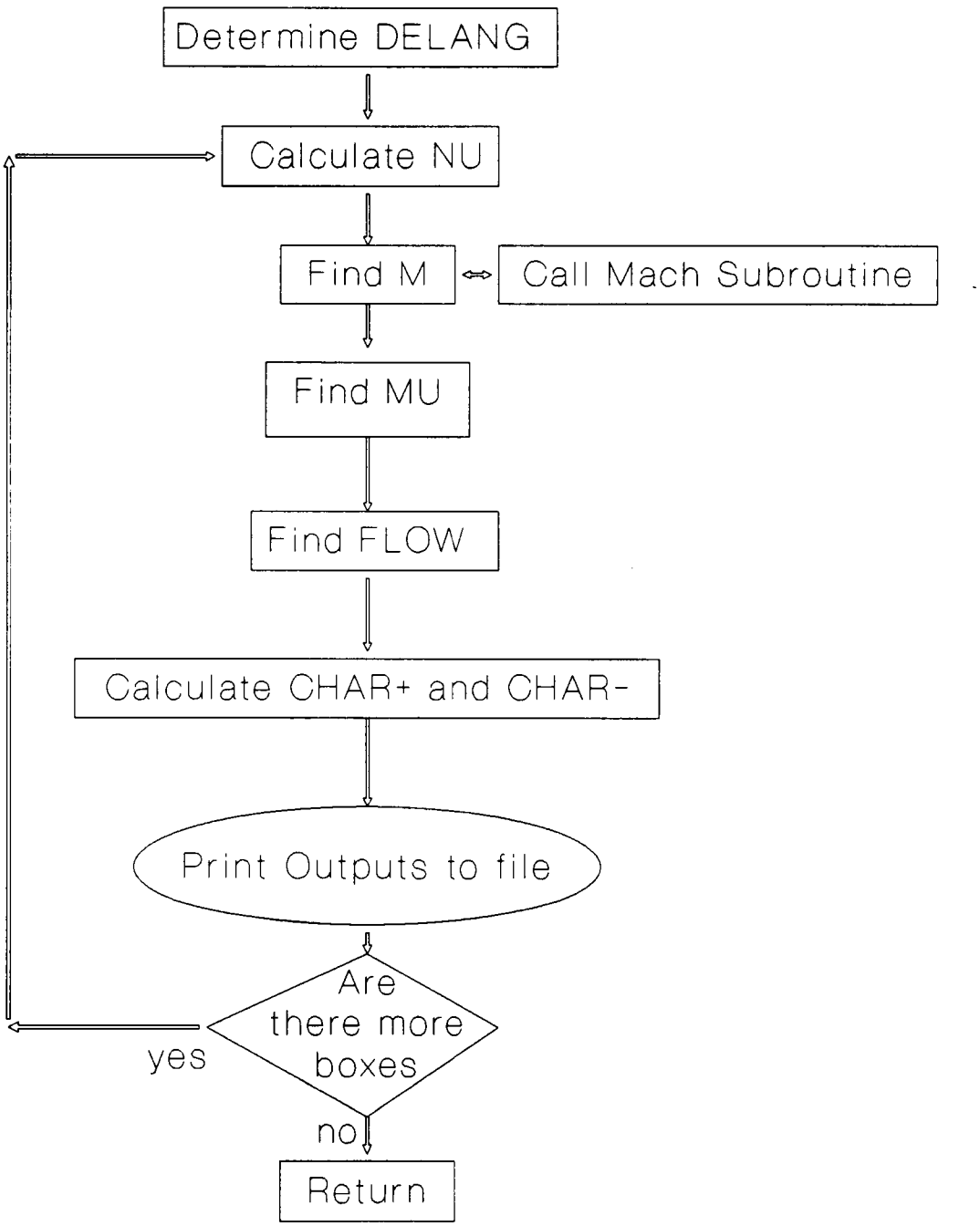
Program Flow Chart
Main Program



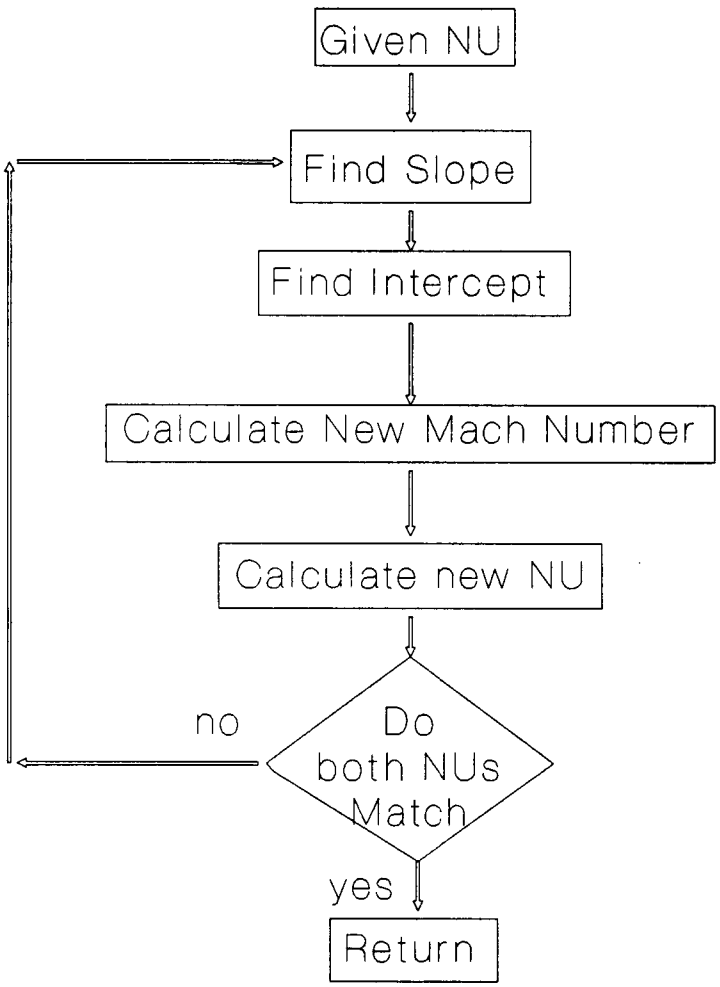
Program Flow Chart
Convergent Section Subroutine



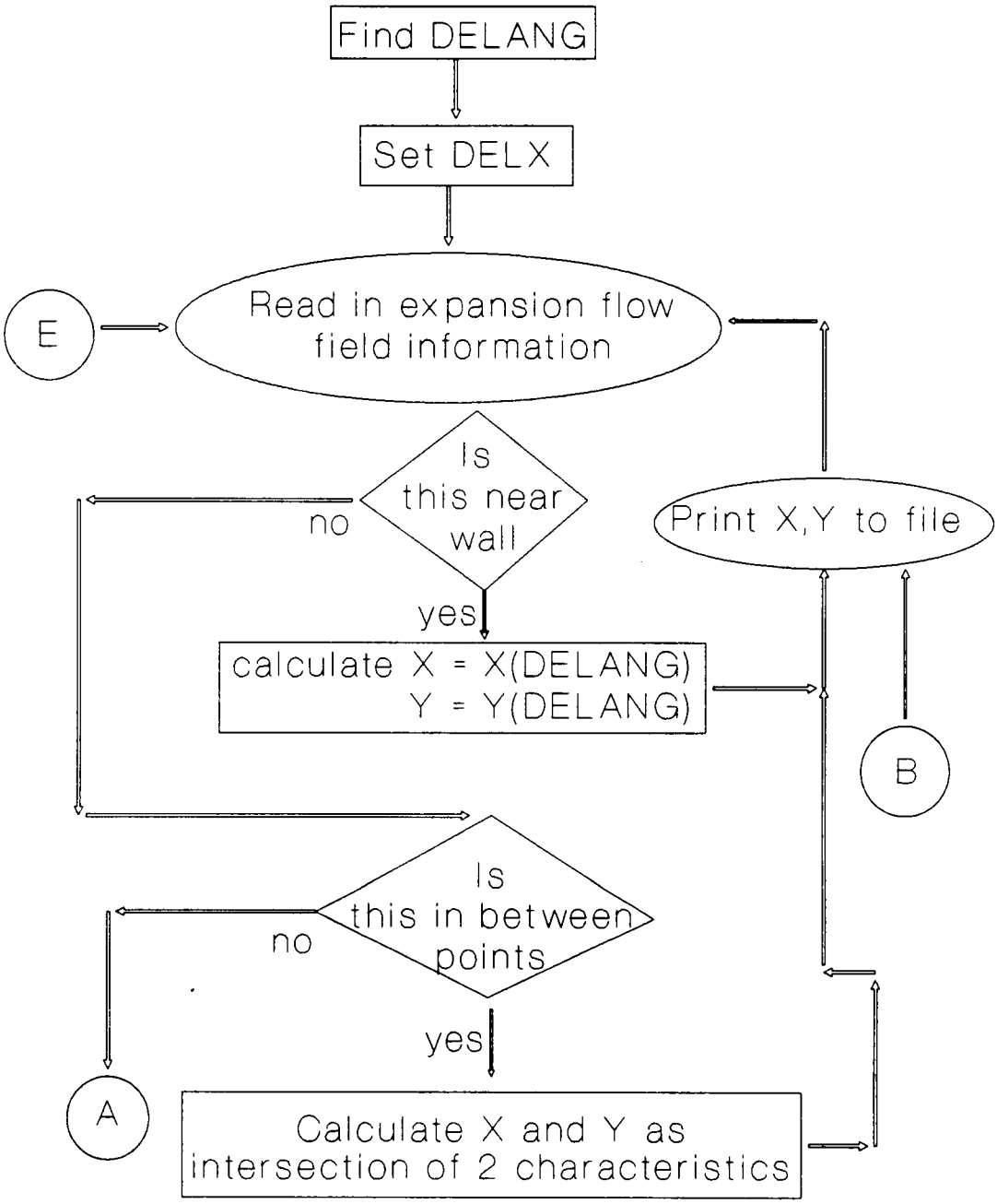
Program Flow Chart
Expansion Flow Field Subroutine



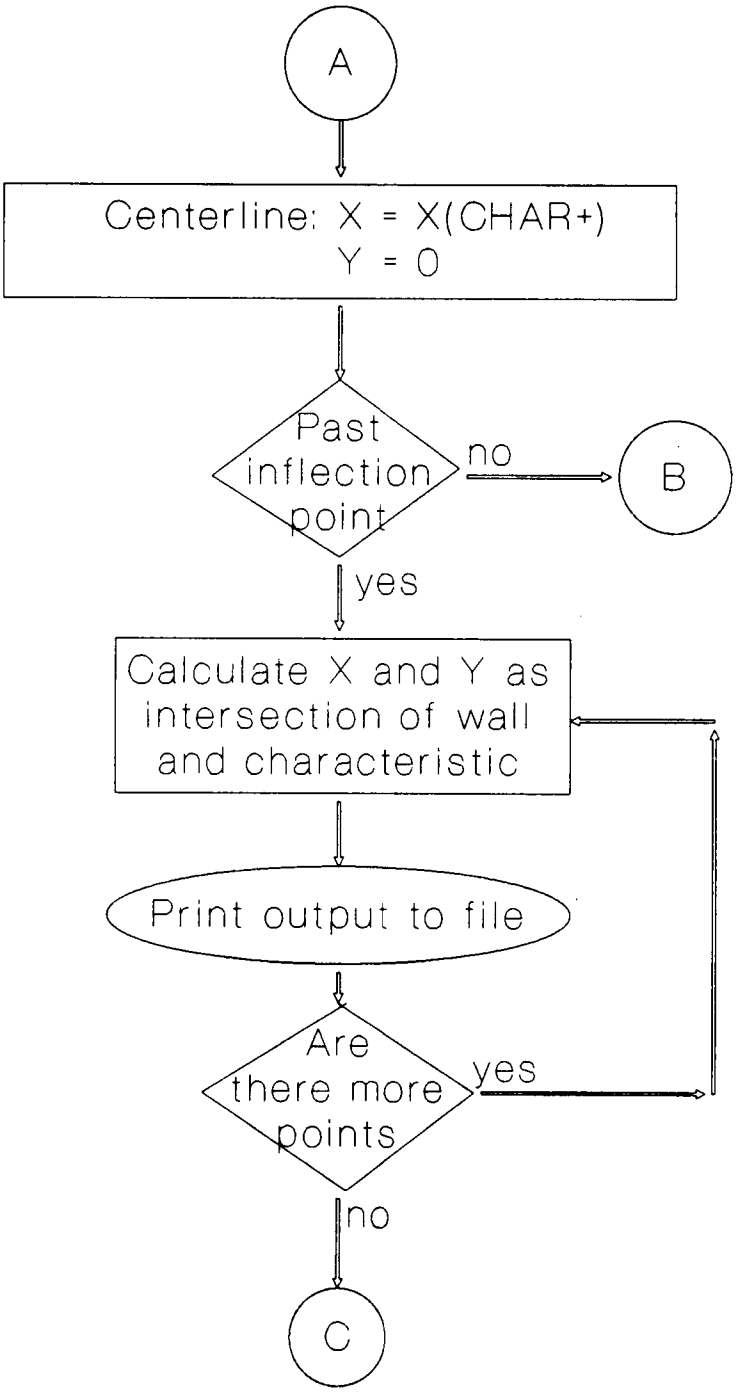
Program Flow Chart
Mach Number Subroutine



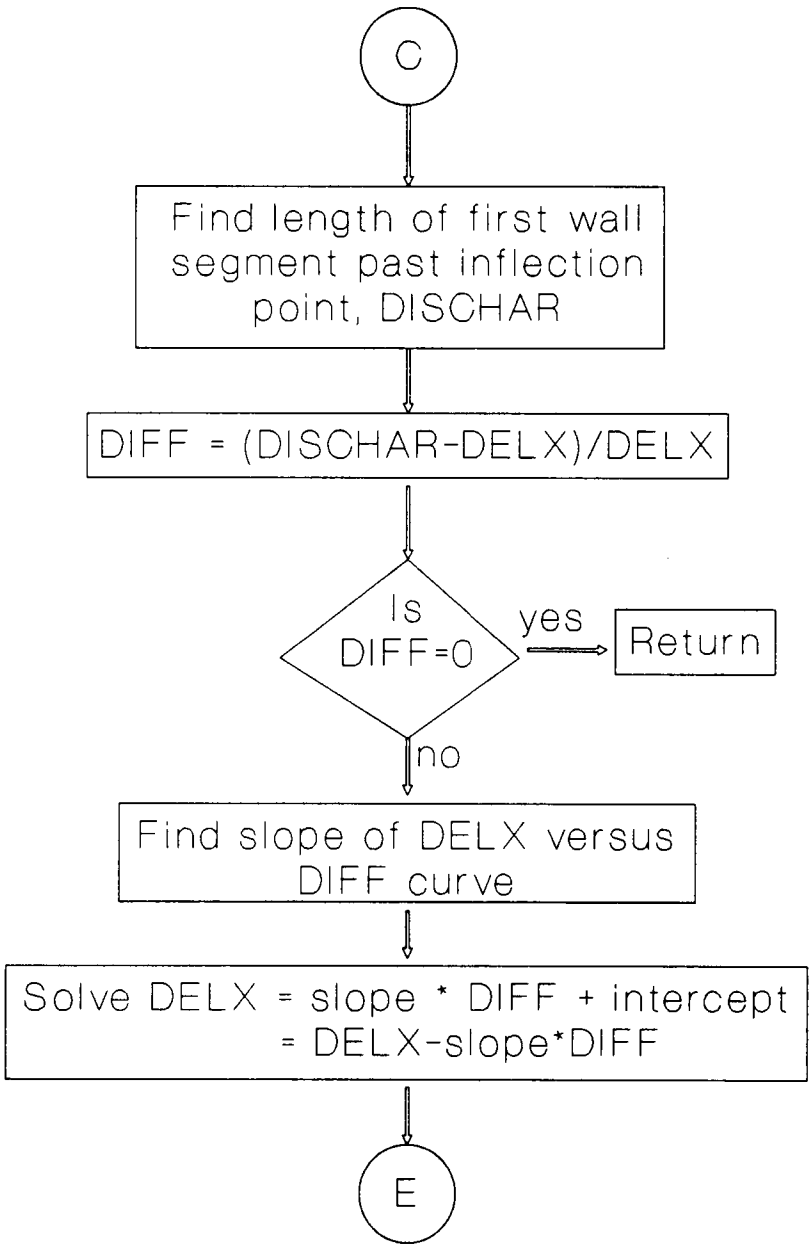
Program Flow Chart
Expansion Geometry Subroutine



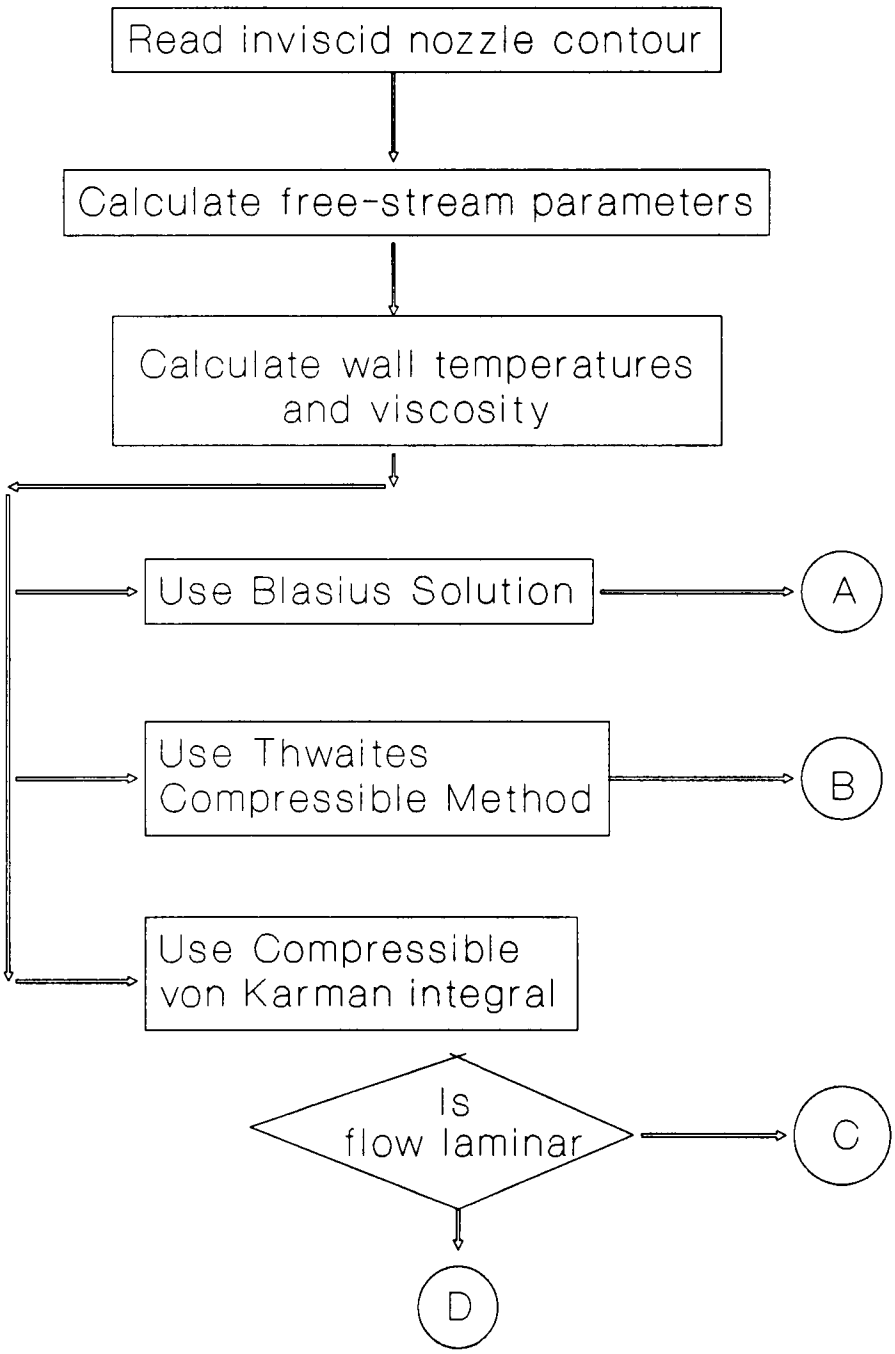
Program Flow Chart
Expansion Geometry Subroutine (cont)



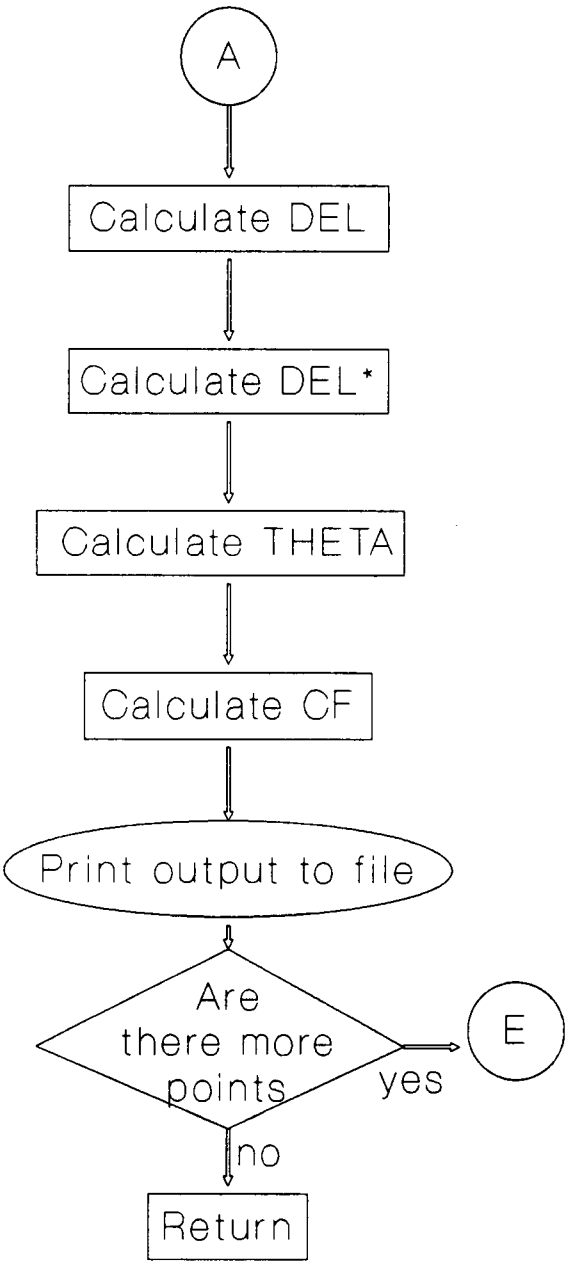
Program Flow Chart
Expansion Geometry Subroutine (cont)



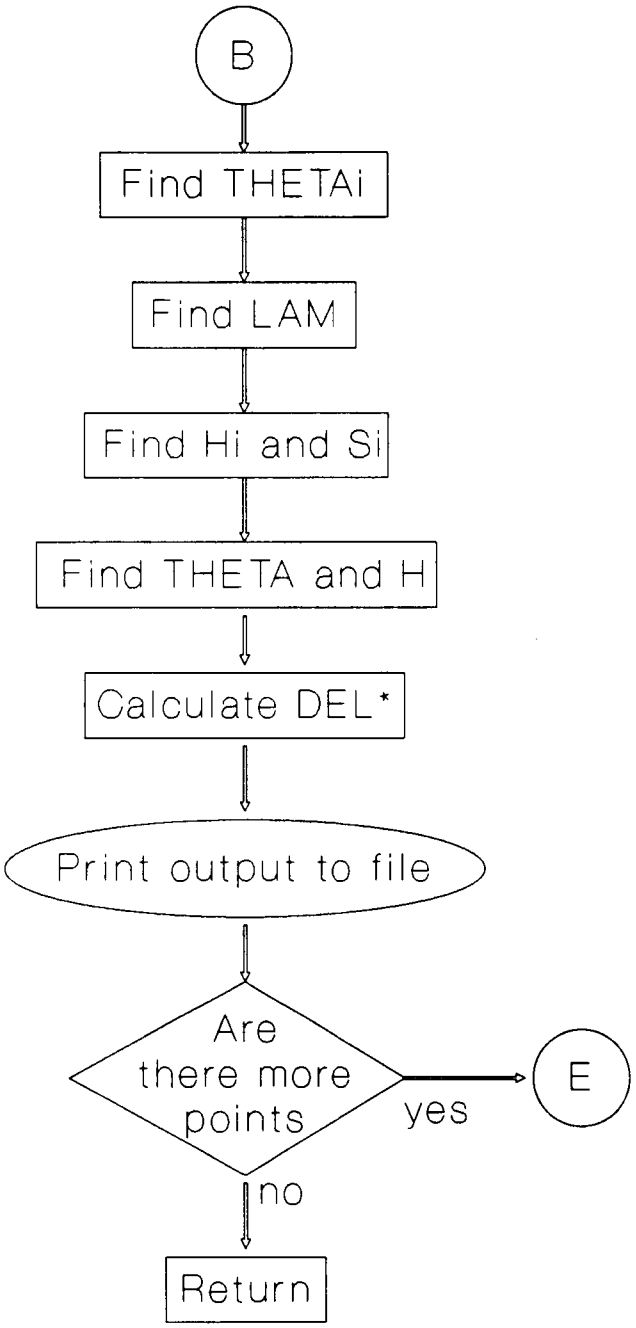
Program Flow Chart
Boundary Layer Subroutine



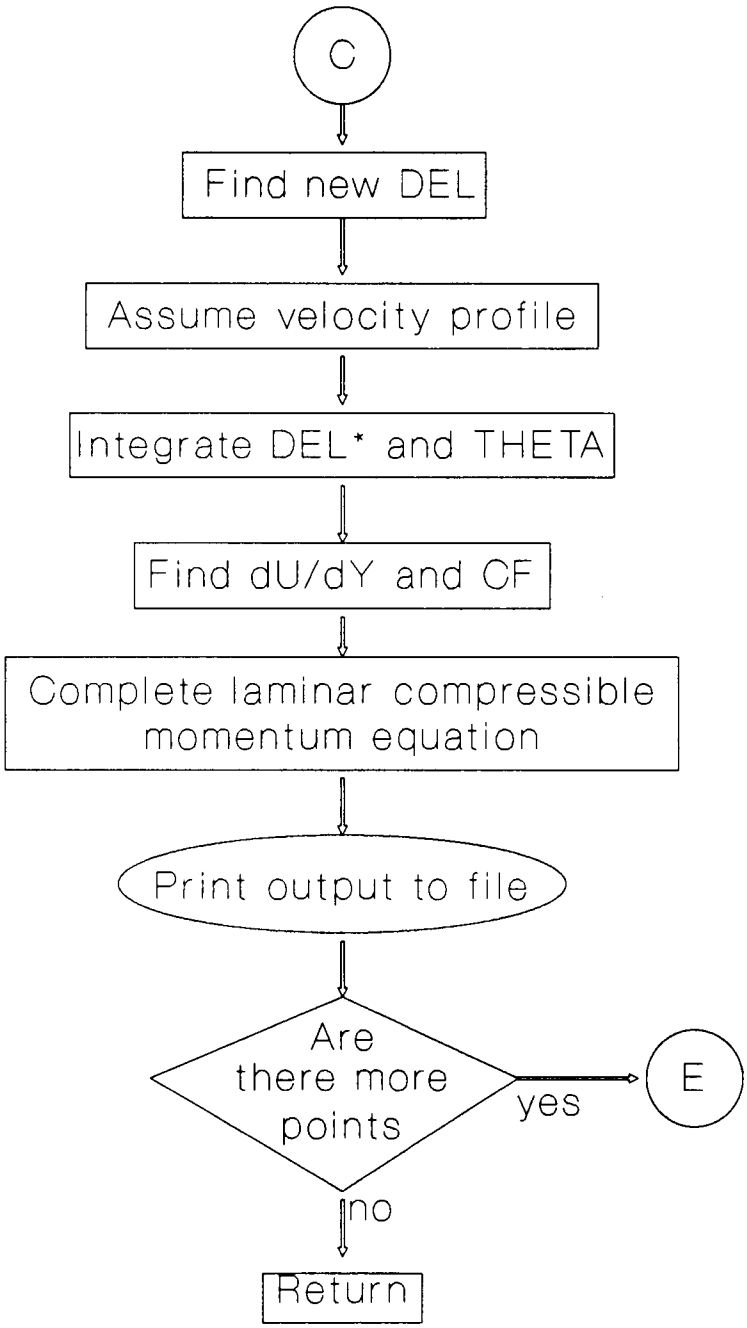
Program Flow Chart
Boundary Layer Subroutine (cont)



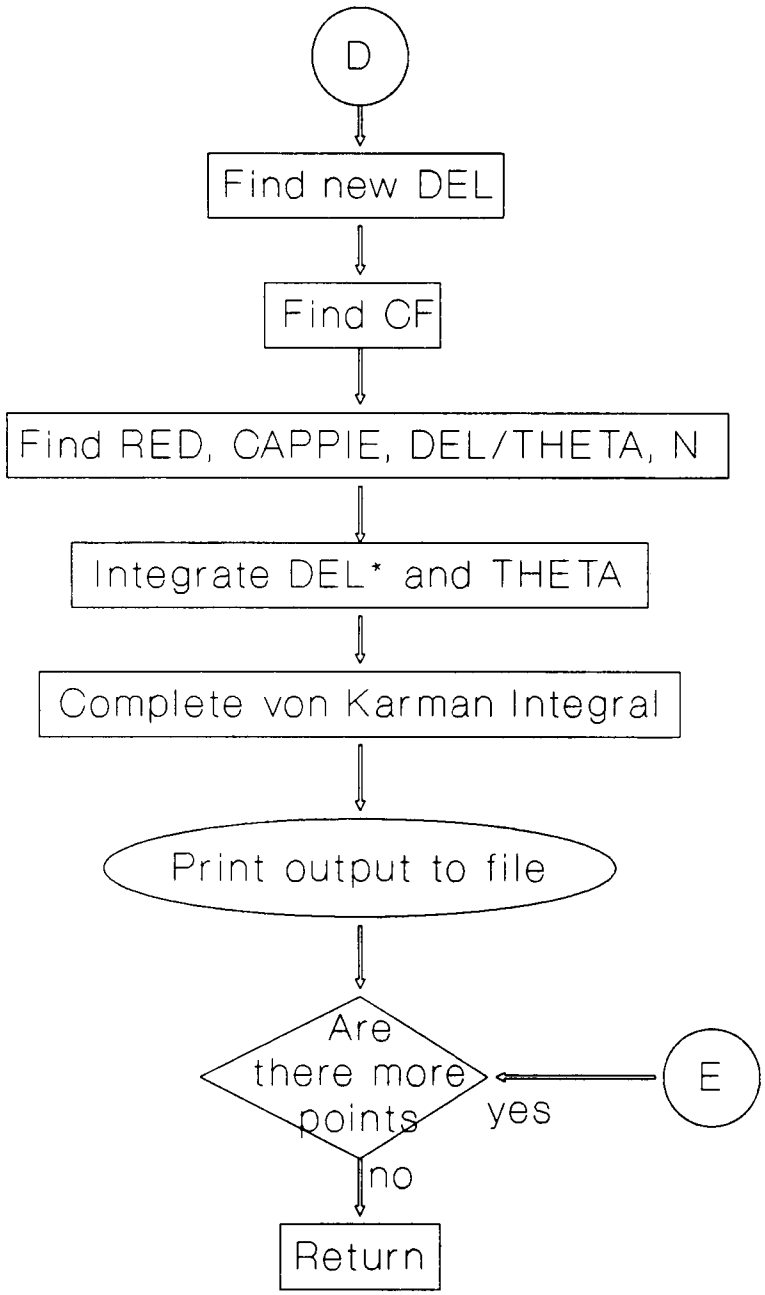
Program Flow Chart
Boundary Layer Subroutine (cont)



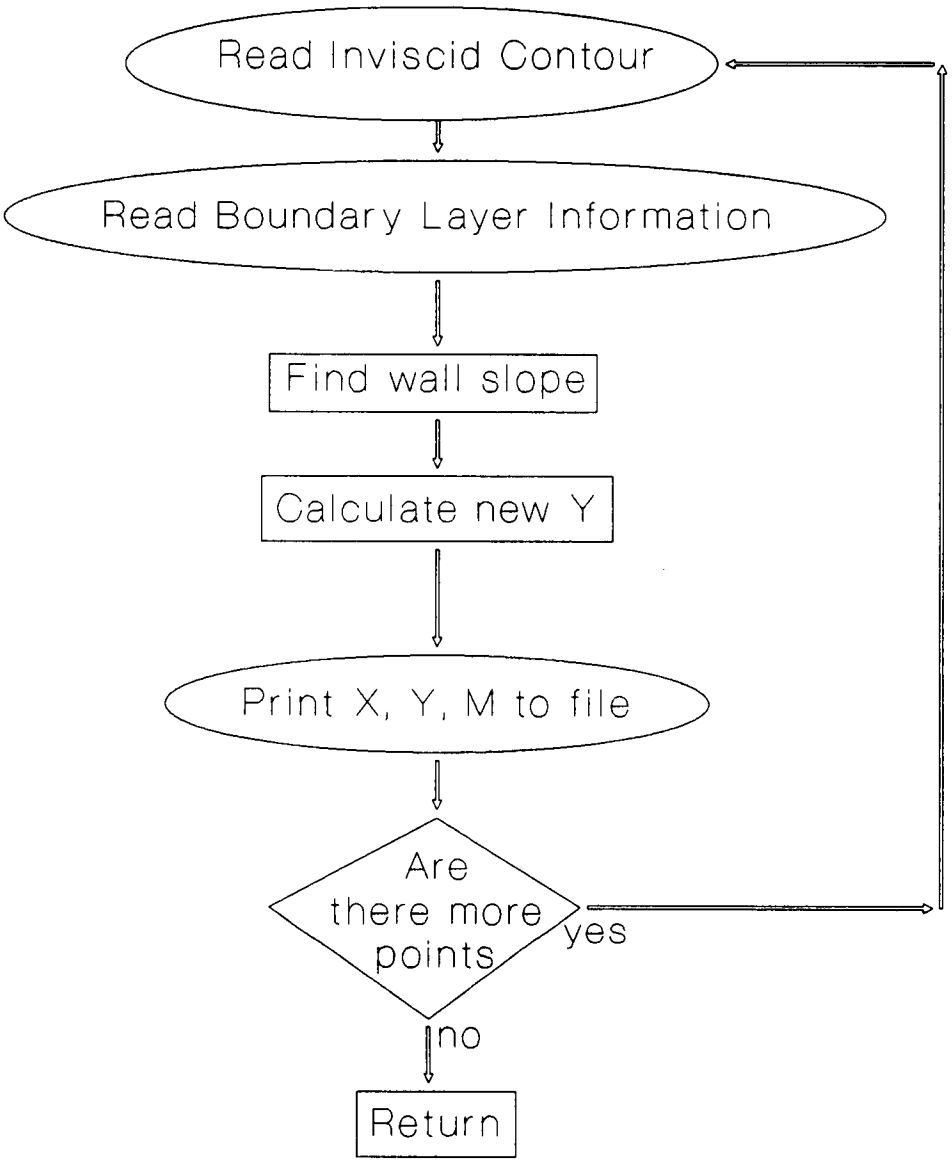
Program Flow Chart
Boundary Layer Subroutine (cont)



Program Flow Chart
Boundary Layer Subroutine (cont)



Program Flow Chart
Add Boundary Layer Subroutine



```
10 CLS
20 PRINT "THIS PROGRAM CALCULATES A 2-DIM. NOZZLE CONTOU
R "
30 PRINT "USING THE METHOD OF CHARACTERISICS "
40 PRINT
50 PRINT "     NOTE: 1) USE CAPITAL LETTERS"
60 PRINT "           2) WRITTEN BY JOHN P. GRUBB "
70 PRINT
80 PRINT
90 PRINT "                STRIKE  ANY KEY TO CONTINUE "
100 JUNK$ = INPUT$(1)
110 CLS
120 REM ************************************************
****************
130 REM          DIMENSION ARRAYS AND SET
140 REM          ERROR TRAPPING ROUTINE
150 REM ************************************************
****************
160     DIM M(40,2),THETAN(40,2),THETAP(40,2),X(40,2),Y
(40,2)
170     DIM XX(1000),YY(1000)
180 PIE = 3.141592654#
190 ON ERROR GOTO 1680
200 REM ************************************************
**********
210 REM        SET GAMMA AND CONSTANTS
220 REM ************************************************
**********
230 PRANDTL = .71
240 GRAV = 32.174
250 RGAS = 53.35 * GRAV
260 GAMMA=1.4
270 CPRESS = RGAS*GAMMA/(GAMMA-1)
280 GM1 = GAMMA-1
290 GP1 = GAMMA+1
300 GM1O2 = (GAMMA-1)/2
310 GOGM1 = GAMMA/(GAMMA-1)
320 GP1O2GM1 = (GAMMA+1)/2/(GAMMA-1)
330 REM ************************************************
**********
340 REM      SET STUFF FOR MACH NUMBER CALCULATION
350 REM ************************************************
**********
360 M1 = 1.5 : NUE1 = 11.905
370 M2 = 2 : NUE2 = 26.308
380 REM  ************************************************
***********
390 REM       INPUT CONSTANT STUFF
400 REM  ************************************************
***********
410 INPUT "DO THE INPUTS EXIST IN A FILE (Y/N) ?  ",ANS
$
```

```
420 IF ANS$ = "N" THEN GOTO 660
430 REM
440 REM ********** READ INPUTS FROM FILE **************
******
450 REM
460   CLS
470   INPUT "INPUT CASE filename (DO NOT USE EXTENSION)
 : ",FILENME$
480     FILE$ = FILENME$ + ".INT"
490   OPEN FILE$ FOR INPUT AS #1
500    INPUT #1, JUNK$,PT
510    INPUT #1, JUNK$,TT
520    INPUT #1, JUNK$,THROAT
530    INPUT #1, JUNK$,THEMAX
540    INPUT #1, JUNK$,NUMANG
550    INPUT #1, JUNK$,DELTX
560    INPUT #1, JUNK$,ANSINC$
570    INPUT #1, JUNK$,ANSTW$
580    INPUT #1, JUNK$,TCWALL
590    INPUT #1, JUNK$,ANSBL$
600   CLOSE #1
610   CLS
620   GOTO 1040
630 REM
640 REM ********** INPUT INTERACTIVELY ***************
****
650 REM
660 CLS
670 INPUT "INPUT CASE filename (DO NOT USE EXTENSION):
",FILENME$
680 PRINT
690 INPUT "INPUT STILLING CHAMBER TOTAL PRESSURE (PSF)
: ",PT
700 PRINT
710 INPUT "INPUT STILLING CHAMBER TOTAL TEMPERATURE (DE
G R) : ",TT
720 PRINT
730 INPUT "TOTAL THROAT HEIGHT (FT) : ",THROAT
740 PRINT
750 INPUT "INPUT MAXIMUM BODY ANGLE (DEG): ",THEMAX
760 PRINT
770 INPUT "INPUT NUMBER OF SEGMENTS: ",NUMANG
780 PRINT
790 INPUT "DO YOU WANT TO OPTIMIZE INCREMENTAL BODY DIS
TANCE (Y/N)? ",ANSINC$
800 IF ANSINC$ = " " THEN ANSINC$ = "Y"
810 IF ANSINC$ = "Y" THEN DELTX = 0 : GOTO 840
820 PRINT
830 INPUT "INPUT INCREMENTAL BODY DISTANCE (IN): ",DELT
X
840 PRINT
850 INPUT "DO YOU WANT COLD WALL OR HOT WALL (H/C)? ",A
```

```
NSTW$
860 IF ANSTW$ = " "  THEN ANSTW$ = "H"
870 PRINT
880 IF ANSTW$ = "C"   THEN INPUT "INPUT WALL TEMPERATURE
 (DEG R): ",TCWALL
890 IF ANSTW$ = "H"   THEN TCWALL = 0
900 PRINT
910 PRINT "INPUT TYPE OF BOUNDARY LAYER: "
920 PRINT "      T  - THWAITES (LAMINAR)"
930 PRINT "      L  - INTERGRAL MOMENTUM (LAMINAR)"
940 PRINT "      B  - BLASSIUS "
950 PRINT "      LT - LAMINAR THEN TURBULENT "
960 PRINT
970 INPUT "INPUT TYPE: ",ANSBL$
980 IF ANSBL$ =  " "  THEN ANSBL$ = "T"
990 PRINT
1000 CLS
1010 REM ************************************************
*********
1020 REM             SAVE INPUTS IN FILE
1030 REM ************************************************
*********
1040 FILE$ = FILENME$ + ".INT"
1050 OPEN FILE$ FOR OUTPUT AS #1
1060 PRINT #1, USING  "STILLING CHAMBER TOTAL PRESSURE
(PSF) : , ######.### ";
         PT
1070 PRINT #1, USING "STILLING CHAMBER TOTAL TEMPERATUR
E (DEG R) : , ####.###
";         TT
1080 PRINT #1, USING "TOTAL THROAT HEIGHT (FT) : , ##.#
######### ";THROAT
1090 PRINT #1, USING "MAXIMUM BODY ANGLE (DEG): , ##.##
#### ";THEMAX
1100 PRINT #1, USING "NUMBER OF BODY SEGMENTS: , ##.###
### ";NUMANG
1110 PRINT #1, USING "INCREMENTAL BODY DISTANCE (FT) :
, ##.#######^^^^";DELTX
1120 PRINT #1, USING "OPTIMIZE INCREMENTAL BODY DISTANC
E (Y/N)? , &";ANSINC$
1130 PRINT #1, USING "USE A HOT OR COLD WALL (H/C): ,
&";ANSTW$
1140 PRINT #1, USING "WALL TEMPERATURE (DEG R): , ###.#
#### ";TCWALL
1150 PRINT #1, USING "TYPE OF BOUNDARY LAYER: , &";ANSB
L$
1160 CLOSE #1
1170 CLS
1180 REM ************************************************
**********
1190 REM      OPTIONS
1200 REM ************************************************
```

```
***********
1210 PRINT "  OPTIONS ARE: "
1220 PRINT "       1- DEFINE CONVERGING SECTION FLOW FIE
LD
1230 PRINT "       2- DEFINE EXPANSION FLOW FIELD "
1240 PRINT "       3- DEFINE EXPANSION GEOMETRY "
1250 PRINT "       4- COMBIND SUBSONIC AND SUPERSONIC PR
OFILES "
1260 PRINT "       5- DETERMINE BOUNDARY LAYER  "
1270 PRINT "       6- ADD BOUNDARY LAYER TO GEOMETERY "
1280 PRINT "       7- PLOT GEOMETERY "
1290 PRINT "       8- DO COMPLETE DESIGN "
1300 PRINT "       9- QUIT PROGRAM  "
1310 PRINT :PRINT :PRINT
1320 INPUT "  OPTION = :",NOWWHAT
1330 IF NOWWHAT <> 8 THEN GOTO  1410
1340 NOWWHAT = 0
1350 NOWWHAT = NOWWHAT + 1
1360 CLS
1370 ON NOWWHAT GOSUB 2130,2670,3450,10350,5280,8880,96
70,1600
1380 IF NOWWHAT <= 5 THEN GOTO 1350
1390 CLS
1400 GOTO 1210
1410 IF NOWWHAT = 1 THEN GOSUB 2130
1420 IF NOWWHAT = 1 THEN CLS:GOTO 1210
1430 IF NOWWHAT = 2 THEN GOSUB 2670
1440 IF NOWWHAT = 2 THEN CLS:GOTO 1210
1450 IF NOWWHAT = 3 THEN GOSUB 3450
1460 IF NOWWHAT = 3 THEN CLS:GOTO 1210
1470 IF NOWWHAT = 4 THEN GOSUB 10350
1480 IF NOWWHAT = 4 THEN CLS:GOTO 1210
1490 IF NOWWHAT = 5 THEN GOSUB 5280
1500 IF NOWWHAT = 5 THEN CLS:GOTO 1210
1510 IF NOWWHAT = 6 THEN GOSUB 8880
1520 IF NOWWHAT = 6 THEN CLS:GOTO 1210
1530 IF NOWWHAT = 7 THEN GOSUB 9670
1540 IF NOWWHAT = 7 THEN CLS:GOTO 1210
1550 IF NOWWHAT = 9 THEN CLS:GOTO 1600
1560 PRINT :PRINT
1570 PRINT " NO INPUT RECIEVED, ENTER DIGIT 1-9 "
1580 PRINT :PRINT
1590 GOTO 1210
1600 END
1610 REM ************************************************
*************
1620 REM
1630 REM
1640 REM                      ERROR TRAP
1650 REM
1660 REM
1670 REM ************************************************
```

```
*************
1680 PRINT "ENTERING ERROR TRAP "
1690 PRINT
1700 PRINT USING "ERROR ### WAS MADE ON LINE ### ";ERR,
ERL
1710 PRINT
1720 REM ****** FILE DOES NOT EXIST ******************
1730 IF ERR = 53 THEN GOTO 1750
1740 IF ERR <> 64 THEN GOTO 1860
1750 PRINT "Bad filename or File does not exist "
1760 PRINT
1770 PRINT "COURSE OF ACTION: CHOOSE ANOTHER filename "

1780 PRINT
1790 FILES
1800 INPUT "INPUT filename: ",FILE$
1810 IF ERL = 490 THEN RESUME 460
1820 IF ERL = 9710 THEN RESUME 0
1830 PRINT " CAUTION, FILE SHOULD EXIST. . . "
1840 RESUME 0
1850 REM ******* DISK FULL *************
1860 IF ERR <> 61 THEN GOTO 1960
1870 PRINT "Disk full "
1880 PRINT
1890 PRINT "COURSE OF ACTION: USE ANOTHER DISK "
1900 PRINT
1910 PRINT "PUT ANOTHER DISK IN DRIVE "
1920 PRINT "     STRIKE ANY KEY TO CONTNUE: "
1930 JUNK$ = INPUT$(1)
1940 RESUME 0
1950 REM ********* PRINTER NOT READY ****************
1960 IF ERR = 27 THEN GOTO 1990
1970 IF ERR = 24 THEN GOTO 1990
1980 IF ERR <> 25 THEN GOTO 2070
1990 PRINT "Problem with printer "
2000 PRINT
2010 PRINT "COURSE OF ACTION: FIX PRINTER "
2020 PRINT
2030 PRINT "WHEN PRINTER IS FIXED, STRIKE ANY KEY TO CO
NTINUE "
2040 JUNK$ = INPUT$(1)
2050 RESUME 0
2060 REM ********** ALL OTHERS ************************
2070 ON ERROR GOTO 0
2080 REM ************************************************
*****
2090 REM
2100 REM       SUBROUTINE CONVERGENT GEOMETRY
2110 REM
2120 REM ************************************************
*****
2130 CLS
```

```
2140 PRINT "CALCULATING SUBSONIC PART OF NOZZLE . . . "

2150 FILE$ = FILENME$ + ".SUB"
2160 OPEN FILE$ FOR OUTPUT AS #2
2170 REM ************************************************
**********
2180 REM                          PRINT TITLE JUNK
2190 REM ************************************************
**********
2200 PRINT #2, "CONVERGENT PART OF NOZZLE "
2210 PRINT #2,   " NORM X        NORM X        X
 Y          MACH "
2220 REM PRINT   " NORM X        NORM X        X
 Y          MACH "
2230 REM PRINT USING "###.###     ###.###    ###.######
 ###.#######
#.#######";                NORMX,NORMX,X,HEIGHT,M
2240 REM PRINT "STRIKE":JUNK$=INPUT$(1)
2250 REM ************************************************
**********
2260 REM       SET MACH NUMBER COEFFICIENTS
2270 REM ************************************************
**********
2280 MBEF = 0
2290    C0 = .9953446
2300    C1 = .4910455
2310    C2 = 5.802925E-02
2320    C3 = -8.186715E-03
2330    C4 = -1.466458E-03
2340    C5 = 8.861818E-05
2350    C6 = 1.535031E-05
2360 REM ************************************************
**********
2370 REM     **** START HEIGHT LOOP ****
2380 REM ************************************************
**********
2390 FOR NORMX = -4 TO 0 STEP .1
2400 M = C0 + C1*NORMX + C2*NORMX^2 + C3*NORMX^3 + C4*N
ORMX^4
            + C5*NORMX^5 + C6*NORMX^6
2410      IF M < MBEF THEN M = MBEF
2420    HEIGHT = THROAT/M*((1+GM1O2*M^2)/(1+GM1O2))^GP1O
2GM1
2430    HEIGHT = -HEIGHT/2
2440    X = NORMX*THROAT
2450 PRINT #2, USING "###.###     ###.###    ###.######
 ###.#######
#.#######";                NORMX,NORMX,X,HEIGHT,M
2460    IF NORMX = -4 THEN INLETH = ABS(2*HEIGHT) : INLET
M = M
2470    MBEF = M
2480 NEXT NORMX
```

```
2490 CLOSE #2
2500 REM ************************************************
*************
2510 REM         PUT INLET PARAMETERS INTO INPUT FILE
2520 REM ************************************************
*************
2530 FILE$ = FILENME$ + ".INT"
2540 OPEN FILE$ FOR APPEND AS #1
2550    PRINT #1,
2560    PRINT #1, "INLET HEIGHT (FT) = ",",",INLETH
2570    PRINT #1, "INLET MACH NUMBER = ",",",INLETM
2580    PRINT #1,
2590 CLOSE #1
2600 CLS
2610 RETURN
2620 REM   ************************************************
**************
2630 REM
2640 REM                    SUBROUTINE EXPANSION FLOW FIE
LD
2650 REM
2660 REM   ************************************************
**************
2670 CLS
2680 PRINT " CALCULATING FLOW FIELD . . .  " : PRINT
2690 FILE$ = FILENME$ + ".SFF"
2700 OPEN FILE$ FOR OUTPUT AS #2
2710 REM
2720 REM *****  (I,2) IS FOR CURRENT COLUMN OF BLOCKS
2730 REM *****  (I,1) IS FOR COLOMN OF BLOCKS BEFORE
2740 REM
2750 REM
2760 REM ************************************************
******************
2770 REM          DEFINE DELTA THETA AND SET INITIAL STU
FF
2780 REM ************************************************
******************
2790 DELTA = THEMAX/NUMANG
2800 LOOP = 0
2810 IDEL = 0
2820 JDEL = DELTA
2830 J=2
2840 M(1,1) = 1
2850 PRINT #2, "SUPERSONIC FLOW FIELD CALCULATESIONS "
2860 PRINT #2, "BOXi  BOXj      NU            M
FLOW      THETA+
THETA- "
2870 REM PRINT  "BOXi  BOXj      NU            M
 FLOW      THETA+
THETA- "
2880 REM PRINT USING "###    ###    ##.####  ##.#######
```

```
 ###.####  ###.#######
###.####### ";IDEL,JDEL,NU,M(1,1),FLOW,THETAP(1,1),THET
AN(1,1)
2890 LOOP = LOOP + 1
2900 REM ********************************
2910 REM *    START LEFT TO RIGHT BLOCKS
2920 REM ********************************
2930 FOR I = 1 TO J-1
2940   NU = .5*((IDEL+(JDEL-DELTA)) + (IDEL+JDEL))
2950   NUE = NU
2960   GOSUB 9410
2970   M(I,2) = M
2980   IF I = 1 THEN MP = .5*(M(I,2) + M(I,1)) : MUEN =
 0   :GOTO 3020
2990           MP = .5*(M(I,2) + M(I,1))
3000           MN = .5*(M(I,2) + M(I-1,2))
3010   MUEN = 180/PIE*ATN((1/MN)/SQR(1-(1/MN)^2))
3020   MUEP = 180/PIE*ATN((1/MP)/SQR(1-(1/MP)^2))
3030   FLOW = .5*((IDEL-(JDEL-DELTA)) + (IDEL-JDEL))
3040   THETAP(I,2) = FLOW + MUEP
3050   THETAN(I,2) = FLOW - MUEN
3060 PRINT #2,  USING "###   ###   ##.####  ##.#######
  ###.####  ###.#######
###.####### ";IDEL,JDEL,NU,M(I,2),FLOW,THETAP(I,2),THET
AN(I,2)
3070   IDEL = IDEL + DELTA
3080 NEXT I
3090 REM ***************************
3100 REM   CORNER BLOCK
3110 REM ***************************
3120 I = J
3130   NU = .5*(((IDEL-DELTA)+(JDEL-DELTA)) + (IDEL+JDEL)
)
3140   NUE = NU
3150   GOSUB 9410
3160   M(I,2) = M
3170   MN = .5*(M(I,2)+M(I-1,2))
3180   MUEN = 180/PIE*ATN((1/MN)/SQR(1-(1/MN)^2))
3190   MUEP=0
3200   FLOW = .5*(((IDEL-DELTA)-(JDEL-DELTA)) + (IDEL-JDEL)
)
3210   THETAP(I,2) = FLOW + MUEP
3220   THETAN(I,2) = FLOW - MUEN
3230 PRINT #2,  USING "###   ###   ##.####  ##.#######
  ###.####  ###.#######
###.####### ";IDEL,JDEL,NU,M(I,2),FLOW,THETAP(I,2),THET
AN(I,2)
3240 REM ************************************************
***********
3250 REM        RENUMBER STUFF FOR NEXT ROUND
3260 REM ************************************************
***********
```

```
3270 FOR K = 1 TO J
3280    M(K,1) = M(K,2)
3290 NEXT K
3300 REM ***********************************************
***********
3310 REM       SET STUFF FOR NEXT ROUND
3320 REM ***********************************************
***********
3330  IDEL = 0
3340  JDEL = JDEL + DELTA
3350  J = J + 1
3360  IF LOOP+1 <  NUMANG THEN GOTO 2890
3370 CLOSE #2
3380 CLS
3390  RETURN
3400 REM  ***********************************************
*********
3410 REM
3420 REM         SUBROUTINE EXPANSION GEOMETERY
3430 REM
3440 REM ***********************************************
***********
3450 CLS
3460 REM
3470 REM ****** XCOUNT IS LOOP COUNTER FOR OPTUMUM DELT
A X  ******
3480 REM ****** XTIME IS NUMBER OF TIMES INITIAL DELTA
X WAS TRIED ***
3490 REM
3500 REM ***** (I,1) IS COLUMN OF BLOCKS BEFORE POINTS
3510 REM ***** (I,2) IS COLUMN OF BLOCKS AFTER  POINTS
3520 REM ***** X(I,2) IS CURRENT COLUMN OF POINTS
3530 REM ***** X(I,1) IS COLUMN OF POINTS BEFORE
3540 REM
3550 REM
3560 DELTA = THEMAX/NUMANG
3570 XCOUNT = 0
3580 XTIME  = 1
3590 CLS
3600 PRINT :PRINT :PRINT
3610 PRINT " CALCULATING EXPANSION GEOMETRY. . .  "
3620 FILEI$ = FILENME$ + ".SFF"
3630 FILEO$ = FILENME$ + ".GEO"
3640 REM
3650 REM ******** SET DELTA X ************************
**8
3660 REM
3670 IF ANSINC$ = "N" THEN GOTO 3690
3680      DELTX = (THROAT * (DELTA*PIE/180))/XTIME
3690 PRINT "       DELTA X = ",DELTX
3700 PRINT
3710 OPEN FILEI$ FOR INPUT AS #2
```

```
3720 OPEN FILEO$ FOR OUTPUT AS #3
3730 INPUT #2, JUNK$
3740 INPUT #2, JUNK$
3750 PRINT #3, "SUPERSONIC GEOMETERY "
3760 PRINT #3, "POINTi  POINTj    X                Y
        MACH "
3770 REM PRINT  "POINTi  POINTj      X                Y
             MACH "
3780 REM PRINT USING " ###    ###    #.#######^^^^    ##
.#######^^^^
##.###### ";          I,J,X(I,J),Y(I,J),M(I,J)
3790 NUMBER = NUMANG
3800 X(1,2) = 0
3810 Y(1,2) = -THROAT/2
3820 M(1,1) = 1
3830 M(2,1) = 1
3840 IDEL = 0
3850 JDEL = DELTA
3860 J = 2
3870 REM ************************************************
**********
3880 REM    READ IN MACH, THETAP, AND THETAN
3890 REM ************************************************
**********
3900 REM
3910 REM   **** READ IN JUNK, NOTE: MACH NUMBER IS NOT
USED IN X/Y
3920 REM        CALCULATIONS.  MACH IS RENUMBERED FROM
A BLOCK TO
3930 REM        A POINT
3940 REM
3950    FOR K = 1 TO J
3960      INPUT #2, JUNK,JUNK,JUNK,M(K,2),JUNK,THETAP(K
,2),THETAN(K,2)
3970    NEXT K
3980    PAST = EOF(2)
3990 REM ************************************************
***
4000 REM   START LEFT TO RIGHT BLOCKS (FIND X/Y COORDIN
ATES)
4010 REM ************************************************
***
4020 FOR I = 1 TO J-1
4030   IF J = 2 THEN GOTO 4180
4040   IF I > 1 THEN GOTO 4140
4050 REM
4060 REM ******* THESE ARE FOR FIRST BOXES
4070 REM
4080      X(I,2) = X(I,1) + DELTX*COS(PIE/180*(2-J)*DELT
A)
4090      Y(I,2) = Y(I,1) + DELTX*SIN(PIE/180*(2-J)*DELT
A)
```

```
4100      GOTO 4180
4110 REM
4120 REM ******* THESE ARE FOR INBETWEEN BOXES
4130 REM
4140   B1 = Y(I-1,2) - TAN(PIE/180*THETAP(I-1,2)) * X(I-1,2
)
4150   B2 = Y(I,1) - TAN(PIE/180*THETAN(I,1)) * X(I,1)
4160   X(I,2) = (B1-B2)/ (  TAN( PIE/180 * THETAN(I,1))
-
         TAN( PIE/180 * THETAP(I-1,2)))
4170   Y(I,2) = TAN(PIE/180*THETAN(I,1)) * X(I,2) + B2
4180 PRINT #3, USING " ###    ###    #.#######^^^^    ##
.#######^^^^
##.###### ";          I,J,X(I,2),Y(I,2),M(I,1)
4190   IDEL = IDEL + DELTA
4200 NEXT I
4210 REM ******************
4220 REM  FIND X/Y FOR CORNER BLOCK
4230 REM ******************
4240  I = J
4250     Y(I,2) = 0
4260     X(I,2) = X(I-1,2) + (0 - Y(I-1,2))/TAN(PIE/180*TH
ETAP(I-1,2))
4270 PRINT #3, USING " ###    ###    #.#######^^^^    ##
.#######^^^^
##.###### ";          I,J,X(I,2),Y(I,2),M(I,1)
4280 REM ****************************
4290 REM     RENUMBER STUFF FOR NEXT ROUND
4300 REM ****************************
4310 FOR K = 1 TO J
4320    X(K,1) = X(K,2)
4330    Y(K,1) = Y(K,2)
4340    M(K+1,1) = M(K,2)
4350    THETAP(K,1) = THETAP(K,2)
4360    THETAN(K,1) = THETAN(K,2)
4370 NEXT K
4380 M(1,1) = M(2,1)
4390 IDEL = 0
4400 JDEL = JDEL + DELTA
4410 J = J + 1
4420 IF PAST = 0 THEN GOTO 3950
4430 REM ************************8
4440 REM  START COMPRESSION SECTION
4450 REM ****************************
4460 M(NUMBER+1,1) = M(NUMBER+1,2)
4470 J = J - 1
4480 JDEL = JDEL - DELTA
4490 FOR I = 1 TO J-1
4500   B1 = Y(I,1) - TAN(PIE/180*(-JDEL + (DELTA*(I-1))))
* X(I,1)
4510   B2 = Y(I+1,1) - TAN(PIE/180*THETAN(I+1,1)) * X(I+
1,1)
```

```
4520   X(I,2) = (B1-B2)/(TAN(PIE/180*THETAN(I+1,1)) -
           TAN(PIE/180*(-JDEL + (DELTA*(I-1)))))
4530   Y(I,2) = TAN(PIE/180*THETAN(I+1,1))*X(I,2) + B2
4540 PRINT #3, USING " ###    ###    #.#######^^^^    ##
.#######^^^^
##.###### ";          1,J+I,X(I,2),Y(I,2),M(I+1,1)
4550 IF I = 1 THEN DISCHAR = SQR((X(1,1)-X(1,2))^2  +
              (Y(1,1)-Y(1,2))^2 )
4560 REM    **** FOR NEXT ROUND
4570   X(I+1,1) = X(I,2)
4580   Y(I+1,1) = Y(I,2)
4590 NEXT I
4600 CLOSE #2
4610 CLOSE #3
4620 REM ************************************
4630 REM   FIND OPTIOMUM DELTA X
4640 REM ****************************
4650 IF ANSINC$ <> "Y" THEN GOTO 5130
4660 XCOUNT = XCOUNT + 1
4670 IF XCOUNT < 15 THEN GOTO 4740
4680    PRINT "TOO MANY ITERATIONS FOR DELTA X "
4690    PRINT "    DISTANCE OF CHARACTERISTIC IS: ",DIS
CHAR
4700    PRINT "    DELTA X IS: ", DELTX
4710    PRINT :PRINT :PRINT "STRIKE ANY KEY TO CONTINUE
"
4720    JUNK$ = INPUT$(1)
4730    GOTO 5130
4740 DIFF = ((DISCHAR-DELTX)/DELTX)
4750 PRINT "OLD DELTA X = ",DELTX
4760 PRINT "NOZZLE WALL LENGTH = ",DISCHAR
4770 PRINT "DIFFERENCE IS ",DIFF
4780 PRINT
4790 IF ABS(DIFF) < .05 THEN  GOTO 5130
4800 REM
4810 REM ************ FOR THE FIRST ROUND, INCREMENT X
AND REDO *****
4820 REM
4830 IF XCOUNT > 1 THEN GOTO 4930
4840     DELTX1 = DELTX
4850     DIFF1 = DIFF
4860     DELTX = DELTX + DELTX*.02
4870     PRINT "      NEW DELTA X IS: ",DELTX
4880     PRINT
4890     GOTO 3710
4900 REM
4910 REM *********** CALCULATE SLOPE OF DELTX VS DIFF,
AND FIND NEW DELTX **
4920 REM
4930 DELTX2 = DELTX
4940 DIFF2 = DIFF
4950 SLOPE = (DELTX2-DELTX1)/(DIFF2-DIFF1)
```

```
4960 DELTX = DELTX2-SLOPE*DIFF2
4970 DELTX1 = DELTX2
4980 DIFF1 = DIFF2
4990 PRINT "      NEW DELTA X IS: ",DELTX
5000 PRINT
5010 REM
5020 REM ******* RESTART IF DELTA X < 0    ************
*
5030 REM
5040 IF DELTX > 0 THEN GOTO 3710
5050 PRINT " *** CAUTION: DELTA X IS LESS THEN ZERO ***
* "
5060 PRINT "     WILL CALCULATE A NEW DELTA X "
5070 XCOUNT = 0
5080 XTIME = XTIME + 1
5090 GOTO 3680
5100 REM ************************************************
***************
5110 REM       SAVE EXIT JUNK, CLOSE INPUT FILE, RETURN

5120 REM ************************************************
***************
5130 FILE$ = FILENME$ + ".INT"
5140 OPEN FILE$ FOR APPEND AS #1
5150    PRINT #1,
5160    PRINT #1, "DELTA X USED = ","",DELTX
5170    PRINT #1, "EXIT MACH NUMBER = ","",M(NUMBER,2)

5180    PRINT #1, "EXIT HEIGTH (FT) = ","",ABS(2*Y(NUM
BER-1,2))
5190 CLOSE #1
5200 RETURN
5210 REM ************************************************
**********
5220 REM
5230 REM
5240 REM         BOUNDARY LAYER DETERMINATION SUBROUTIN
E
5250 REM
5260 REM
5270 REM ************************************************
***********
5280 CLS
5290 PRINT "CALCULATING BOUNDARY LAYER THICKNESS . . .
"
5300 REM ************************************************
***********
5310 REM        OPEN FILE AND READ HEADING
5320 REM ************************************************
***********
5330 FILEI$ = FILENME$ + ".PRF"
5340 FILEO$ = FILENME$ + ".BLC"
```

```
5350 OPEN FILEI$ FOR INPUT AS #1
5360 OPEN FILEO$ FOR OUTPUT AS #2
5370 INPUT #1, JUNK$
5380 INPUT #1, JUNK$
5390 IF ANSBL$ = "B" THEN PRINT #2, "THIS IS BLASIUS BOU
NDARY LAYER   "
5400 IF ANSBL$ = "T" THEN PRINT #2, "THIS IS THWAITES BO
UNDARY LAYER   "
5410 IF ANSBL$ = "L" THEN PRINT #2, "THIS IS LAMINAR MOM
ENTUM INTEGRAL
BOUNDARY LAYER   "
5420 IF ANSBL$ = "LT" THEN PRINT #2, "THIS IS LAMINAR MO
MENTUM
INTEGRAL/TURBULENT  BOUNDARY LAYER   "
5430 IF ANSBL$ = "B" THEN PRINT #2,  "  X2       REX
    CF              DEL
         DEL*           THETA"
5440 IF ANSBL$ = "T" THEN PRINT #2,  "  X2       REX
   LAMDA             H
         DEL*           THETA"
5450 IF ANSBL$ = "L" THEN PRINT #2,  "  X2       REX
   CF                DEL
         DEL*          THETA"
5460 IF ANSBL$ = "LT" THEN PRINT #2,  "  X2       REX
  ( CF OR N)
DEL          DEL*           THETA"
5470 REM PRINT USING "##.####  ##.###^^^^  ##.###^^^^
 ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,LAMDA,DEL,DELSTAR
,THETA
5480 REM  PRINT USING "##.####^^^^ ##.####^^^^ ##.####^
^^^ .#####  #.###
##.####^^^^   ##.####";THETAI,THETA,RETHETAI,CFI,CAPPIE
,REDEL,N
5490 REM ************************************************
***********
5500 REM      SET INITIAL STUFF
5510 REM ************************************************
***********
5520 INPUT #1, I,J,XB,YB,MB
5530 JUNK =  0
5540 PRINT #2, USING "##.####  ##.###^^^^  ##.###^^^^
 ##.######^^^^
##.######^^^^  ##.######^^^^ ";XB,JUNK,JUNK,JUNK,JUNK,J
UNK
5550 UB = MB*SQR(GAMMA*RGAS*TT/(1+GM1O2*MB^2))
5560 DELB =  0
5570 DELSB = 0
5580 THETAB = 0
5590 DISTANCE = 0
5600 REM
5610 REM ***** THESE ARE USED IN THWAITS METHOD
```

```
5620 REM
5630 SUMUE = 0
5640 REM
5650 REM ***** THESE ARE USED FOR DELTA ITERATION IN BO
TH
5660 REM ***** LAMINAR AND TURBULEMT MOMENTUN INTERGRAL
S
5670 REM
5680 COUNT = 0
5690 DEL1 = .00004
5700 DIFF1 = -9.119999E-03
5710 DEL2 = .00016
5720 DIFF2 = -.002
5730 REM
5740 REM ******** THIS IS FOR TURBULENT STUFF
5750 REM
5760 N = 2
5770 REM ************************************************
*************
5780 REM          SET STILLING CHAMBER JUNK
5790 REM ************************************************
*************
5800 MU0 = 2.27E-08*TT^1.5/(198.6 + TT)
5810 RHO0 = PT/RGAS/TT
5820 REM ************************************************
**************
5830 REM
5840 REM                          FREE-STREAM JUNK
5850 REM
5860 REM ************************************************
**************
5870 INPUT #1, I,J,X2,Y2,M2
5880 PAST = EOF(1)
5890    DS =  SQR((X2-XB)^2 + (Y2-YB)^2)
5900    DISTANCE  = DISTANCE + DS
5910 TINF = TT/(1+GM1O2*M2^2)
5920 UINF = M2*SQR(GAMMA*RGAS*TINF)
5930      DMDS = (M2-MB)/DS
5940      DUDS = (UINF-UB)/DS
5950 PINF = PT/(1+GM1O2*M2^2)^GOGM1
5960 RHOINF = PINF/RGAS/TINF
5970 QINF = .5*RHOINF * UINF^2
5980 MUINF = (2.27E-08*TINF^1.5)/(198.6+TINF)
5990 REX = RHOINF*UINF*DISTANCE/MUINF
6000 REM ************************************************
*************
6010 REM      CALCULATE WALL TEMP & VISCOSITY
6020 REM ************************************************
*************
6030 IF ANSTW$  = "C" THEN TWALL = TCWALL : GOTO 6050
6040     TWALL = TINF + SQR(PRANDTL)*UINF^2/2/CPRESS
6050 MUWALL = 2.27E-08*TWALL^1.5/(198.6+TWALL)
```

```
6060 TREF = TINF * (.5+.039*M2^2+.5*TWALL/TINF)
6070 MUREF = 2.27E-08*TREF^1.5/(198.6+TREF)
6080 REM ************************************************
*************
6090 REM
6100 REM          SPLIT  INTO  PROPER    ROUTINE
6110 REM
6120 REM ************************************************
*************
6130 IF (ANSBL$ = "B") THEN  GOTO 6210
6140 IF (ANSBL$ = "T") THEN  GOTO 6370
6150 IF (ANSBL$ = "L") THEN  GOTO 6860
6160 IF (ANSBL$ = "LT") THEN IF REX > 6000000! THEN GOTO
 8010
6170 GOTO 6860
6180 REM ************************************************
*************
6190 REM           CALCULATE BLASIUS SOLUTION
6200 REM ************************************************
*************
6210 BDEL = 5.2 * DISTANCE/SQR(REX)
6220 BDELS = 1.721 * DISTANCE/SQR(REX)
6230 BTHETA = .664 * DISTANCE/SQR(REX)
6240 BCF = .664/SQR(REX)
6250 PRINT #2, USING "##.####  ##.###^^^^  ##.#####
 ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,BCF,BDEL,BDELS,BT
HETA
6260 IF PAST = 0 THEN GOTO 5870
6270 GOTO 8780
6280 REM ************************************************
*************
6290 REM ************************************************
*************
6300 REM
6310 REM          THWAITES COMPRESSIBLE METHOD
6320 REM
6330 REM ************************************************
*************
6340 REM ************************************************
*************
6350 REM                 FIND THETAi
6360 REM ************************************************
*************
6370      SUMUE = SUMUE + UINF^5 * DS
6380      THE2ONU = .45/UINF^6*SUMUE
6390      THETAI = SQR(THE2ONU*MUINF/RHOINF)
6400      DTHE2DS = (THETAI - THETAB)^2/DS
6410 REM ************************************************
*************
6420 REM         FIND LAMDA, H(LAMDA), AND S(LAMDA)
6430 REM ************************************************
```

```
**************
6440 LAMDA = THE2ONU*DUDS
6450 LAMDA = THE2ONU*(MUINF/RHOINF)/(MU0/RHO0)*DUDS
6460      A0 = 2.608267     : B0 = .2176646
6470      A1 = -3.700521    : B1 = 1.504052
6480      A2 = 12.09578     : B2 = .7109906
6490      A3 = -276.4393    : B3 = 16.04095
6500      A4 = 3148.932     : B4 = -639.1872
6510      A5 = -14105.58    : B5 = 4043.9
6520      A6 = 21933.74     : B6 = -7541.629
6530 HI = A0 + A1*LAMDA + A2*LAMDA^2 + A3*LAMDA^3 +A4*L
AMDA^4 + A5*LAMDA^5
             + A6*LAMDA^6
6540 SI = B0 + B1*LAMDA + B2*LAMDA^2 + B3*LAMDA^3 +B4*L
AMDA^4 + B5*LAMDA^5
             + B6*LAMDA^6
6550 REM ***********************************************
*************
6560 REM      SOLVE THWAITES MOMENTUM INTERGRAL
6570 REM ***********************************************
*************
6580 DIFF = UINF*RHO0/MU0*DTHE2DS - (.45-6*LAMDA) -
          2*SI*(TINF/TT*MUREF/MU0 - 1)
6590 REM ***********************************************
*************
6600 REM      FIND COMPRESSIBLE THETA AND DEL*
6610 REM ***********************************************
*************
6620 THETA = THETAI * (TT/TINF)^3
6630 H = HI*(TWALL/TT)*(1+GM1O2*M2^2)+GM1O2*M2^2
6640 DELSTAR = H*THETAI
6650 DELSTARI = HI*THETAI
6660      PRINT #2, USING "##.####  ##.###^^^^  ##.###^^
^^    ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,LAMDA,H,DELSTAR,T
HETA
6670 REM PRINT #2, USING "##.####  ##.###^^^^  ##.###^^
^^    ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,LAMDA,HI,DELSTARI
,THETAI
6680 REM ***********************************************
***********8
6690 REM       SET  VARIABLES FOR NEXT TIME AROUND
6700 REM ***********************************************
***********8
6710 XB = X2
6720 YB = Y2
6730 UB = UINF
6740 THETAB = THETA
6750 THETAB = THETAI
6760 IF PAST = 0 THEN GOTO 5870
6770 GOTO 8780
```

```
6780 REM ************************************************
*************
6790 REM
6800 REM          INTERGRATION OF COMPRESSIBLE MOMENTUN
EQT
6810 REM
6820 REM ************************************************
*************
6830 REM ************************************************
*************
6840 REM                    GUESS NEW DELTA
6850 REM ************************************************
*************
6860      SLOPE = (DIFF2-DIFF1)/(DEL2-DEL1)
6870      INTER = DIFF2-(SLOPE*DEL2)
6880      DEL = ABS(INTER/SLOPE)
6890 REM ************************************************
*************
6900 REM          FIND LAMDA AND u/Ue COEFFICIENTS
6910 REM
6920 REM   NOTE: UOUE = AA1*YOD^AA2 + BB*YOD + CC*YOD^2
 + DD*YOD^3 + EE*YOD^4
6930 REM ************************************************
*************
6940 REM
6950 REM  ************** USE POHALUSEN ****************
*************
6960 REM
6970     AA1 = 0 : AA2 = 1
6980     LAMDA = DEL^2*RHOINF/MUINF*DUDS
6990     BB = 2+LAMDA/6
7000     CC = -LAMDA/2
7010     DD = -2+LAMDA/2
7020     EE = 1-LAMDA/6
7030 REM
7040 REM *************  ASSUME LINEAR PROFILE  *********
*************
7050 REM
7060 REM   AA1=0 : AA2 = 1: BB=1:CC=0:DD=0:EE=0
7070 REM
7080 REM ***** ASSUME (Y/DEL)^1/2 PROFILE *************
*************
7090 REM
7100 REM    AA1=1 : AA2 = .5 : BB=0 : CC=0 : DD=0 : EE=
0
7110 REM ***** ASSUME SIN(Y/DEL*PIE/2) PROFILE ********
*************
7120 REM
7130        AA1=0 : AA2 = 0 : BB=0 : CC=0 : DD=0 : EE=0

7140 REM
7150 REM ************************************************
```

```
*************
7160 REM           FIND DEL*  AND THETA INTERGRALS
7170 REM ***********************************************
*************
7180 YOD = 0
7190 INTDELS1 = 1
7200 INTTHE1 = 0
7210 DELTAY = .1
7220 DELSTAR = 0
7230 THETA = 0
7240 YOD = YOD +.1
7250   UOUE = AA1*YOD^AA2 + BB*YOD + CC*YOD^2 + DD*YOD^
3 + EE*YOD^4
7260   UOUE = SIN(PIE/2*YOD)
7270   RHORHE = TINF/(TWALL + (TINF-TWALL)*UOUE^2)
7280 REM    RHORHE = 1/(1+(1-UOUE^2)*GM1O2*M2^2)
7290 REM    RHORHE = 1
7300   INTDELS2 = (1-RHORHE*UOUE)
7310   INTTHE2 = (1-UOUE)*RHORHE*UOUE
7320   DELSTAR = DELSTAR + ((INTDELS1+INTDELS2)/2)*DELT
AY
7330   THETA = THETA + ((INTTHE1+INTTHE2)/2)*DELTAY
7340 IF  YOD >= 1 THEN GOTO 7410
7350     INTDELS1 = INTDELS2
7360     INTTHE1 = INTTHE2
7370     GOTO 7240
7380 REM ***********************************************
*************
7390 REM     DEL*, THETA, AND dTHETA/dS
7400 REM ***********************************************
*************
7410     DELSTAR = DELSTAR * DEL
7420     THETA = THETA * DEL
7430     DTHEDS = (THETA-THETAB)/DS
7440 REM ***********************************************
*************
7450 REM          COMPLETE MOMENTUM INTERGRAL
7460 REM ***********************************************
*************
7470 REM
7480 REM **** PHOHAUSIAN ****
7490 REM
7500 REM   DUDY = UINF/DEL*(BB + 2*CC*.1 + 3*DD*.1^2 +
4*EE*.1^3)
7510 REM
7520 REM **** LINEAR ****
7530 REM
7540 REM   DUDY = UINF/DEL
7550 REM
7560 REM **** Y/DEL^1/2 ****
7570 REM
7580 REM   DUDY = .1581*UINF/DEL
```

```
7590 REM
7600 REM **** SIN(Y/DEL*PIE/2) ****
7610 REM
7620       DUDY = UINF/DEL*PIE/2
7630 REM
7640 CF = MUWALL*DUDY/QINF
7650 DIFF = DTHEDS + THETA*DUDS/UINF*(2+DELSTAR/THETA -
M2^2) - CF/2
7660     COUNT = COUNT + 1
7670    IF COUNT < 3 THEN GOTO 7700
7680    IF ABS(DIFF) < .001 THEN GOTO 7780
7690        IF COUNT > 15 THEN PRINT "STUCK IN ITERATIO
N: " :
                    PRINT "DIFF = ",DIFF : GOTO 7780
7700        DEL1 = DEL2
7710        DEL2 = DEL
7720        DIFF1 = DIFF2
7730        DIFF2 = DIFF
7740  GOTO 6860
7750 REM
7760 REM ******** POHALUSEN PRINT *******
7770 REM
7780 REM PRINT #2, USING "##.####  ##.###^^^^  ##.###^^
^^    ##.######
##.######^^^^  ##.######^^^^ ";X2,REX,LAMDA,DEL,DELSTAR
,THETA
7790 REM
7800 REM ********* Y/DEL TYPE PRINT ********
7810 REM
7820     PRINT #2, USING "##.####  ##.###^^^^  ##.###^^
^^    ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,CF,DEL,DELSTAR,TH
ETA
7830 REM ************************************************
***********8
7840 REM       SET  VARIABLES FOR NEXT TIME AROUND
7850 REM ************************************************
***********8
7860 COUNT = 0
7870 XB = X2
7880 YB = Y2
7890 UB = UINF
7900 DELB = DEL
7910 THETAB = THETA
7920 IF PAST = 0 THEN GOTO 5870
7930 GOTO 8780
7940 REM ************************************************
***********8
7950 REM
7960 REM         START TURBULENT BOUNDARY LAYER
7970 REM
7980 REM ************************************************
```

```
****
7990 REM       GUESS DELTA AND CALCULATE Cf
8000 REM ***********************************************
****
8010 SLOPE = (DIFF2-DIFF1)/(DEL2-DEL1)
8020 INTER = DIFF2-(SLOPE*DEL2)
8030 DEL = ABS(INTER/SLOPE)
8040 REM ***********************************************
****
8050 REM       FIND  CFi
8060 REM ***********************************************
****
8070 THETAI = DEL*(1/(1/N+1)-1/(2/N+1))
8080 RETHETAI = PINF*M2*THETAI/SQR(RGAS*TINF/GAMMA)/MUI
NF
8090     IF RETHETAI < 3.5 THEN DEL = DEL+.001: GOTO 80
70
8100   LOGRE = .434294482#*LOG(RETHETAI)
8110   CFI = .0773/((LOGRE+4.561)*(LOGRE-.546))
8120      IF CFI <= 0 THEN CFI = .001
8130   FC = (TWALL*MUINF/TINF/MUWALL)
8140   CF = CFI/FC
8150 REM ***********************************************
****
8160 REM       FIND  PROFILE SHAPE
8170 REM ***********************************************
****
8180   REDELI = PINF*M2*DEL/SQR(RGAS*TINF/GAMMA)/MUINF
8190   REDEL = REDELI/(SQR(TINF)*MUINF) * (SQR(FC*TWALL
)*MUWALL)
8200     K = .41
8210     C = 5
8220   CAPPIE = .5*(K*SQR(2/CFI) - LOG(REDELI) - .5*LOG(C
FI/2) - K*C)
8230   DELSODEL = (1+CAPPIE)/K*SQR(CFI/2)
8240   THEODEL = DELSODEL - CFI/2/K*(2+3.179*CAPPIE+1.5*
CAPPIE^2)
8250   DELOTHE = 1/THEODEL
8260     IF DELOTHE < 5.83 THEN IF DELOTHE > .17 THEN
                  DEL = THETAI * 5.9   :  GOTO 8070
8270   N = .5*(DELOTHE - 3 + (DELOTHE*(DELOTHE-6) + 1)^.5
 )
8280     IF N < 1 THEN N = 1
8290 REM ***********************************************
************
8300 REM     FIND DEL* AND THETA INTERGRALS
8310 REM  ***********************************************
*************
8320 YOD = 0
8330 INTDELS1 = 1
8340 INTTHE1 = 0
8350 DELTAY = .1
```

```
8360 DELSTAR = 0
8370 THETA = 0
8380 YOD = YOD +.1
8390   UOUE = YOD^(1/N)
8400   RHORHE = TINF/(TWALL + (TINF-TWALL)*UOUE^2)
8410   INTDELS2 = (1-RHORHE*UOUE)
8420   INTTHE2 = (1-UOUE)*RHORHE*UOUE
8430   DELSTAR = DELSTAR + ((INTDELS1+INTDELS2)/2)*DELT
AY
8440   THETA = THETA + ((INTTHE1+INTTHE2)/2)*DELTAY
8450 IF  YOD >= 1 THEN GOTO 8520
8460     INTDELS1 = INTDELS2
8470     INTTHE1 = INTTHE2
8480     GOTO 8380
8490 REM ************************************************
*************
8500 REM     DEL*, THETA, AND dTHETA/dS
8510 REM ************************************************
*************
8520     DELSTAR = DELSTAR * DEL
8530     THETA = THETA * DEL
8540     DTHEDS = (THETA-THETAB)/DS
8550 REM ************************************************
************
8560 REM       FIND LEFT HAND SIDE AND RIGHT HAND SIDE
TO
8570 REM       von Karman INTERGRAL
8580 REM  ************************************************
*************
8590    DIFF = DTHEDS + THETA*DUDS/UINF*(2*DELSTAR/THET
A - M2^2) - CF/2
8600    COUNT = COUNT + 1
8610    IF COUNT < 3 THEN GOTO 8640
8620    IF ABS(DIFF) < .001  THEN GOTO 8690
8630        IF COUNT > 50 THEN PRINT "STUCK IN ITERATIO
N: " :
                PRINT "DIFF = ",DIFF :  GOTO 8690
8640        DEL1 = DEL2
8650        DEL2 = DEL
8660        DIFF1 = DIFF2
8670        DIFF2 = DIFF
8680  GOTO 8010
8690 PRINT #2, USING "##.####  ##.###^^^^  ##.######
 ##.######^^^^
##.######^^^^  ##.######^^^^ ";X2,REX,N,DEL,DELSTAR,THE
TA
8700 PRINT USING "##.####^^^^ ##.####^^^^ ##.####^^^^ .
#####  #.###
##.####^^^^   ##.####";THETAI,THETA,RETHETAI,CFI,CAPPIE
,REDELI,N
8710 XB = X2
8720 YB = Y2
```

```
8730 MB = M2
8740 DELB = DEL
8750 DELSB = DELSTAR
8760 COUNT = 0
8770 IF PAST = 0 THEN GOTO 5870
8780 CLOSE #1
8790 CLOSE #2
8800 RETURN
8810 REM ************************************************
*************
8820 REM
8830 REM
8840 REM          SUBROUTINE TO ADD BOUNDARY LAYER TO C
ONTOUR
8850 REM
8860 REM
8870 REM ************************************************
*************
8880 CLS
8890 PRINT "     ADDING BOUNDARY LAYER . . . "
8900 PRINT :PRINT :PRINT
8910 FILEFF$ = FILENME$ + ".PRF"
8920 FILEBL$ = FILENME$ + ".BLC"
8930 FILEO$ = FILENME$ + ".FIN"
8940 OPEN FILEFF$ FOR INPUT AS #1
8950 OPEN FILEBL$ FOR INPUT AS #2
8960 OPEN FILEO$ FOR OUTPUT AS #3
8970 REM ************************************************
*************
8980 REM          SET INTIAL STUFF
8990 REM ************************************************
*************
9000 INPUT #1, JUNK$
9010 INPUT #1, JUNK$
9020 INPUT #2, JUNK$
9030 INPUT #2, JUNK$
9040 DISTANCE = 0
9050 DISB = 0
9060 INPUT #1, JUNK,JUNK,X1,Y2,MACH
9070 INPUT #2, JUNK,JUNK,JUNK,DEL,DELS,THETA
9080 YB = ABS(Y2)
9090 PRINT #3, "THIS IS THE FINIAL CONTOUR "
9100 PRINT #3, "   X              Y                MACH   "
9110 REM PRINT  "      X              Y                  M
ACH "
9120 REM PRINT USING " ##.#######     ##.#######^^^^
 ##.######## ";
              DISTANCE,YB,MACH
9130 PRINT #3, USING " ##.#######     ##.#######^^^^
 ##.######## ";
              DISTANCE,YB,MACH
9140 REM ************************************************
```

```
**************
9150 REM         START THE LOOP
9160 REM ***********************************************
**************
9170 INPUT #1, JUNK,JUNK,X2,Y2,MACH
9180 INPUT #2, JUNK,JUNK,JUNK,DEL,DELS,THETA
9190 PAST = EOF(1)
9200 DISTANCE = X2-X1
9210 Y2 = ABS(Y2)
9220    IF (DISTANCE-DISB) = 0 THEN PHI = 0 : GOTO 9240
9230 PHI = 180/PIE*ATN((YB-Y2)/(DISTANCE-DISB))
9240 YNEW = Y2 + DELS/COS(PIE/180*PHI)
9250 PRINT #3, USING " ##.#######     ##.#######^^^^
 ##.######## ";
              DISTANCE,YNEW,MACH
9260 IF PAST < 0 THEN GOTO 9300
9270    DISB = DISTANCE
9280    YB = Y2
9290    GOTO 9170
9300 CLOSE #1
9310 CLOSE #2
9320 CLOSE #3
9330 RETURN
9340 REM ***********************************************
**************
9350 REM
9360 REM
9370 REM                SUBROUTINE TO FIND MACH #
9380 REM
9390 REM
9400 REM ***********************************************
**************
9410 COUNT = 0
9420 SLOPE = (NUE2-NUE1)/(M2-M1)
9430 INTER = NUE2 - (SLOPE*M2)
9440 M = (NUE-INTER)/SLOPE
9450 IF M > 1.01 THEN GOTO 9490
9460      M1 = 2 : NUE1 = 26.38
9470      M2 = 2.2 : NUE2 = 31.732
9480      GOTO 9420
9490 NEW2 = SQR(GP1/GM1) * 180/PIE * ATN(SQR(GM1/GP1*(M
^2-1)))  -
             180/PIE * ATN(SQR(M^2-1))
9500 DIFF = ABS((NUE-NEW2)/NUE*100)
9510 IF DIFF < .1 THEN GOTO 9590
9520   COUNT = COUNT + 1
9530   IF COUNT > 20 THEN PRINT "MACH STUCK" : GOTO 959
0
9540   NUE1 = NUE2
9550   NUE2 = NEW2
9560   M1 = M2
9570   M2 = M
```

```
9580 GOTO 9420
9590 RETURN
9600 REM ************************************************
**
9610 REM
9620 REM
9630 REM SUBROUTINE TO PLOT GEOMETRY
9640 REM
9650 REM
9660 REM ************************************************
**
9670 CLS
9680 INPUT "INPUT FILE TO BE PLOTTED: ",FILE$
9690 CLS
9700 INPUT "Do you want axes drawn? ",ANS$
9710 OPEN FILE$ FOR INPUT AS #2
9720 REM ************************************
9730 REM    READ IN INITIAL JUNK
9740 REM ************************************
9750   INPUT #2,JUNK$
9760   INPUT #2,JUNK$
9770 REM
9780 REM     ******** ASSUMES FILE IS I,J,X,Y,M ******
9790 REM
9800 I = 0
9810 I = I+1
9820 INPUT #2, JUNK,JUNK,XX(I),YY(I),JUNK
9830 PAST = EOF(2)
9840 IF PAST = 0 THEN GOTO 9810
9850 REM ************************************
9860 REM    SET NUBER OF POINTS, MIN/MAX, AND BOARDERS
9870 REM ************************************
9880 NP = I
9890 XMAX = XX(1)
9900 YMAX = YY(1)
9910 XMIN = XX(1)
9920 YMIN = YY(1)
9930 FOR I = 1 TO NP
9940   IF XX(I) > XMAX THEN XMAX = XX(I)
9950   IF XX(I) < XMIN THEN XMIN = XX(I)
9960   IF YY(I) > YMAX THEN YMAX = YY(I)
9970   IF YY(I) < YMIN THEN YMIN = YY(I)
9980 NEXT I
9990 XINC = ((XMAX-XMIN)*.2)
10000 YINC = ((YMAX-YMIN)*.2)
10010 INC = XINC
10020 IF YINC > XINC THEN INC = YINC
10030 XSPAN = XMAX-XMIN
10040 YSPAN = YMAX-YMIN
10050 SPAN = XSPAN
10060 IF YSPAN > XSPAN THEN SPAN = YSPAN
10070 SCREEN  2
```

```
10080 REM COLOR 2
10090 WIDTH 80
10100 CLS
10110     WINDOW  (XMIN-INC,YMIN-INC)-(XMIN+SPAN+INC,YMIN+
SPAN+INC)
10120 REM WINDOW  (-.1,-.2)-(.1,.2)
10130 FOR I = 1 TO NP
10140   PSET(XX(I),YY(I))
10150 NEXT I
10160 IF ANS$ <> "Y" THEN GOTO 10190
10170 LINE (XX(1),0)-(XX(NP),0)
10180 LINE (0,0)-(0,YY(NP))
10190 PRINT "STRIKE ANY KEY TO CONTINUE "
10200 JUNK$ = INPUT$(1)
10210 SCREEN  0
10220 WIDTH 80
10230 CLS
10240 CLOSE #2
10250 RETURN
10260 REM ************************************************
***************
10270 REM
10280 REM
10290 REM          THIS ROUTINE READS IN THE "file.SUB"
 FILES
10300 REM             AND THE "file.GEO" FILE
10310 REM             AND STORES THE CONTOURS IN "file.P
RF"
10320 REM
10330 REM
10340 REM ************************************************
***************
10350 CLS
10360 PRINT " COMBINDING FILES . . . "
10370 FILEO$ = FILENME$ + ".PRF"
10380 OPEN FILEO$ FOR OUTPUT AS #1
10390 PRINT #1, "CONBINED PROFILE"
10400 PRINT #1, "      I         J            X
  Y                MACH "
10410 REM PRINT USING " ###.###    ###.###    ###.#######
#   ##.######^^^^
##.####### ";II,JJ,X,Y,M
10420 REM ************************************************
***************
10430 REM         READ IN THE CONVERGENT NOZZLE
10440 REM ************************************************
***************
10450    FILEI$ = FILENME$ + ".SUB"
10460    OPEN FILEI$ FOR INPUT AS #2
10470    INPUT #2, JUNK$
10480    INPUT #2, JUNK$
10490       INPUT #2, NORMX,VEL,X,Y,M
```

```
10500       PAST = EOF(2)
10510          IF NORMX = 0 THEN GOTO 10540
10520       PRINT #1, USING " ###.###   ###.###   ###.##
######  ##.######^^^^
##.####### ";NORMX,NORMX,X,Y,M
10530       IF PAST = 0 THEN GOTO 10490
10540    CLOSE #2
10550 REM ************************************************
***************
10560 REM         READ IN THE DIVERGENT  NOZZLE
10570 REM ************************************************
***************
10580    FILEI$ = FILENME$ + ".GEO"
10590    OPEN FILEI$ FOR INPUT AS #2
10600    INPUT #2, JUNK$
10610    INPUT #2, JUNK$
10620       INPUT #2, II,JJ,X,Y,M
10630       PAST = EOF(2)
10640 REM ****** SKIP THE FIRST POINT *****************

10650 REM  IF JJ = 2 THEN GOTO 10400
10660       IF II = 1 THEN PRINT #1, USING " ###.###   #
##.###   ###.########
##.######^^^^    ##.####### ";II,JJ,X,Y,M
10670        IF PAST = 0 THEN  GOTO 10620
10680    CLOSE #2
10690 CLOSE #1
10700 RETURN
```

VITA

John P. Grubb was born in Owego, New York on June 11, 1962. After graduating from high school at the Owego Free Academy, he moved to Austin, Texas, to live with his father. After working for six months, John attended the University of Texas at Austin (UT) where he studied Aerospace Engineering. During school, John met and married his sweetheart, Roxanne, on June 4, 1983. John graduated from UT with a Bachelor of Science in Aerospace Engineering in May, 1986.

John then moved to Murfreesboro Tennessee and began working at Calspan, a contractor at the Arnold Engineering Development Center located on Arnold Air Force Base. John is in charge of wind tunnel tests performed for various contractors in the supersonic and hypersonic facilities.

While working at AEDC, John began his Master's degree from the University of Tennessee at Knoxville, taking class from its branch office, the University of Tennessee Space Institute, located at Tullahoma, Tennessee. John obtained his degree from the University of Tennessee at Knoxville in December 1990.