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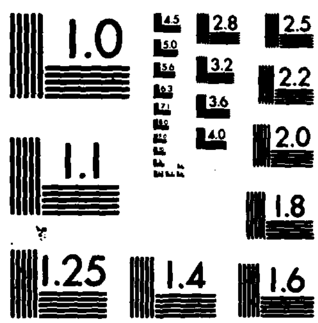

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TRANNOZ: A COMPUTER PROGRAM FOR ANALYSIS OF TRANSONIC THROAT FLOW IN AXISYMMETRIC, PLANAR, AND ANNULAR SUPERSONIC NOZZLES

by
J. C. DUTTON
A. L. ADDY

APRIL 1980

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A FORTRAN computer program has been developed for the analysis of transonic throat flowfields in annular, planar, and axisymmetric supersonic nozzles. The program evaluates the series expansion solution developed by Dutton and Addy. The subroutines in the code are described together with the definitions of the input and output variables, detailed input instructions, and an example input file with the corresponding output. A brief summary of the theory upon which the expansion solution is based is also included.

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TRANNOZ: A COMPUTER PROGRAM FOR ANALYSIS OF TRANSONIC THROAT FLOW IN AXISYMMETRIC, PLANAR, AND ANNULAR SUPERSONIC NOZZLES

by

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NOMENCLATURE

A complete listing of the subroutine names and their functions, the input NAMELISTS, and the input and output variables is contained in Sections III.A and III.B. Other quantities not defined there are listed below:

Text	Computer Program	Meaning
a		speed of sound
a^*		critical speed of sound
A^*	ASTAR	throat area
C_D	CD	discharge coefficient, defined in Eq. (II-32)
C_{D1}, C_{D2}, C_{D3}	CD1,CD2,CD3	discharge coefficient constants, Eq. (II-33)
d	D	distance between the throat locations at the inner and outer walls, Fig. II.1
g, h		equations of the inner and outer nozzle wall contours in the x-y coordinate system, Fig. II.1
g_1, h_1, g_2, h_2	G1,H1,G2,H2	dimensionless quantities defined in Eq. (II-25)
G, H		equations of the inner and outer nozzle wall contours in the R-Z coordinate system, Fig. II.1
M	M	Mach number
M^*	MSTAR	ratio of the speed at a point to the critical speed of sound
O		used to denote physical order of magnitude
p/p_0	PPØ	static-to-stagnation pressure ratio
R	R	radial coordinate in cylindrical coordinate system, Fig. II.1

Text	Computer Program	Meaning
$\bar{R}_c$		average radius of curvature for the two bounding walls at the annular nozzle throat
R_{ci}, R_{co}	RCI,RCØ	radii of curvature of the inner and outer nozzle walls at the nozzle throat
R_i, R_o	RI,RØ	radial coordinates of the inner and outer wall throat locations, Fig. II.1
Re_{2d}		Reynolds number based on sonic conditions and twice the throat separation distance, d
u,v	U,V	dimensionless velocity components in the x-y coordinate system defined in Eqs. (II-5) and (II-6), Fig. II.1
$\tilde{u}$,$\tilde{v}$		transonic perturbation velocity components defined in Eqs. (II-10) and (II-11)
u_1,v_1,u_2,v_2, u_3,v_3	U1,V1,U2,V2, U3,V3	transonic perturbation velocity components of the first three orders defined by the expansions in Eqs. (II-19) and (II-20)
U,V		velocity components in the cylindrical R-Z coordinate system, Fig. II.1
x,y	X,Y	rotated coordinate system nondimensionalized with respect to the throat separation distance, d, and oriented such that the y-axis lies along the minimum area cross-section and the origin is on the Z-axis of symmetry, Eqs. (II-3) and (II-4) and Fig. II.1
y_i,y_o	YI,YØ	y- coordinates of the inner and outer throat wall locations, Fig. II.1

Text	Computer Program	Meaning
z	Z	stretched axial coordinate defined in Eq. (II-25)
Z	Z	axial coordinate in the cylindrical coordinate system, Fig. II.1
Z^*	ZSTAR	displacement of the x-y origin from the R-Z origin along the Z-axis of symmetry, Fig. II.1
Z_i, Z_o	ZI,ZØ	axial coordinates of the inner and outer throat wall locations, Fig. II.1

Greek Symbols

Text	Computer Program	Meaning
β	BETA	inclination angle of the x-axis from the Z-axis of symmetry, positive counterclockwise, Fig. II.1
β_1	BETA1	dimensionless quantity defined in Eq. (II-25)
γ	G	specific heat ratio of the gas
ε	EPS	expansion variable defined in Eq. (II-18)
η	ETA	parameter in the expansion variable definition, Eq. (II-18)
θ	THETA	angle of inclination of the velocity vector from the x-axis, positive counterclockwise
ρ		density
ρ^*		critical density

I. INTRODUCTION

Annular supersonic nozzles constitute an integral part of a number of devices of practical importance. These applications include turbofan bypass nozzles, unconventional propulsion nozzles such as the spike, plug, and expansion-deflection designs, as well as the supersonic-supersonic ejector and axial-flow aerodynamic window. In order to analyze the supersonic flowfield in these nozzles using either the method-of-characteristics or a finite difference technique, an accurate initial value line is required. One natural place to start these calculations is in the throat region of the nozzles using an appropriate analysis of the transonic flowfield which occurs there. Given this starting line, the marching-type computations for the steady, supersonic portion of the flowfield can then proceed in the streamwise direction.

Several methods have been utilized to analyze transonic flow in the throat region of annular supersonic nozzles. These methods include inverse techniques [1,2]†, series expansion methods [3-5], time-dependent numerical techniques [6-8], the method of integral relations [9], and type-dependent numerical relaxation [10]. However, each of these previous methods either applies only to a specialized class of annular

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†Numbers in brackets refer to entries in REFERENCES.

nozzles, such as those with cylindrical centerbodies or located a large distance from the axis of symmetry, or the numerical technique employed requires an inordinate amount of computer time and/or memory. In addition, the inverse techniques require iteration for the direct problem of analyzing the flowfield in a nozzle of given contour. Only the recent numerical methods of Cline [8] and Brown, et al. [10] have shown promise of analyzing nozzle throat flows with reasonable amounts of computer time.

What is desired, therefore, is a direct method which can accurately and economically describe the transonic flowfield in the throat region of a large class of annular, supersonic nozzles. Just such a method was developed by the present authors in [11]. A series expansion technique similar to the one used originally by Hall [12] for axisymmetric and planar nozzles was utilized to find an approximate solution to the inviscid, irrotational governing equations. This solution may be applied to a variety of annular nozzle configurations including those for which the centerbody and outer wall contours are both circular arcs or, alternately, those for which one boundary is straight. In addition, the main flow direction may be either parallel or inclined with respect to the axis of symmetry. In the limit as the centerbody radius approaches zero and the outer wall, respectively, the solutions for the simpler cases of axisymmetric and planar nozzles are obtained so that these cases may also be analyzed. Since the solution is of the series expansion type, one of its major advantages is the speed and reliability of its numerical implementation, making feasible parametric studies and iterative calculations.

The purpose of the present report is to describe the FORTRAN computer program TRANNOZ which has been developed to implement the solution just discussed. After a brief summary of the theoretical development of the expansion solution, the computer code is discussed in detail including descriptions of its subroutines and functions and of its input and output variables. Input instructions are also given together with a sample input file and the resulting output. A listing of the program is included in the Appendix.

II. THEORY

A sketch of the configuration to be analyzed is shown in Fig. II.1. It consists of an annular supersonic nozzle which, in general, may be inclined with respect to the axis of symmetry. The R-Z coordinate system is the standard cylindrical coordinate system, while the x-y coordinate system is rotated in such a manner that the y-axis lies along the cross section of minimum area in the nozzle throat. The x-axis is perpendicular to the y-axis, and the origin of this coordinate system is located on the Z-axis of symmetry a distance Z* from the R-Z origin. The angle β is the inclination angle between the x-axis and the Z-axis, and d is the distance in the R-Z coordinate system between the inner and outer throat wall locations. The coordinates of these last two points as well as those of the x-y origin and the equations of the inner and outer wall contours in the meridional plane are also given in both the R-Z and x-y coordinate systems in the figure. It is to be noted that for the general case of an inclined, annular nozzle the minimum area cross section does not correspond to the cross section of minimum distance between the nozzle walls. Because of the radial factor involved in calculating the annular area, the minimum area cross section is located nearer the axis of symmetry than the minimum distance cross section. More will be said about this when subroutine ARMIN is discussed.

Under the assumptions of steady, inviscid, irrotational, adiabatic flow of a perfect gas, the governing equations in the cylindrical coordinate system can be taken as the irrotationality condition and the "gas dynamic equation" [13],

$$U_R - V_Z = 0 \tag{II-1}$$

$$\left(U^2-a^2\right)U_Z + \left(V^2-a^2\right)V_R + 2UVU_R - \frac{a^2V}{R} = 0 \tag{II-2}$$

$a \equiv$ speed of sound ,

where the subscripts are used to denote partial differentiation with respect to Z and R. Transforming from the R-Z to the rotated x-y coordinate system where lengths are non-dimensionalized with respect to the throat separation distance, d, and velocities with respect to the critical speed of sound, a*,

$$x = \frac{(Z-Z^*)}{d}\cos\beta + \frac{R}{d}\sin\beta \tag{II-3}$$

$$y = -\frac{(Z-Z^*)}{d}\sin\beta + \frac{R}{d}\cos\beta \tag{II-4}$$

$$u = \frac{U}{a^*}\cos\beta + \frac{V}{a^*}\sin\beta \tag{II-5}$$

$$v = -\frac{U}{a^*}\sin\beta + \frac{V}{a^*}\cos\beta \ , \tag{II-6}$$

and using the adiabatic relation,

$$\left(\frac{a}{a^*}\right)^2 = \frac{\gamma+1}{2} - \frac{\gamma-1}{2}\left(u^2+v^2\right) \ , \tag{II-7}$$

the governing equations become

$$u_y - v_x = 0 \tag{II-8}$$

$$\left(1-u^2-\frac{\gamma-1}{\gamma+1}v^2\right)u_x - \frac{4}{\gamma+1}uvu_y + \left(1-v^2-\frac{\gamma-1}{\gamma+1}u^2\right)v_y$$

$$+\frac{\left(1-\frac{\gamma-1}{\gamma+1}u^2-\frac{\gamma-1}{\gamma+1}v^2\right)(v\cos\beta+u\sin\beta)}{y\cos\beta+x\sin\beta}=0\ . \qquad \text{(II-9)}$$

The next step in the analytical development involves introduction of the transonic perturbation velocity components, $\tilde{u}$ and $\tilde{v}$, by the relations

$$u = 1 + \tilde{u} \qquad \text{(II-10)}$$

$$v = \tilde{v}\ , \qquad \text{(II-11)}$$

which, when substituted into Eqs. (II-8) and (II-9) result in

$$\tilde{u}_y - \tilde{v}_x = 0 \qquad \text{(II-12)}$$

$$\left(-2\tilde{u}-\tilde{u}^2-\frac{\gamma-1}{\gamma+1}\tilde{v}^2\right)\tilde{u}_x - \frac{4}{\gamma+1}(1+\tilde{u})\tilde{v}\tilde{u}_y + \left(\frac{2}{\gamma+1}-\tilde{v}^2-2\frac{\gamma-1}{\gamma+1}\tilde{u}-\frac{\gamma-1}{\gamma+1}\tilde{u}^2\right)\tilde{v}_y$$

$$+\frac{\left(\frac{2}{\gamma+1}-2\frac{\gamma-1}{\gamma+1}\tilde{u}-\frac{\gamma-1}{\gamma+1}\tilde{u}^2-\frac{\gamma-1}{\gamma+1}\tilde{v}^2\right)[\tilde{v}\cos\beta+(1+\tilde{u})\sin\beta]}{y\cos\beta+x\sin\beta}=0\ . \qquad \text{(II-13)}$$

The boundary conditions for this inviscid analysis are that the nozzle walls must be streamlines. Taking $y=g(x)$ and $y=h(x)$ as the equations for the inner and outer wall contours, respectively, the boundary conditions may be written as

$$\tilde{v}(x,g(x)) = [1+\tilde{u}(x,g(x))]g'(x) \qquad \text{(II-14)}$$

$$\tilde{v}(x,h(x)) = [1+\tilde{u}(x,h(x))]h'(x)\ , \qquad \text{(II-15)}$$

where the prime is used to denote differentiation with respect to x.

To this point in the development no approximations to either the governing partial differential equations or the boundary conditions have been made. In order to proceed, an expansion parameter must be defined so that the perturbation velocity components can be expanded in appropriate series and substituted into the equations and boundary conditions. Based on the experience of Kliegel and Levine [14] and Thompson and Flack [5], the expansion parameter used in this investigation is

$$\varepsilon = (\bar{R}_c + \eta)^{-1} \tag{II-16}$$

where $\bar{R}_c$ is an average dimensionless radius of curvature for the two bounding walls. The parameter η is included in order to improve the convergence properties of the series solution for nozzles with a small wall radius of curvature. For $\eta > 1$, ε is less than unity regardless of how small $\bar{R}_c$ may be. Defining $\bar{R}_c$ in terms of the second derivatives of the equations for the wall contours,

$$\bar{R}_c \equiv \frac{2}{h''(0) - g''(0)}\ , \tag{II-17}$$

the definition of ε becomes,

$$\varepsilon = \frac{h''(0) - g''(0)}{2 + \eta[h''(0) - g''(0)]}\ . \tag{II-18}$$

This is the definition actually used in the evaluation of the series solution.

The solution technique then proceeds by investigating the orders of magnitude of the various terms in the equations and boundary conditions and by defining appropriate $O(1)$ quantities.

Expanding the perturbation velocity components $\tilde{u}$ and $\tilde{v}$ as,

$$\tilde{u}(z,y) = u_1(z,y)\varepsilon + u_2(z,y)\varepsilon^2 + u_3(z,y)\varepsilon^3 + \ldots \quad \text{(II-19)}$$

$$\tilde{v}(z,y) = \left[\frac{\gamma+1}{2}\varepsilon\right]^{1/2}\left[v_1(z,y)\varepsilon + v_2(z,y)\varepsilon^2 + v_3(z,y)\varepsilon^3 + \ldots\right], \quad \text{(II-20)}$$

substituting into governing Eqs. (II-12) and (II-13) and boundary conditions (II-14) and (II-15), and gathering coefficients of like powers of ε results in the formulations for the various solution orders in the expansion technique. For the first order solution, the governing equations are

$$\frac{\partial u_1}{\partial y} - \frac{\partial v_1}{\partial z} = 0 \quad \text{(II-21)}$$

$$-2u_1\frac{\partial u_1}{\partial z} + \frac{\partial v_1}{\partial y} + \frac{\beta_1 + v_1}{y} = 0 \quad \text{(II-22)}$$

with corresponding boundary conditions

$$v_1\left(z,y_i\right) = g_1 + g_2 z \quad \text{(II-23)}$$

$$v_1\left(z,y_o\right) = h_1 + h_2 z\,. \quad \text{(II-24)}$$

where,

$$z \equiv \left[\frac{\gamma+1}{2}\varepsilon\right]^{-1/2} x \qquad \beta_1 \equiv \left[\frac{\gamma+1}{2}\right]^{-1/2}\varepsilon^{-3/2}\tan\beta$$

$$g_1 \equiv \left[\frac{\gamma+1}{2}\right]^{-1/2}\varepsilon^{-3/2}g'(0) \qquad h_1 \equiv \left[\frac{\gamma+1}{2}\right]^{-1/2}\varepsilon^{-3/2}h'(0) \quad \text{(II-25)}$$

$$g_2 \equiv \frac{2g''(0)}{h''(0) - g''(0)} \qquad h_2 \equiv \frac{2h''(0)}{h''(0) - g''(0)}\,.$$

In the definitions in (II-25) note, in particular, the transformation from the coordinate x to the stretched, axial coordinate z. The formulations for the higher order solutions are similar although they contain many more terms than the first order formulation.

Equations (II-21)-(II-24) and the corresponding equations for the higher order solutions are the ones which must be solved in order to obtain the (u_1, v_1), (u_2, v_2), (u_3, v_3), ... perturbation velocity components. As discussed in [11], the series solution has been carried to the third order using the method of Hall [12]. The result is an approximate, analytical solution for the perturbation velocities consisting of a rather large and algebraically complicated set of constants and functions. However, because of the closed-form nature of the solution, these quantities can be rapidly evaluated in a straightforward manner using a digital computer.

With the resulting expressions for the (u_1, v_1), (u_2, v_2), and (u_3, v_3) components determined, other quantities of interest may also be found. The series expansions for the following flowfield variables are given below: the velocity components u and v in the x-y coordinate system; M^*, the ratio of the local speed to the critical speed of sound; θ, the angle of inclination of the velocity vector from the x-axis; the Mach number, M; and the local static-to-stagnation pressure ratio, P/P_0;

$$u(z,y) = 1 + \tilde{u} = 1 + u_1\varepsilon + u_2\varepsilon^2 + u_3\varepsilon^3 + \ldots \qquad \text{(II-26)}$$

$$v(z,y) = \tilde{v} = \left[\frac{\gamma+1}{2}\,\varepsilon\right]^{1/2}\left[v_1\varepsilon + v_2\varepsilon^2 + v_3\varepsilon^3 + \ldots\right] \tag{II-27}$$

$$M^*(z,y) = \left(u^2+v^2\right)^{1/2} = 1 + u_1\varepsilon + u_2\varepsilon^2 + \left(u_3 + \frac{\gamma+1}{4}\,v_1^2\right)\varepsilon^3 + \ldots \tag{II-28}$$

$$\theta(z,y) = \tan^{-1}(v/u) = \left[\frac{\gamma+1}{2}\,\varepsilon\right]^{1/2}\left[v_1\varepsilon + \left(v_2 - u_1v_1\right)\varepsilon^2 + \left(v_3 - u_1v_2 - u_2v_1 + u_1^2v_1\right)\varepsilon^3 + \ldots\right] \tag{II-29}$$

$$M(z,y) = \left[\frac{\frac{2}{\gamma+1}\,M^{*2}}{1 - \frac{\gamma-1}{\gamma+1}\,M^{*2}}\right]^{1/2} = 1 + \left(\frac{\gamma+1}{2}\right)\left[u_1\varepsilon + \left[u_2 + \frac{3}{4}\,(\gamma-1)u_1^2\right]\varepsilon^2 + \left[u_3 + \frac{\gamma+1}{4}\,v_1^2 + \frac{3}{2}\,(\gamma-1)u_1u_2 + \frac{\left(5\gamma^2-8\gamma+3\right)}{8}\,u_1^3\right]\varepsilon^3 + \ldots\right] \tag{II-30}$$

$$\frac{p}{p_0}\,(z,y) = \left[1 - \frac{\gamma-1}{\gamma+1}\,M^{*2}\right]^{\gamma/(\gamma-1)} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}\left[1 - \gamma\left[u_1\varepsilon + u_2\varepsilon^2 + \left(u_3 + \frac{\gamma+1}{4}\,v_1^2 - \frac{\gamma+1}{6}\,u_1^3\right)\varepsilon^3 + \ldots\right]\right] . \tag{II-31}$$

Another quantity of interest is the discharge or flow coefficient, C_D, which is defined as the ratio of the actual nozzle mass flowrate to that obtained from the ideal approximation of uniform, sonic flow at the throat,

$$C_D = \int_{y_1}^{y_0}\left[\frac{\rho}{\rho^*}\,u\,\frac{dA}{A^*}\right]_{x=0} . \tag{II-32}$$

Substituting the appropriate expressions for the quantities in the integrand and carrying out the integration, the relation for C_D becomes

$$C_D = 1 - \frac{(\gamma+1)\epsilon^2}{\left(Y_e^2 - Y_i^2\right)} \left[C_{D1} + C_{D2}\epsilon + C_{D3}\epsilon^2 + \ldots\right] \qquad \text{(II-33)}$$

where C_{D1}, C_{D2}, and C_{D3} are constants.

Thus with the (u_1, v_1), (u_2, v_2), (u_3, v_3) transonic perturbation velocity components and the C_{D1}, C_{D2}, C_{D3} discharge coefficient constants determined, all of the flowfield variables of interest are known to third order in the present series approximations. For further details concerning the development of the expansion solution including the extensive series of checks and parametric studies which have been performed, reference [11] should be consulted.

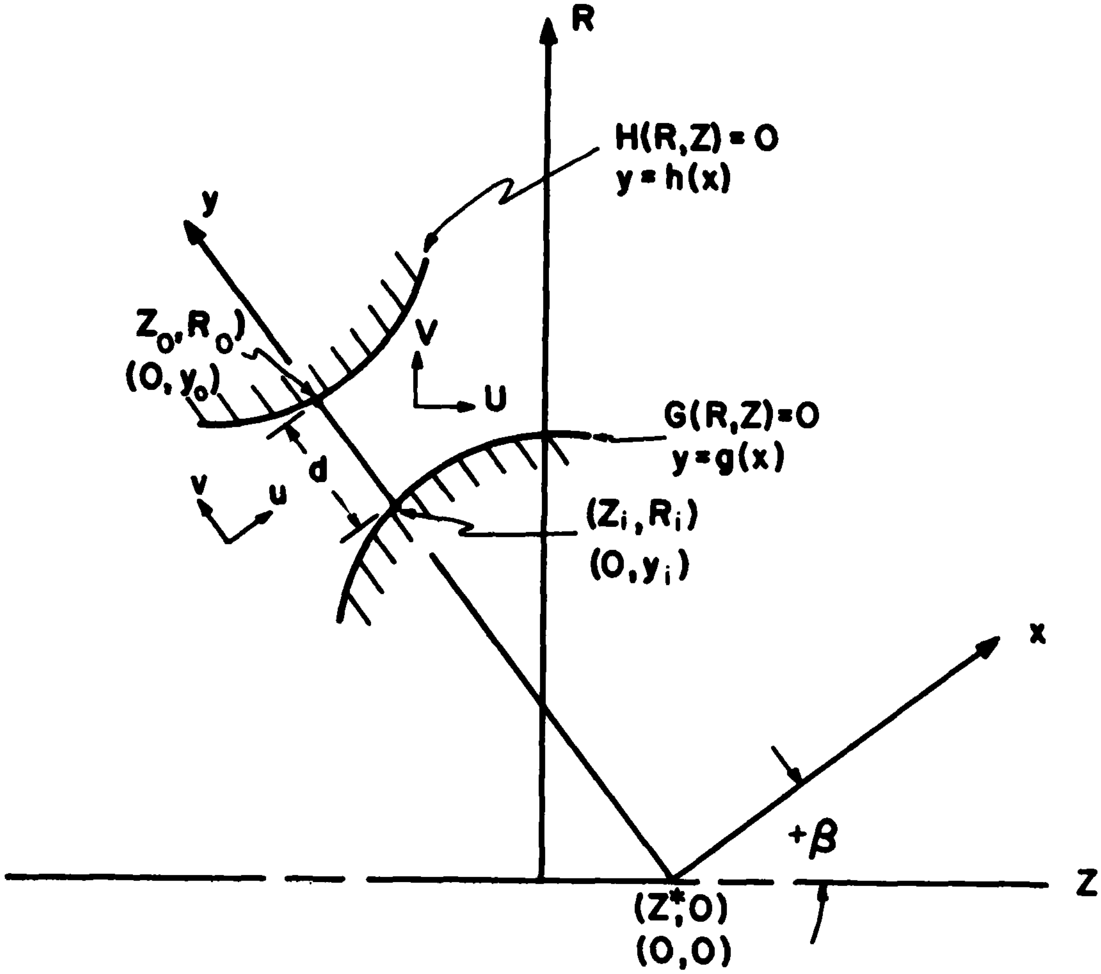

Figure II.1 Configuration for throat flowfield analysis of annular supersonic nozzles

III. COMPUTER PROGRAM TRANNOZ

The TRANNOZ computer code is a FORTRAN program for analyzing the transonic flowfield in the throat region of annular supersonic nozzles. This task is accomplished by evaluating the series expansion solution developed in [11] and outlined in the preceding chapter. Since the series evaluation consists essentially of the straightforward calculation of a set of constants and functions, and since the solution can be applied to a variety of nozzle configurations including the annular, planar, and axisymmetric cases, many nozzle throat flowfields of interest can be calculated in a routine and inexpensive manner. This feature makes possible parametric studies and iterative calculations as might be necessary, for example, in a design situation.

A. PROGRAM, FUNCTIONS, AND SUBROUTINES

The TRANNOZ code consists of a main program, two function subprograms, and twelve subroutines. A brief description of each of these routines is given below. A complete listing of TRANNOZ is contained in the Appendix.

1. PROGRAM MAIN

The main program reads and writes the input variables, calls subroutines ARMIN and DISCO to calculate some initial parameters necessary in the series evaluation, calls the four main worker subroutines CONTOUR, STLINE, XPLANE, and ZPLANE as desired, and writes the results. It is to be emphasized that under normal circumstances all reading and writing is done by program MAIN. If an error condition is encountered, a limited number of diagnostics are written by subroutine ERROR (see below).

2. FUNCTION IBND

Function IBND is the equation of the inner wall contour in the explicit form R=IBND(Z). In the present form of IBND, the inner boundary may be either a circular arc or a straight line in the meridional plane, although any contour which satisfies the assumptions of the analysis could be used.

3. FUNCTION OBND

Function OBND is the equation of the outer boundary in the explicit form R=OBND(Z). As for the inner boundary, TRANNOZ allows the outer wall contour to be either a circular arc or a straight line in the meridian plane, although other contours could also be utilized.

4. SUBROUTINE ARMIN

Subroutine ARMIN locates the cross section of minimum area in the nozzle throat and calculates some initial parameters necessary in evaluating the series solution. As discussed briefly in the previous chapter, for the general case of an inclined, annular nozzle the minimum area cross section does not coincide with the cross section of minimum distance between the nozzle walls, so that the throat location is not known *a priori*. ARMIN employs an iterative, numerical technique [5] to locate the throat whereby the location of the outer wall point is first fixed and the location of the inner wall point is varied until a minimum in the cross-sectional area is found. The inner wall point is then fixed and the outer boundary point location is varied until the area is again minimized. This process is continued until the fractional change in these successively determined minimum areas is less than 10^{-10}. This technique has been thoroughly tested by substituting the throat wall locations found numerically into the algebraic equations resulting from the constrained minimization problem† of locating the throat of an annular nozzle with circular arc contours. In all cases, the equations were found to be satisfied to within a high degree of numerical accuracy thus verifying the method.

With the throat location determined, ARMIN then evaluates the following geometrical parameters shown in Fig. II.1: A^*, d, Z^*, β, y_i, y_o, $g'(0)$, $h'(0)$, $g''(0)$, and $h''(0)$ where A^* is the throat area and $y=g(x)$ and $y=h(x)$ are the equations of the inner and outer contours in the x-y coordinate system. The dimensionless parameters, ϵ, g_1, h_1, g_2, h_2, and β_1, defined in Eqs. (II-18) and (II-25), are also calculated.

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†After elimination of the two Lagrange multipliers, the formulation of the constrained minimization problem consists of four nonlinear, simultaneous, algebraic equations for the coordinates of the inner and outer throat wall points (Z_i, R_i), (Z_o, R_o) in terms of the coordinates of the centers and radii of curvature of the circular arc boundaries.

5. SUBROUTINE DISCO

Subroutine DISCO evaluates the discharge coefficient, C_D, for the nozzle under consideration by calling subroutine AATRANS to calculate the constants C_{D1}, C_{D2}, and C_{D3} in the series approximation for C_D, Eq. (II-33).

The next four subroutines are called at the user's discretion to perform the major functions of the program.

6. SUBROUTINE CONTOUR

Subroutine CONTOUR finds the R-Z coordinates of the points on contours of constant Mach number, M, dimensionless speed ratio, M*, or static-to-stagnation pressure ratio, p/p_0. A maximum of 53 points is allowed on each contour. A contour point is found on both the inner and outer boundaries and the remaining points are equally spaced in the y-coordinate from y_i to y_o. If the contour points at $y=y_i$ and $y=y_o$ are essentially coincident with the adjacent points on the boundaries (difference in y coordinates less than 10^{-3}), they are omitted. The order of the points on output is from the outer wall to the inner and all of the flow quantities along the contour are printed.

7. SUBROUTINE STLINE

Subroutine STLINE calculates the flowfield variables along a supersonic initial value line for starting method-of-characteristics or finite difference computations for the supersonic portion of the flowfield downstream from the nozzle throat. The starting line which is calculated is the constant Mach number contour from the throat wall location with the higher Mach number. This line is employed since, under the assumptions of the analysis, it is the most accurate of the alternatives considered. It is realized that this initial value line may not be compatible with the particular algorithm used to analyze the supersonic flowfield. However, routines to evaluate other starting lines can easily be developed by using STLINE as an example.

8. SUBROUTINE XPLANE

Subroutine XPLANE evaluates the flowfield variables of interest at a specified number of points along planes of constant x-coordinate (Fig. II.1) in the nozzle throat. The points are equally spaced in the y-coordinate from y_i to y_o, and a maximum of 51 points on each plane is allowed. This subroutine has been used primarily to test the series solution obtained in [11] for the general annular configuration against previous solutions for simpler geometries.

9. SUBROUTINE ZPLANE

Subroutine ZPLANE computes the flowfield quantities at a specified number of points along planes of constant axial coordinate, Z. A maximum of 51 points is allowed on each plane, and they are equally spaced in the radial coordinate, R, from the inner to the outer wall.

The next six subroutines are secondary routines and are called a number of times by the main worker subroutines in order to carry out specific tasks.

10. SUBROUTINE TRRZXY

Subroutine TRRZXY transforms the coordinates of a point from the R-Z cylindrical coordinate system to the dimensionless x-y system. This transformation is the one indicated by Eqs. (II-3) and (II-4).

11. SUBROUTINE TRXYRZ

Subroutine TRXYRZ carries out the coordinate transformation of a point from the rotated x-y coordinate system to the R-Z cylindrical system. This is the inverse of the transformation expressed in Eqs. (II-3) and (II-4).

12. SUBROUTINE ITER

Subroutine ITER is a general iteration subroutine used to find the value of the independent variable corresponding to a given value of the dependent variable in a functional relationship. The iterations are continued until error tests on either the independent or dependent variable are satisfied. This routine is used by subroutine CONTOUR for finding points along contours of constant M, M*, or p/p_0.

13. SUBROUTINE VARSOR

Subroutine VARSOR is utilized to determine which of the three dependent variables M, M*, or p/p_0 is being held constant along a contour. It is used in conjunction with the iteration subroutine ITER by worker routine CONTOUR.

14. SUBROUTINE ERROR

Subroutine ERROR writes a limited number of diagnostics for error conditions encountered in other subroutines and terminates program execution. Four of the diagnostics are involved with the iterations in subroutine ARMIN for locating the minimum area section in the nozzle throat and initializing the solution parameters. Another diagnostic is written when the iterations in subroutine CONTOUR for a given point on a contour do not converge. The final diagnostic is written when subroutine STLINE is called and the Mach number at neither of the throat wall locations is supersonic. Since none of these error conditions has ever been encountered, they will not be discussed in further detail.

15. SUBROUTINE AATRANS

Subroutine AATRANS is the longest routine in the program. It evaluates all of the constants, functions, and flowfield quantities in the three term series expansion solution developed in [11]. In the form presented here, all of the constants and functions in AATRANS are double precision variables so that annular nozzles in the planar limit as the dimensionless distance from the axis of symmetry becomes very large, can also be analyzed without incurring significant roundoff errors. The penalty for adding this feature is increased compilation and execution times, but since the program is extremely fast the effect of this penalty is minimal.

B. INPUT AND OUTPUT VARIABLES

As will be discussed in more detail in the next section, input to the TRANNOZ code is achieved through the use of six NAMELISTS: PARAM, CONTROL, NAMECON, NAMEST, NAMEXPL, and NAMEZPL. A description of each of the input variables which comprise these NAMELISTS follows.

1. NAMELIST PARAM

NGEOM----an integer variable describing the nozzle geometry, Fig. III.1. If NGEOM=1, both the inner and outer boundaries are circular arcs in the meridional plane. If NGEOM=2, the inner boundary is a straight line and the outer boundary is a circular arc. If NGEOM=3, the inner boundary is a circular arc and the outer boundary is a straight line. (default=1)

AI-------Z coordinate of the center of curvature of the inner boundary if it is a circular arc (NGEOM=1 or 3) or slope of the inner boundary if it is a straight line (NGEOM=2), Fig. III.1.

BI-------R coordinate of the center of curvature of the inner boundary if it is a circular arc (NGEOM=1 or 3) or intercept of the inner boundary if it is a straight line (NGEOM=2), Fig. III.1.

RCI------radius of curvature of the inner boundary if it is a circular arc (NGEOM=1 or 3), Fig. III.1.

AØ-------Z coordinate of the center of curvature of the outer boundary if it is a circular arc (NGEOM=1 or 2) or slope of the outer boundary if it is a straight line (NGEOM=3), Fig. III.1.

BØ-------R coordinate of the center of curvature of the outer boundary if it is a circular arc (NGEOM=1 or 2) or intercept of the outer boundary if it is a straight line (NGEOM=3), Fig. III.1.

RCØ------radius of curvature of the outer boundary if it is a circular arc (NGEOM=1 or 2), Fig. III.1

The next four input variables in NAMELIST PARAM are used to establish a "window" area in the nozzle throat. Subroutine ARMIN searches only this region for the minimum area cross section and subroutine CONTOUR searches only this region for points on the contours of constant Mach number, M*, or static-to-stagnation pressure ratio.

ZIMIN----minimum Z coordinate on the inner boundary for establishing the throat window, Fig. III.2.

ZIMAX----maximum Z coordinate on the inner boundary for establishing the throat window, Fig. III.2.

ZØMIN----minimum Z coordinate on the outer boundary for establishing the throat window, Fig. III.2.

ZØMAX----maximum Z coordinate on the outer boundary for establishing the throat window, Fig. III.2.

G--------specific heat ratio of the gas, γ. (default=1.4)

ETA------parameter η in the definition of the expansion variable, Eqs. (II-16) or (II-18). (default=2.Ø)

NTERM----number of terms from the expansion solution to be used in evaluating the nozzle discharge coefficient, C_D. (default=3)

2. NAMELIST CONTROL

NCONT----an integer variable which indicates the number of contours of constant M, M*, or p/p_0 to be found. (default=Ø) NAMELIST NAMECON is read NCONT times.

START----a logical variable which if .TRUE. causes a supersonic initial value line to be found for starting method-of-characteristics or finite difference calculations. (default=.FALSE.) If START=.TRUE., NAMELIST NAMEST is read.

NXPL-----an integer variable which specifies the number of planes of constant x coordinate along which flow-field quantities are to be found. (default=Ø) NAMELIST NAMEXPL is read NXPL times.

NZPL-----an integer variable which indicates the number of planes of constant Z coordinate along which the flow variables are to be determined. (default=Ø) NAMELIST NAMEZPL is read NZPL times.

3. NAMELIST NAMECON

NVAR-----an integer variable which determines which dependent variable is to be held constant along the desired contour. For NVAR=1, the dependent variable is Mach number, M; for NVAR=2, it is the dimensionless speed ratio M*; and for NVAR=3, it is the static-to-stagnation pressure ratio, p/p_0. (default=1)

VALUE----the value of the dependent variable along the desired contour.

NPTS-----the number of points to be found along the contour (minimum=4; maximum=53).

NTERM----number of terms from the series expansion solution to be utilized in finding the contour.

4. NAMELIST NAMEST

NPTS-----number of points to be found along the supersonic starting line (minimum=4; maximum=53).

NTERM----number of terms from the series solution to be used in determining flowfield quantities along the initial value line.

5. NAMELIST NAMEXPL

X--------x coordinate of the plane along which the flowfield quantities are to be determined.

NPTS-----number of points along the plane of constant x coordinate at which the flow variables are to be found (minimum=2; maximum=51).

NTERM----number of terms from the series solution to be utilized in finding the quantities of interest along the x=constant plane.

6. NAMELIST NAMEZPL

Z--------Z coordinate of the plane along which the flowfield quantities are to be determined.

NPTS-----number of points along the plane of constant Z coordinate at which the flow variables are to be found (minimum=2; maximum=51).

NTERM----number of terms from the expansion solution to be used in finding the quantities of interest along the Z=constant plane.

The first page of output consists of a listing of the parameters from input NAMELISTS PARAM and CONTROL, as just described, together with the following initial quantities determined by subroutines ARMIN and DISCO:

ZI-------Z coordinate of the inner boundary throat location, Z_i, Fig. II.1.

RI-------R coordinate of the inner boundary throat location, R_i, Fig. II.1.

ZØ-------Z coordinate of the outer boundary throat location, Z_o, Fig. II.1.

RØ-------R coordinate of the outer boundary throat location, R_o, Fig. II.1.

ASTAR----throat area.

D--------separation distance, d, between the inner and outer throat wall locations in the R-Z coordinate system, Fig. II.1.

BETA-----angle of inclination, β, of the x-axis from the Z-axis of symmetry (positive counterclockwise), Fig. II.1.

YI-------y coordinate of the throat at the inner boundary, y_i, Fig. II.1.

YØ-------y coordinate of the throat at the outer boundary, y_o, Fig. II.1.

EPS------value of the expansion variable, ε, Eq. (II-18).

CD-------nozzle discharge coefficient, C_D, Eq. (II-33).

The remaining pages of output consist of listings of the parameters in the optional input NAMELISTS NAMECON, NAMEST, NAMEXPL, and NAMEZPL, as used, as well as the following flow-field variables along each contour or plane:

Z--------axial coordinate of the contour point.

R--------radial coordinate of the contour point or of the point on the plane of constant Z coordinate.

Y--------y coordinate of the point on the plane of constant x coordinate.

U--------component of velocity, u, parallel to the x-axis nondimensionalized with respect to the critical speed of sound, Eq. (II-5).

V--------component of velocity, v, parallel to the y-axis nondimensionalized with respect to the critical speed of sound, Eq. (II-6).

M*-------dimensionless ratio of the speed at a point to the critical speed of sound.

THETA----angle of inclination of the velocity vector from the x-axis, $\theta = \tan^{-1}(v/u)$ (positive counterclockwise).

M--------Mach number, M, which is the dimensionless ratio of the speed at a point to the speed of sound at that point.

P/P0-----static-to-stagnation pressure ratio at a point.

C. INPUT INSTRUCTIONS AND EXAMPLE

The input deck (file) is constructed in the following manner. The first card is a title card which may be any message of up to 80 characters at the user's discretion. This message can be used for identification of both the input file and the output since it is also the first line of output. The title card is followed by cards containing NAMELISTS PARAM and CONTROL where the usual conventions for reading NAMELISTS are observed. As discussed in the preceding section, the variables in NAMELIST PARAM are geometrical and other parameters necessary in the initialization of the problem, while those in NAMELIST CONTROL are variables which control the further operation of the program. Thus, these NAMELISTS must always appear in the input deck.

The remaining cards in the input file contain, in order, the optional NAMELISTS NAMECON, NAMEST, NAMEXPL, and NAMEZPL. The number of times each of these NAMELIST cards appears in the input deck is determined by the values of the control variables read in NAMELIST CONTROL. NAMELIST NAMECON is read NCONT times; NAMELIST NAMEST is read if START=.TRUE.; NAMELIST NAMEXPL is read NXPL times; and NAMELIST NAMEZPL is read NZPL times. Note that if any of the control variables is left at its default value, the corresponding optional NAMELIST does not appear in the input deck.

Any number of problems can be solved with a single input file by simply repeating the sequence described above. It is important to note, however, that the default values are reset at the beginning of each new problem.

The dimensional variables on input are AI, BI, RCI, AØ, BØ, RCØ, ZIMIN, ZIMAX, ZØMIN, ZØMAX, and Z which all have dimensions of length. The units for these input parameters must be consistent and are simply the units of the R-Z coordinate system. On output these variables, together with ZI, RI, ZØ, RØ, and D, will have these same units and the throat area, ASTAR, will have this unit squared.

As an example consider the annular nozzle shown in Fig. III.3. Both the inner and outer boundaries are circular arcs in the meridional plane so that NGEOM=1. The centers of curvature of both surfaces lie along the Z=0 plane, AI=AØ=Ø., with radial coordinates BI=-1.625 and BØ=2.Ø. The radii of curvature of the inner and outer boundaries are RCI=2.Ø and RCØ=1.Ø, respectively.

The input file for this example is shown in Fig. III.4. Following the title card, NAMELIST PARAM is read. In addition to the geometrical parameters just discussed, the throat "window" is set by ZIMIN=-Ø.5, ZIMAX=Ø.5, ZØMIN=-Ø.5, and ZØMAX=Ø.5. The remaining variables in PARAM are left at their default values, G=1.4, ETA=2.Ø, and NTERM=3. In this example five contours are to be found as well as a supersonic initial value line. Thus, in NAMELIST CONTROL the values NCONT=5 and START=.TRUE. are specified. Variables NXPL and NZPL remain at their default values of zero. The next five cards are used to specify the values of the parameters for each desired contour. In each case 23 points along a constant Mach number contour are desired with three terms from the series solution to be utilized. Therefore, NVAR=1, NPTS=23, and NTERM=3 are specified. The desired Mach number along the first contour is 0.6 so VALUE=Ø.6. Following the NAMELIST convention, only the variables which are changed need to be specified on successive reads of a given NAMELIST. Therefore, only the different values of the Mach number, VALUE=Ø.8,1.Ø,1.2, and 1.4, are included on the next four NAMECON cards. The final card in the input file specifies that three terms from the expansion solution are to be used to find 22 points along the starting line, NTERM=3 and NPTS=22.

The corresponding output is shown in Fig. III.5. The first page, as discussed in the previous section, consists of the title card, the input variables from NAMELISTS PARAM and CONTROL, and some initialization parameters determined by subroutines ARMIN and DISCO. The next five pages contain listings of the coordinates of the M=0.6, 0.8, 1.0, 1.2, and 1.4 contours as well as the flowfield properties along these contours. The variable NSOLV listed on these pages is the number of contour points actually found. It is included because the contour may pass out of the window area, thus reducing the number of points actually found, and also because if the contour points at y_i or y_o are essentially coincident with those on the corresponding boundaries, they are eliminated. The latter is the case for the M=1.0 and 1.2 contours for which NSOLV=22. The last page of output is a listing of the supersonic initial value line, which in this case is the constant Mach number contour $M \cong 1.16$ originating from the outer throat wall location.

The Mach number contours listed in Fig. III.5 are plotted in Fig. III.6 together with the corresponding data obtained in [11]. The agreement between the data and the series solution is seen to be quite satisfactory. Note that the values of R_{ci} and R_{ce} listed in the figure are the radii of curvature of the inner and outer boundaries non-dimensionalized with respect to the throat separation distance, d, which in this case has a value of 0.625.

D. GENERAL DISCUSSION

In addition to annular nozzles, the solution developed in [11] and the TRANNOZ code can be used to analyze throat flowfields for the simpler cases of planar nozzles and axisymmetric nozzles without centerbodies. However, some care must be exercised in specifying the nozzle geometry for these cases so that the proper results are obtained.

The axisymmetric nozzle configuration is obtained in the limit as the inner boundary of the general annular nozzle approaches the axis of symmetry, $y_i \to 0$, for the case of a straight inner boundary, NGEOM=2. The inner boundary cannot be made to *coincide* with the axis of symmetry, $y_i = 0$, though, since this leads both to division by zero and to zero as the argument of the natural log in the evaluation of the various constants and functions in TRANNOZ. However, the y-coordinate of the inner boundary *can* be made arbitrarily small, e.g., $y_i = 10^{-10}$, thus providing the desired axisymmetric results.

The planar configuration, on the other hand, is obtained in the limit as the dimensionless distance from the axis of symmetry to the inner boundary of the annular nozzle becomes unbounded, $y_i \to \infty$, since the transverse curvature effect becomes negligible in that limit. However, this distance cannot be taken as arbitrarily large in running the TRANNOZ code because of roundoff error considerations. This is due to the fact that the constants and functions in the expansion solution are proportional to powers of y, y_i, and y_o so that as the latter quantities become large, the evaluation of the desired quantities involves sums and differences of very large, approximately equal quantities. Above certain values of the y coordinates, roundoff error persists. Table III.1 shows the limiting values of y_i above which roundoff error affects the solutions for the various orders of both the perturbation velocity components, (u_1, v_1), (u_2, v_2), and (u_3, v_3), and the discharge coefficient constants, C_{D1}, C_{D2}, and C_{D3}. These limiting values are shown for both single and double precision versions of subroutine AATRANS, the double precision version being the one routinely used and the one presented here. Notice that the limits on the discharge coefficient constants are stricter than those on the velocity components which is a result of the definition of C_D as being the integral of the density-velocity product, Eq. (II-32). The discharge coefficient constants therefore contain higher powers of y, y_i, and y_o than do the corresponding perturbation velocity components. For the double precision version of AATRANS, Table III.1 shows that for a 60-bit machine and third order solutions, a value no larger than $y_i=1000$ should be utilized for investigation of the velocity components and a value no larger than $y_i=250$ should be used for determination of the discharge coefficient. Both of these values provide a very good approximation to the planar configuration.

It is to be noted that in analyzing the planar limit any of the three geometrical options, NGEOM=1, 2, or 3, can be used, Fig. III.1. In particular, utilizing NGEOM=1 allows investigation of asymmetric, planar nozzles, i.e., planar nozzles with unequal radii of curvature for the two bounding walls.

Some limitations of the series expansion solution should also be mentioned. During the course of the series solution development, the estimates $x=O(\varepsilon^{1/2})$ and $\tan\beta/y=O(\varepsilon^{3/2})$ were made to satisfy order-of-magnitude consistency requirements in the governing equations. The first estimate implies that the solution is valid only in the transonic region near the throat plane, $x=0$. However, as demonstrated in Fig. III.6, the results appear to be quite accurate through a wide region of the throat. The second estimate, $\tan\beta/y=O(\varepsilon^{3/2})$, means that for annular nozzles located a small dimensionless distance from the axis of symmetry, $y=O(1)$, only small angles of inclination to the axis of symmetry can be analyzed. However, this would seem to be the only physically realistic case anyway, as one would not expect to encounter applications in which the nozzle is both near and highly inclined to the axis of symmetry. As the distance from the axis of symmetry becomes larger, the requirement of small inclination angles can be relaxed. A final limitation is the result of the definition of the expansion parameter, $\varepsilon=(\bar{R}_c+\eta)^{-1}$. As discussed more fully in [11], the series solution is limited to nozzles whose wall radius of curvature is of the order of the throat separation distance, d, or larger. For nozzles with $\bar{R}_c \ll d$, unrealistic results are obtained.

Despite these limitations, it is felt that the TRANNOZ code provides a fast, inexpensive, and easy-to-use tool for analyzing throat flowfields in a number of nozzle configurations of interest. On a CDC 7600 computer, the compilation time (FTN compiler) for TRANNOZ is approximately 11 seconds while the CPU time required for the sample problem presented in Figs. III.4-III.6 is 1.1 seconds. Also, since the TRANNOZ code was written as a flexible subroutine library, other worker subroutines similar to CONTOUR, STLINE, XPLANE, and ZPLANE can easily be developed to carry out functions not currently included in the program.

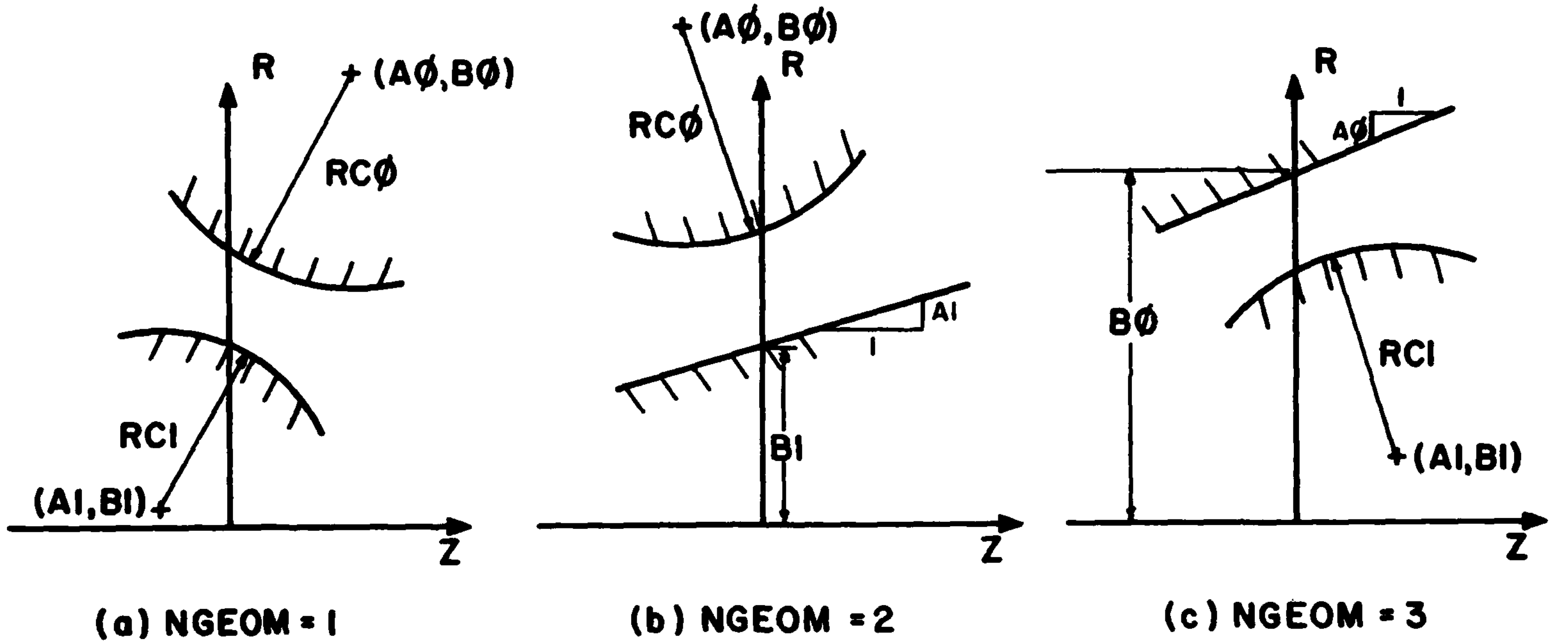

Figure III.1 Sketch depicting input variables NGEOM, AI, BI, RCI, AØ, BØ, RCØ

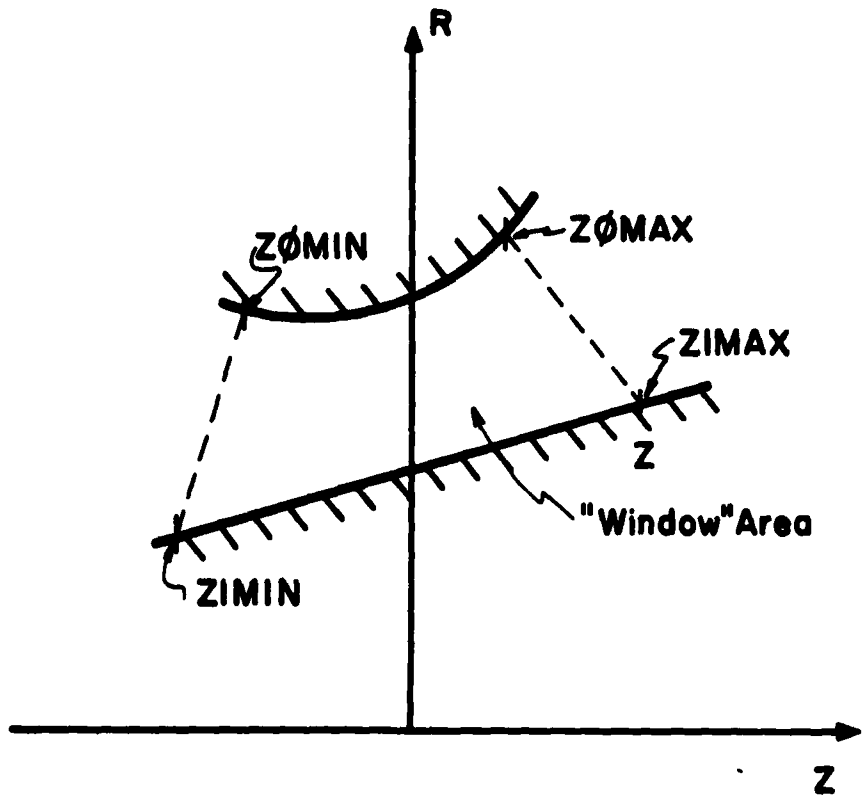

Figure III.2 Sketch depicting input variables ZIMIN, ZIMAX, ZØMIN, ZØMAX

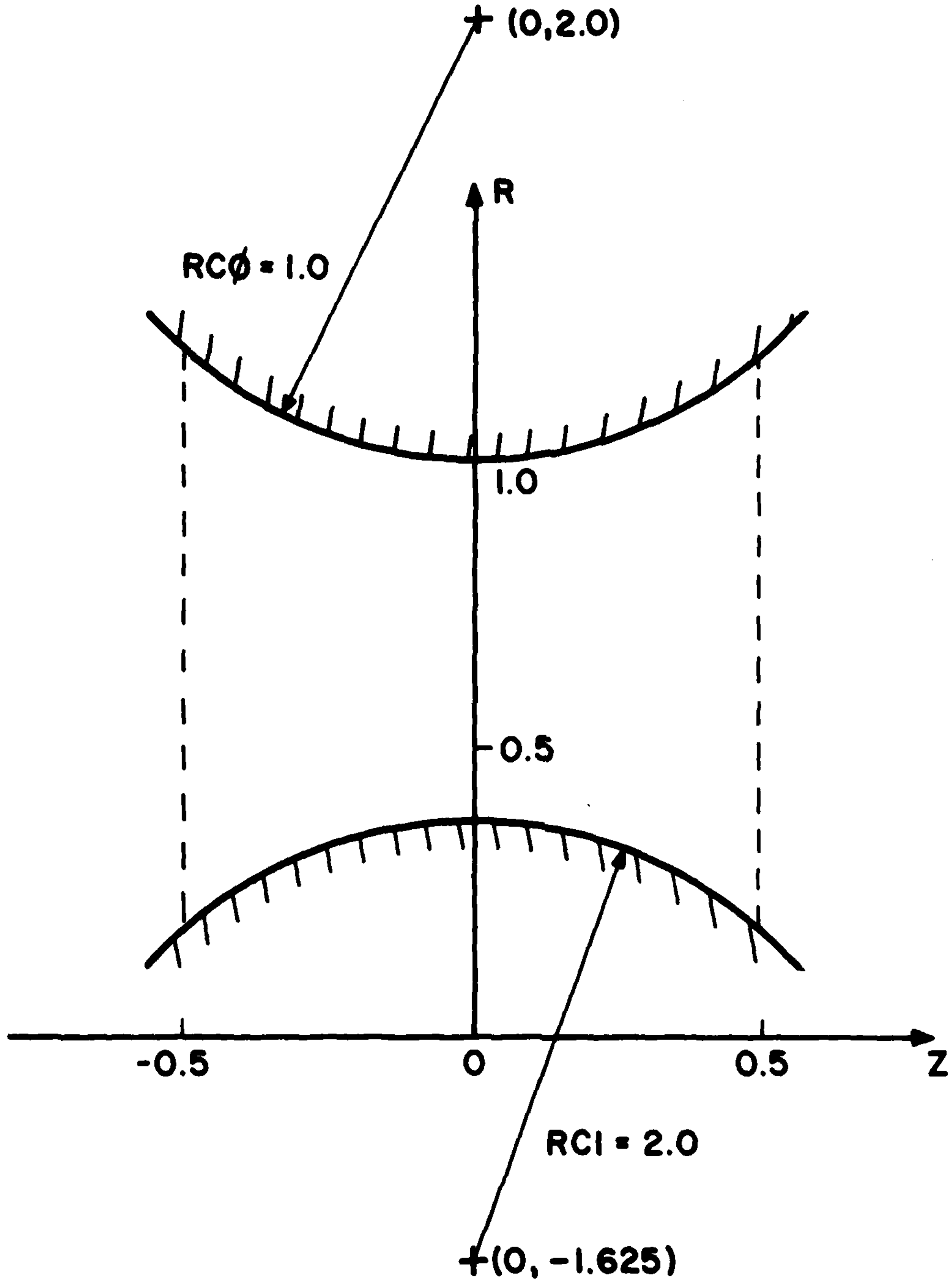

Figure III.3 Geometry of annular nozzle for example input and output

```
EXAMPLE INPUT AND OUTPUT--MACH NUMBER CONTOURS IN AN ANNULAR NOZZLE
 $PARAM NGEOM=1,AI=0.0,BI=-1.625,RCI=2.0,AO=0.0,BO=2.0,RCO=1.0,
  ZIMIN=-0.5,ZIMAX=0.5,ZOMIN=-0.5,ZOMAX=0.5$
 $CONTROL NCONT=5,START=.T.$
 $NAMECON NVAR=1,VALUE=0.6,NPTS=23,NTERM=3$
 $NAMECON VALUE=0.8$
 $NAMECON VALUE=1.0$
 $NAMECON VALUE=1.2$
 $NAMECON VALUE=1.4$
 $NAMEST NPTS=22,NTERM=3$
```

Figure III.4 Example input file

```
RESULTS FROM THE TRANNOZ CODE FOR ANALYZING NOZZLE THROAT FLOWS--BY J.C. DUTTON

     EXAMPLE INPUT AND OUTPUT--MACH NUMBER CONTOURS IN AN ANNULAR NOZZLE

THE GEOMETRY, NGEOM=1, IS A SUPERSONIC NOZZLE WITH:

     A CIRCULAR ARC INNER BOUNDARY SUCH THAT IN THE MERIDIONAL PLANE:

     AI=ZCENTER= 0.              BI=RCENTER=-1.6250          RCI=RADIUS= 2.0000

     A CIRCULAR ARC OUTER BOUNDARY SUCH THAT IN THE MERIDIONAL PLANE:

     AO=ZCENTER= 0.              BO=RCENTER= 2.0000          RCO=RADIUS= 1.0000

THE WINDOW FOR THE THROAT PLANE AND CONTOUR SEARCHES IS SET BY:

     ZIMIN=-.50000               ZIMAX= .50000
     ZOMIN=-.50000               ZOMAX= .50000

THE VALUES OF OTHER, NON-GEOMETRICAL PARAMETERS ARE:

     G=GAMMA= 1.4000             ETA= 2.0000                 NTERM= 3

THE VALUES OF THE CONTROL VARIABLES ARE:

     NCONT= 5                    START= T
     NXPL= 0                     NZPL= 0

THE INNER AND OUTER WALL THROAT LOCATIONS ARE:

     ZI=-.50000E-05              RI= .37500
     ZO=-.25000E-05              RO= 1.0000

THE THROAT AREA, INNER WALL-TO-OUTER WALL THROAT SEPARATION DISTANCE,
AND ANGLE OF INCLINATION OF THE X-AXIS FROM THE Z-AXIS ARE:

     ASTAR= 2.6998               D= .62500                   BETA=-.40000E-05

THE Y-COORDINATES OF THE INNER AND OUTER WALL THROAT LOCATIONS AND THE
VALUE OF THE EXPANSION PARAMETER ARE:

     YI= .60000                  YO= 1.6000                  EPS= .24194

THE VALUE OF THE NOZZLE DISCHARGE COEFFICIENT IS:

     CD= .99632
```

Figure III.5 Example output

DATA FOR A CONTOUR OF CONSTANT MACH NO. (NVAR=1)

VALUE= .60000 NTERM= 3
NPTS= 23 NSOLV= 23

Z	R	U	V	M*	THETA	M	P/PO
-.46061	1.1124	.60893	-.37606	.64288	-.48963	.60000	.78985
-.43315	1.0000	.61205	-.26910	.63704	-.37272	.60000	.79224
-.42609	.96875	.61333	-.24557	.63587	-.34454	.60000	.79252
-.41903	.93750	.61484	-.22414	.63495	-.31773	.60000	.79263
-.41186	.90625	.61655	-.20449	.63428	-.29204	.60000	.79258
-.40452	.87500	.61846	-.18632	.63386	-.26730	.60000	.79239
-.39697	.84375	.62052	-.16936	.63367	-.24334	.60000	.79208
-.38925	.81250	.62268	-.15332	.63370	-.22000	.60000	.79167
-.38142	.78125	.62489	-.13796	.63392	-.19717	.60000	.79120
-.37358	.75000	.62710	-.12306	.63430	-.17473	.60000	.79069
-.36587	.71875	.62924	-.10842	.63479	-.15256	.60000	.79016
-.35844	.68750	.63127	-.93832E-01	.63537	-.13056	.60000	.78963
-.35145	.65625	.63315	-.79138E-01	.63600	-.10857	.60000	.78913
-.34509	.62500	.63485	-.64160E-01	.63666	-.86424E-01	.60000	.78866
-.33951	.59375	.63633	-.48715E-01	.63732	-.63926E-01	.60000	.78824
-.33490	.56250	.63756	-.32597E-01	.63797	-.40810E-01	.60000	.78787
-.33140	.53125	.63852	-.15560E-01	.63860	-.16749E-01	.60000	.78755
-.32917	.50000	.63917	.27048E-02	.63918	.86797E-02	.60000	.78729
-.32838	.46875	.63946	.22593E-01	.63971	.36020E-01	.60000	.78709
-.32916	.43750	.63932	.44627E-01	.64020	.65986E-01	.60000	.78695
-.33170	.40625	.63865	.69512E-01	.64064	.99533E-01	.60000	.78688
-.33620	.37500	.63726	.98217E-01	.64102	.13797	.60000	.78686
-.34247	.34546	.63503	.13010	.64133	.18044	.60000	.78690

Figure III.5 Example output (cont.)

DATA FOR A CONTOUR OF CONSTANT MACH NO. (NVAR=1)

VALUE= .80000 NTERM= 3
NPTS= 23 NSOLV= 23

Z	R	U	V	M*	THETA	M	P/PO
-.28306	1.0409	.81549	-.23222	.82664	-.26482	.80000	.65610
-.26264	1.0000	.81704	-.20154	.82622	-.23147	.80000	.65634
-.24765	.96875	.81812	-.18067	.82597	-.20842	.80000	.65648
-.23322	.93750	.81912	-.16175	.82578	-.18725	.80000	.65657
-.21939	.90625	.82006	-.14454	.82565	-.16778	.80000	.65662
-.20620	.87500	.82092	-.12886	.82556	-.14985	.80000	.65665
-.19370	.84375	.82171	-.11450	.82552	-.13329	.80000	.65664
-.18198	.81250	.82243	-.10132	.82552	-.11798	.80000	.65661
-.17110	.78125	.82309	-.89145E-01	.82555	-.10378	.80000	.65656
-.16115	.75000	.82368	-.77848E-01	.82561	-.90545E-01	.80000	.65649
-.15222	.71875	.82421	-.67286E-01	.82569	-.78153E-01	.80000	.65642
-.14440	.68750	.82468	-.57321E-01	.82578	-.66457E-01	.80000	.65634
-.13779	.65625	.82510	-.47808E-01	.82588	-.55301E-01	.80000	.65625
-.13248	.62500	.82546	-.38590E-01	.82598	-.44513E-01	.80000	.65616
-.12856	.59375	.82577	-.29492E-01	.82609	-.33892E-01	.80000	.65608
-.12614	.56250	.82603	-.20306E-01	.82619	-.23204E-01	.80000	.65599
-.12532	.53125	.82624	-.10784E-01	.82630	-.12161E-01	.80000	.65591
-.12620	.50000	.82639	-.61789E-03	.82639	-.41062E-03	.80000	.65584
-.12892	.46875	.82647	.10587E-01	.82648	.12501E-01	.80000	.65577
-.13359	.43750	.82646	.23346E-01	.82657	.27164E-01	.80000	.65570
-.14038	.40625	.82631	.38353E-01	.82665	.44370E-01	.80000	.65564
-.14945	.37500	.82597	.56564E-01	.82672	.65208E-01	.80000	.65559
-.15138	.36926	.82588	.60354E-01	.82673	.69541E-01	.80000	.65558

Figure III.5 Example output (cont.)

DATA FOR A CONTOUR OF CONSTANT MACH NO. (NVAR=1)

VALUE= 1.0000   NTERM= 3
NPTS= 23   NSOLV= 22

Z	R	U	V	M*	THETA	M	P/PO
-.11603	1.0068	.99823	-.10259	1.0000	-.10286	1.0000	.52828
-.11135	1.0000	.99835	-.98664E-01	1.0000	-.98923E-01	1.0000	.52828
-.90243E-01	.96875	.99882	-.82003E-01	1.0000	-.82180E-01	1.0000	.52828
-.70092E-01	.93750	.99918	-.67656E-01	1.0000	-.67773E-01	1.0000	.52828
-.50998E-01	.90625	.99945	-.55429E-01	1.0000	-.55480E-01	1.0000	.52828
-.33060E-01	.87500	.99963	-.45141E-01	1.0000	-.45157E-01	1.0000	.52828
-.16374E-01	.84375	.99977	-.36625E-01	1.0000	-.36613E-01	1.0000	.52828
-.10315E-02	.81250	.99985	-.29723E-01	1.0000	-.29693E-01	1.0000	.52827
.12876E-01	.78125	.99991	-.24283E-01	1.0000	-.24243E-01	1.0000	.52827
.25264E-01	.75000	.99994	-.20157E-01	1.0000	-.20114E-01	1.0000	.52827
.36055E-01	.71875	.99996	-.17202E-01	1.0000	-.17158E-01	1.0000	.52828
.45172E-01	.68750	.99997	-.15276E-01	1.0000	-.15233E-01	1.0000	.52828
.52540E-01	.65625	.99998	-.14234E-01	1.0000	-.14192E-01	1.0000	.52828
.58086E-01	.62500	.99998	-.13930E-01	1.0000	-.13890E-01	1.0000	.52828
.61730E-01	.59375	.99997	-.14206E-01	1.0000	-.14167E-01	1.0000	.52828
.63387E-01	.56250	.99996	-.14887E-01	1.0000	-.14851E-01	1.0000	.52828
.62963E-01	.53125	.99996	-.15768E-01	1.0000	-.15737E-01	1.0000	.52828
.60350E-01	.50000	.99995	-.16602E-01	1.0000	-.16579E-01	1.0000	.52828
.55420E-01	.46875	.99995	-.17068E-01	1.0000	-.17056E-01	1.0000	.52828
.48029E-01	.43750	.99995	-.16741E-01	1.0000	-.16743E-01	1.0000	.52828
.38005E-01	.40625	.99997	-.15035E-01	1.0000	-.15052E-01	1.0000	.52828
.25077E-01	.37484	.99999	-.11092E-01	1.0000	-.11118E-01	1.0000	.52827

Figure III.5 Example output (cont.)

DATA FOR A CONTOUR OF CONSTANT MACH NO. (NVAR=1)

VALUE= 1.2000 NTERM= 3
NPTS= 23 NSOLV= 22

Z	R	U	V	M*	THETA	M	P/PO
.26876E-01	1.0004	1.1606	.26660E-01	1.1607	.23949E-01	1.2000	.40979
.53524E-01	.96875	1.1602	.37715E-01	1.1604	.33627E-01	1.2000	.41007
.78617E-01	.93750	1.1597	.45741E-01	1.1601	.40545E-01	1.2000	.41034
.10239	.90625	1.1593	.51089E-01	1.1598	.45055E-01	1.2000	.41060
.12454	.87500	1.1589	.53965E-01	1.1596	.47371E-01	1.2000	.41085
.14512	.84375	1.1586	.54572E-01	1.1593	.47701E-01	1.2000	.41107
.16396	.81250	1.1584	.53108E-01	1.1591	.46239E-01	1.2000	.41127
.18097	.78125	1.1583	.49766E-01	1.1590	.43168E-01	1.2000	.41144
.19604	.75000	1.1582	.44729E-01	1.1589	.38656E-01	1.2000	.41157
.20909	.71875	1.1583	.38168E-01	1.1588	.32853E-01	1.2000	.41168
.22004	.68750	1.1583	.30240E-01	1.1587	.25894E-01	1.2000	.41174
.22881	.65625	1.1585	.21087E-01	1.1587	.17896E-01	1.2000	.41177
.23532	.62500	1.1586	.10837E-01	1.1587	.89581E-02	1.2000	.41177
.23949	.59375	1.1587	-.39599E-03	1.1588	-.83018E-03	1.2000	.41173
.24121	.56250	1.1588	-.12500E-01	1.1588	-.11387E-01	1.2000	.41166
.24037	.53125	1.1589	-.25361E-01	1.1589	-.22629E-01	1.2000	.41156
.23683	.50000	1.1589	-.38842E-01	1.1590	-.34454E-01	1.2000	.41143
.23043	.46875	1.1589	-.52759E-01	1.1592	-.46724E-01	1.2000	.41126
.22098	.43750	1.1588	-.66847E-01	1.1594	-.59230E-01	1.2000	.41106
.20825	.40625	1.1587	-.80701E-01	1.1596	-.71639E-01	1.2000	.41082
.19199	.37500	1.1587	-.93692E-01	1.1599	-.83421E-01	1.2000	.41054
.16677	.36626	1.1587	-.97046E-01	1.1600	-.86498E-01	1.2000	.41046

Figure III.5 Example output (cont.)

DATA FOR A CONTOUR OF CONSTANT MACH NO. (NVAR=1)

VALUE= 1.4000　　NTERM= 3
NPTS= 23　　NSOLV= 23

Z	R	U	V	M*	THETA	M	P/PO
.14570	1.0107	1.3069	.16560	1.3100	.13570	1.4000	.30156
.15661	1.0000	1.3063	.16775	1.3095	.13696	1.4000	.30197
.18768	.96875	1.3046	.17155	1.3084	.13862	1.4000	.30315
.21730	.93750	1.3031	.17161	1.3073	.13746	1.4000	.30432
.24532	.90625	1.3018	.16881	1.3062	.13377	1.4000	.30546
.27160	.87500	1.3008	.16280	1.3052	.12784	1.4000	.30653
.29598	.84375	1.3000	.15406	1.3044	.11991	1.4000	.30754
.31834	.81250	1.2996	.14285	1.3036	.11025	1.4000	.30845
.33857	.78125	1.2993	.12943	1.3029	.99069E-01	1.4000	.30926
.35656	.75000	1.2993	.11404	1.3024	.86563E-01	1.4000	.30995
.37221	.71875	1.2995	.96886E-01	1.3020	.72889E-01	1.4000	.31051
.38541	.68750	1.2998	.78138E-01	1.3017	.58171E-01	1.4000	.31095
.39608	.65625	1.3002	.57931E-01	1.3015	.42488E-01	1.4000	.31125
.40410	.62500	1.3007	.36356E-01	1.3014	.25880E-01	1.4000	.31142
.40937	.59375	1.3011	.13462E-01	1.3014	.83476E-02	1.4000	.31145
.41175	.56250	1.3015	-.10740E-01	1.3015	-.10149E-01	1.4000	.31133
.41108	.53125	1.3017	-.36268E-01	1.3017	-.29681E-01	1.4000	.31106
.40717	.50000	1.3018	-.63153E-01	1.3021	-.50344E-01	1.4000	.31063
.39980	.46875	1.3018	-.91415E-01	1.3026	-.72239E-01	1.4000	.31004
.38869	.43750	1.3016	-.12102	1.3032	-.95443E-01	1.4000	.30926
.37356	.40625	1.3012	-.15181	1.3040	-.11996	1.4000	.30829
.35404	.37500	1.3008	-.18345	1.3050	-.14566	1.4000	.30710
.33264	.34714	1.3006	-.21180	1.3061	-.16922	1.4000	.30587

Figure III.5 Example output (cont.)

SUPERSONIC STARTING LINE DATA--CONSTANT MACH NUMBER CONTOUR

NPTS= 22 NSOLV= 22
NTERM= 3

Z	R	U	V	M*	THETA	M	P/PO
-.25825E-05	1.0000	1.1292	.15905E-05	1.1292	.14268E-05	1.1596	.4329[illegible]
.25328E-01	.96875	1.1290	.12192E-01	1.1290	.11067E-01	1.1596	.43310
.49463E-01	.93750	1.1287	.21621E-01	1.1288	.19552E-01	1.1596	.43327
.72275E-01	.90625	1.1284	.28491E-01	1.1286	.25671E-01	1.1596	.43344
.93644E-01	.87500	1.1282	.32998E-01	1.1284	.29631E-01	1.1596	.43360
.11345	.84375	1.1280	.35336E-01	1.1283	.31628E-01	1.1596	.43374
.13159	.81250	1.1278	.35692E-01	1.1282	.31850E-01	1.1596	.43387
.14795	.78125	1.1277	.34249E-01	1.1280	.30474E-01	1.1596	.43398
.16246	.75000	1.1276	.31181E-01	1.1280	.27661E-01	1.1596	.43406
.17503	.71875	1.1276	.26652E-01	1.1279	.23564E-01	1.1596	.43412
.18557	.68750	1.1277	.20816E-01	1.1279	.18318E-01	1.1596	.43416
.19402	.65625	1.1277	.13817E-01	1.1279	.12047E-01	1.1596	.43417
.20029	.62500	1.1278	.57855E-02	1.1279	.48611E-02	1.1596	.43417
.20430	.59375	1.1279	-.31510E-02	1.1279	-.31342E-02	1.1596	.43414
.20595	.56250	1.1280	-.12867E-01	1.1280	-.11836E-01	1.1596	.43409
.20514	.53125	1.1280	-.23224E-01	1.1280	-.21134E-01	1.1596	.43402
.20174	.50000	1.1280	-.34061E-01	1.1281	-.30893E-01	1.1596	.43393
.19559	.46875	1.1280	-.45160E-01	1.1282	-.40935E-01	1.1596	.43382
.18652	.43750	1.1279	-.56219E-01	1.1284	-.51000E-01	1.1596	.43369
.17431	.40625	1.1279	-.66789E-01	1.1285	-.60700E-01	1.1596	.43353
.15872	.37500	1.1279	-.76196E-01	1.1287	-.69435E-01	1.1596	.43334
.15530	.36896	1.1279	-.77800E-01	1.1288	-.70941E-01	1.1596	.43331

Figure III.5 Example output (cont.)

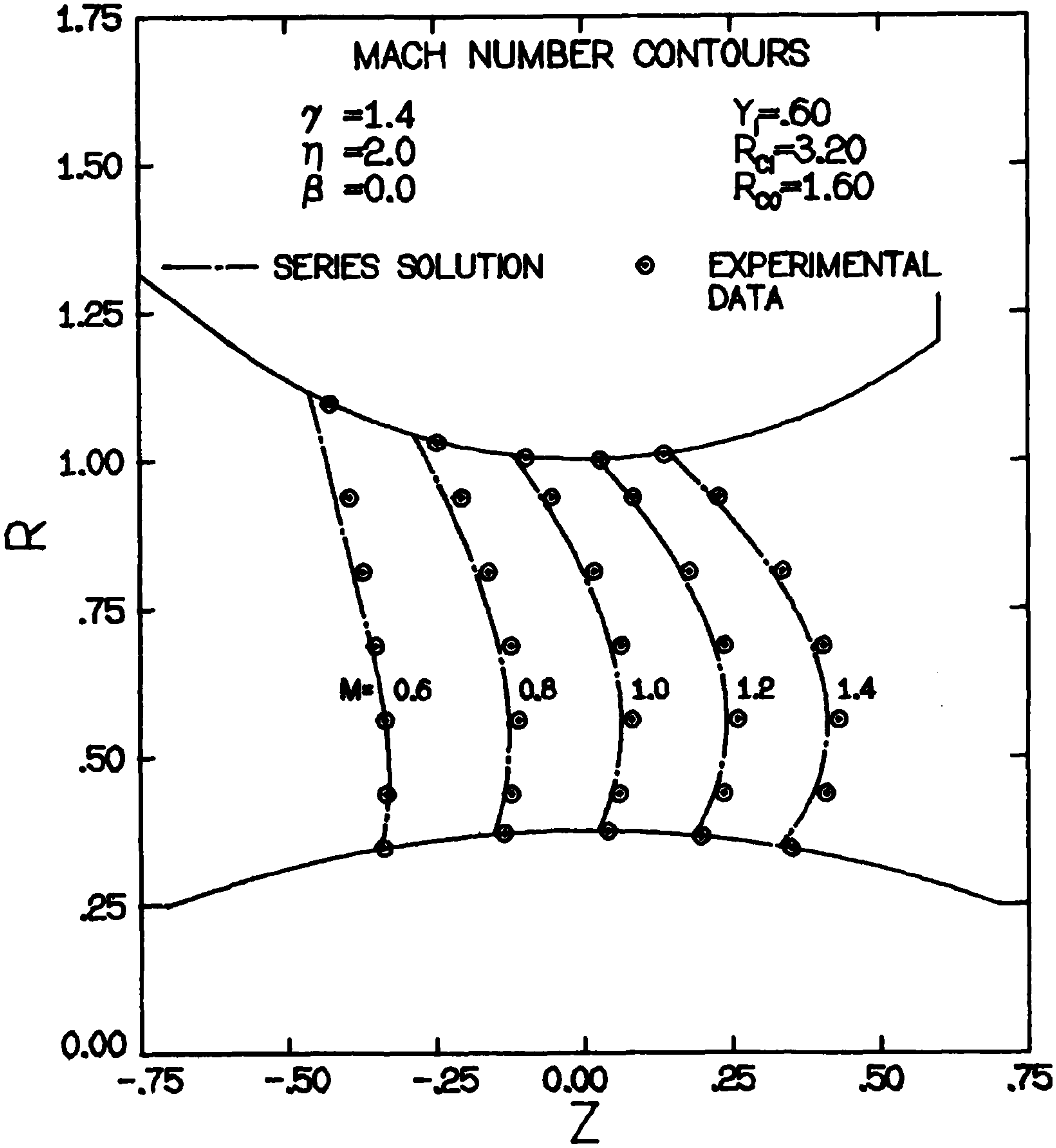

Figure III.6 Comparison of constant Mach number contours from series expansion solution with experimental data for annular nozzle with centerbody center of curvature along Z = 0 plane; $Re_{2d} = 1.96 \times 10^6$ for experiments

Table III.1 Roundoff Error Investigation

(a) Approximate values of y_i at which roundoff error† affects solutions for perturbation velocity components:

	Single Precision	Double Precision
First Order $\{u_1, v_1\}$	3000	$\sim 10^7$
Second Order $\{u_2, v_2\}$	60	30,000
Third Order $\{u_3, v_3\}$	15	1000

(b) Approximate values of y_i at which roundoff error† affects solutions for discharge coefficient constants:

	Single Precision	Double Precision
First Order $\{C_{D1}\}$	120	50,000
Second Order $\{C_{D2}\}$	20	1500
Third Order $\{C_{D3}\}$	10	250

†On the University of Illinois CDC Cyber 175 digital computer

IV. CONCLUSIONS

A FORTRAN computer program, TRANNOZ, has been developed to analyze the transonic throat flowfields in annular, planar, and axisymmetric supersonic nozzles. The program evaluates the series expansion solution developed by Dutton and Addy in [11]. Among its capabilities are options to find contours of constant Mach number, M*, or static-to-stagnation pressure, to calculate an accurate initial value line for starting method-of-characteristics or finite difference calculations, and to determine flowfield quantities along various planes in the nozzle throat. Major features of TRANNOZ are its numerical speed and reliability so that computations can be carried out easily and routinely.

The functioning of the various subroutines in the code has been described together with the definitions of the input and output variables, detailed input instructions, and an example input file with the corresponding output. A brief description of the theory upon which the solution is based has also been included.

As a result of the characteristics described above, it is felt that the TRANNOZ program provides an efficient means for obtaining approximate solutions for the flowfields in the throat regions of a variety of supersonic nozzles of interest.

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APPENDIX. TRANNOZ PROGRAM LISTING

TRANNOZ CODE...PROGRAM MAIN

```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C                            WRITTEN BY:
C                            J.C. DUTTON
C         DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING
C             UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
C                       URBANA, ILLINOIS  61801
C                            FEBRUARY 1980
C
C...PROGRAM MAIN IS THE MAIN PROGRAM IN THE TRANNOZ CODE FOR ANA-
C...LYZING TRANSONIC FLOW IN THE THROAT REGION OF ANNULAR, AXI-
C...SYMMETRIC, AND PLANAR SUPERSONIC NOZZLES.  THE SERIES SOLUTION
C...DEVELOPED BY DUTTON (PH.D. THESIS, UNIVERSITY OF ILLINOIS
C...AT URBANA-CHAMPAIGN, 1979) IS USED TO EVALUATE THE FLOWFIELD
C...VARIABLES OF INTEREST.  THE MAIN PROGRAM SIMPLY READS THE
C...INPUT PARAMETERS, CALLS SUBROUTINES ARRIN, DISCO, CONTOUR,
C...STLINE, XPLANE, AND ZPLANE FOR INITIALIZING AND CALCULATING
C...THE DESIRED FLOWFIELD QUANTITIES, AND WRITES THE RESULTS.
C
C...THE INPUT VARIABLES FROM FILE INPUT ARE AS FOLLOWS.
C...FIRST FROM NAMELIST PARAM:
C
C...   NGEOM---AN INTEGER VARIABLE DESCRIBING THE NOZZLE GEOMETRY.
C...           IF NGEOM=1, BOTH THE INNER AND OUTER BOUNDARIES
C...           ARE CIRCULAR ARCS IN THE MERIDIONAL PLANE.  IF
C...           NGEOM=2, THE INNER BOUNDARY IS A STRAIGHT LINE AND
C...           THE OUTER BOUNDARY IS A CIRCULAR ARC.  IF NGEOM=3,
C...           THE INNER BOUNDARY IS A CIRCULAR ARC AND THE OUTER
C...           BOUNDARY IS A STRAIGHT LINE (DEFAULT=1)
C...   AI------Z COORDINATE OF THE CENTER OF CURVATURE OF THE INNER
C...           BOUNDARY FOR A CIRCULAR ARC (NGEOM=1 OR 3) OR SLOPE
C...           OF THE INNER BOUNDARY FOR A STRAIGHT LINE (NGEOM=2)
C...   BI------R COORDINATE OF THE CENTER OF CURVATURE OF THE INNER
C...           BOUNDARY FOR A CIRCULAR ARC (NGEOM=1 OR 3) OR
C...           INTERCEPT OF THE INNER BOUNDARY FOR A STRAIGHT LINE
C...           (NGEOM=2)
C...   RCI-----RADIUS OF THE INNER BOUNDARY FOR A CIRCULAR ARC
C...           (NGEOM=1 OR 3)
C...   AO------Z COORDINATE OF THE CENTER OF CURVATURE OF THE OUTER
C...           BOUNDARY FOR A CIRCULAR ARC (NGEOM=1 OR 2) OR SLOPE
C...           OF THE OUTER BOUNDARY FOR A STRAIGHT LINE (NGEOM=3)
C...   BO------R COORDINATE OF THE CENTER OF CURVATURE OF THE OUTER
C...           BOUNDARY FOR A CIRCULAR ARC (NGEOM=1 OR 2) OR
C...           INTERCEPT OF THE OUTER BOUNDARY FOR A STRAIGHT LINE
C...           (NGEOM=3)
C...   RCO-----RADIUS OF THE OUTER BOUNDARY FOR A CIRCULAR ARC
C...           (NGEOM=1 OR 2)
C...   ZIMIN---MINIMUM Z COORDINATE ON THE INNER BOUNDARY FOR
C...           ESTABLISHING THE THROAT "WINDOW"
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
C...  ZIMAX---MAXIMUM Z COORDINATE ON THE INNER BOUNDARY FOR
C...          ESTABLISHING THE THROAT "WINDOW"
C...  ZOMIN---MINIMUM Z COORDINATE ON THE OUTER BOUNDARY FOR
C...          ESTABLISHING THE THROAT "WINDOW"
C...  ZOMAX---MAXIMUM Z COORDINATE ON THE OUTER BOUNDARY FOR
C...          ESTABLISHING THE THROAT "WINDOW"
C...  G-------SPECIFIC HEAT RATIO OF THE GAS  (DEFAULT=1.4)
C...  ETA-----PARAMETER IN THE EXPANSION VARIABLE  (DEFAULT=2.0)
C...  NTERM---NUMBER OF TERMS FROM THE EXPANSION SOLUTION TO BE
C...          USED IN EVALUATING THE NOZZLE DISCHARGE COEFFICIENT
C...          (DEFAULT=3)
C
C...FROM NAMELIST CONTROL:
C
C...  NCONT---NUMBER OF CONTOURS OF CONSTANT MACH NUMBER, MSTAR,
C...          OR P/PO TO BE FOUND  (DEFAULT=0)
C...  START---LOGICAL VARIABLE WHICH IF .TRUE. CAUSES A SUPERSONIC
C...          STARTING LINE FOR METHOD-OF-CHARACTERISTICS (OR
C...          OTHER) CALCULATIONS TO BE FOUND  (DEFAULT=.FALSE.)
C...  NXPL----NUMBER OF PLANES OF CONSTANT X COORDINATE ALONG
C...          WHICH FLOWFIELD QUANTITIES ARE TO BE FOUND
C...          (DEFAULT=0)
C...  NZPL----NUMBER OF PLANES OF CONSTANT Z COORDINATE ALONG
C...          WHICH FLOWFIELD QUANTITIES ARE TO BE FOUND
C...          (DEFAULT=0)
C
C...FROM NAMELIST NAMECON:
C
C...  NVAR----AN INTEGER VARIABLE WHICH DETERMINES WHICH DEPENDENT
C...          VARIABLE IS CONSTANT ALONG THE DESIRED CONTOUR.  FOR
C...          NVAR=1, THE DEPENDENT VARIABLE IS MACH NUMBER, WHILE
C...          FOR NVAR=2 IT IS MSTAR, AND FOR NVAR=3 IT IS P/PO.
C...          (DEFAULT=1)
C...  VALUE---THE VALUE OF THE DEPENDENT VARIABLE ALONG THE DESIRED
C...          CONTOUR
C...  NPTS----THE NUMBER OF POINTS TO BE FOUND ALONG THE DESIRED
C...          CONTOUR  (MIN.=4; MAX.=53)
C...  NTERM---NUMBER OF TERMS FROM THE EXPANSION SOLUTION TO BE
C...          USED IN FINDING THE CONTOUR
C
C...FROM NAMELIST NAMEST:
C
C...  NPTS----NUMBER OF POINTS TO BE FOUND ALONG THE SUPERSONIC
C...          STARTING LINE  (MIN.=4; MAX.=53)
C...  NTERM---NUMBER OF TERMS FROM THE EXPANSION SOLUTION TO BE
C...          USED IN DETERMINING FLOWFIELD QUANTITIES ALONG THE
C...          STARTING LINE
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
C
C...FROM NAMELIST NAMEXPL:
C
C...   X-------X COORDINATE OF THE PLANE ALONG WHICH FLOWFIELD
C...           QUANTITIES ARE TO BE FOUND
C...   NPTS----NUMBER OF POINTS ALONG THE CONSTANT X PLANE AT WHICH
C...           FLOWFIELD QUANTITIES ARE TO BE FOUND  (MIN.=2;
C...           MAX.=51)
C...   NTERM---NUMBER OF TERMS FROM THE EXPANSION SOLUTION TO BE
C...           USED IN FINDING QUANTITIES ALONG THE X=CONSTANT
C...           PLANE
C
C...FROM NAMELIST NAMEZPL:
C
C...   Z-------Z COORDINATE OF THE PLANE ALONG WHICH FLOWFIELD
C...           QUANTITIES ARE TO BE FOUND
C...   NPTS----NUMBER OF POINTS ALONG THE CONSTANT Z PLANE AT WHICH
C...           FLOWFIELD QUANTITIES ARE TO BE FOUND  (MIN.=2;
C...           MAX.=51)
C...   NTERM---NUMBER OF TERMS FROM THE EXPANSION SOLUTION TO BE
C...           USED IN FINDING QUANTITIES ALONG THE Z=CONSTANT
C...           PLANE
C
C...THE INPUT FILE IS CONSTRUCTED AS FOLLOWS.  THE FIRST CARD IS A
C...TITLE CARD (MAXIMUM OF 80 CHARACTERS) TO BE USED FOR IDENT-
C...IFICATION PURPOSES.  ANY MESSAGE MAY BE USED AND THIS MESSAGE
C...IS THE FIRST LINE ON THE OUTPUT.  THIS CARD IS FOLLOWED BY
C...CARDS CONTAINING NAMELIST PARAM AND NAMELIST CONTROL, RESPEC-
C...TIVELY.  THESE TWO NAMELISTS MUST ALWAYS APPEAR IN THE INPUT
C...DECK.  THE REMAINING CARDS IN THE INPUT FILE CONTAIN, IN ORDER,
C...NAMELISTS NAMECON, NAMEST, NAMEXPL, AND NAMEZPL, ALTHOUGH
C...SOME OF THESE NAMELISTS MAY BE REPEATED AND SOME MAY NOT
C...APPEAR AT ALL.  NAMELIST NAMECON IS REPEATED NCONT TIMES;
C...NAMELIST NAMEST APPEARS ONLY IF START=.TRUE.; NAMELIST NAMEXPL
C...IS REPEATED NXPL TIMES; AND NAMELIST NAMEZPL IS REPEATED NZPL
C...TIMES.  SINCE NCONT, NXPL, AND NZPL MAY BE ZERO, NAMELISTS
C...NAMECON, NAMEXPL, AND NAMEZPL DO NOT NECESSARILY APPEAR IN THE
C...INPUT FILE.  ANY NUMBER OF PROBLEMS CAN BE SOLVED WITH A SINGLE
C...INPUT FILE BY REPEATING THE SEQUENCE DESCRIBED ABOVE.  IT IS
C...IMPORTANT TO NOTE, HOWEVER, THAT THE DEFAULT VALUES ARE RESET
C...AT THE BEGINNING OF EACH NEW PROBLEM.
C
C...THE FIRST PAGE OF OUTPUT CONSISTS OF THE TITLE CARD, A LISTING
C...OF THE PARAMETERS FROM INPUT NAMELISTS PARAM AND CONTROL, AS
C...WELL AS THE FOLLOWING VARIABLES DESCRIBING THE THROAT GEOMETRY:
C
C...   ZI------Z COORDINATE OF THE THROAT AT THE INNER BOUNDARY
C...   RI------R COORDINATE OF THE THROAT AT THE INNER BOUNDARY
C...   ZO------Z COORDINATE OF THE THROAT AT THE OUTER BOUNDARY
C...   RO------R COORDINATE OF THE THROAT AT THE OUTER BOUNDARY
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
C...   ASTAR---THROAT AREA                                          MAI1470
C...   D-------SEPARATION DISTANCE BETWEEN THE INNER AND OUTER THROAT MAI1480
C...           WALL LOCATIONS IN THE Z-R COORDINATE SYSTEM          MAI1490
C...   BETA----ANGLE OF INCLINATION OF THE ROTATED X-AXIS FROM THE  MAI1500
C...           Z-AXIS OF SYMMETRY  (POSITIVE COUNTERCLOCKWISE)      MAI1510
C...   YI------Y COORDINATE OF THE THROAT AT THE INNER BOUNDARY     MAI1520
C...   YO------Y COORDINATE OF THE THROAT AT THE OUTER BOUNDARY     MAI1530
C...   EPS-----VALUE OF THE EXPANSION VARIABLE                      MAI1540
C...   CD------NOZZLE DISCHARGE COEFFICIENT                         MAI1550
C                                                                   MAI1560
C...THE REMAINING PAGES OF OUTPUT CONSIST OF LISTINGS OF THE PARA-  MAI1570
C...METERS FROM THE OPTIONAL INPUT NAMELISTS NAMECON, NAMEST,       MAI1580
C...NAMEXPL, NAMEZPL, AS USED, TOGETHER WITH THE FOLLOWING VARI-    MAI1590
C...ABLES ALONG THE CONTOUR OR PLANE:                               MAI1600
C                                                                   MAI1610
C...   Z-------AXIAL COORDINATE OF THE CONTOUR POINT                MAI1620
C...   R-------RADIAL COORDINATE OF THE CONTOUR POINT OR OF THE     MAI1630
C...           POINT ON THE Z=CONSTANT PLANE                        MAI1640
C...   Y-------ROTATED RADIAL COORDINATE OF THE POINT ON THE X=     MAI1650
C...           CONSTANT PLANE  (THE Y-AXIS LIES ALONG THE THROAT    MAI1660
C...           PLANE AND THE X-AXIS IS PERPENDICULAR TO IT SUCH     MAI1670
C...           THAT THE ORIGIN LIES ON THE Z-AXIS OF SYMMETRY.      MAI1680
C...           THE X AND Y COORDINATES ARE NON-DIMENSIONALIZED WITH MAI1690
C...           RESPECT TO THE THROAT SEPARATION DISTANCE, D.)       MAI1700
C...   U-------COMPONENT OF VELOCITY PARALLEL TO THE X-AXIS NON-    MAI1710
C...           DIMENSIONALIZED WITH RESPECT TO THE CRITICAL SPEED   MAI1720
C...           OF SOUND                                             MAI1730
C...   V-------COMPONENT OF VELOCITY PARALLEL TO THE Y-AXIS NON-    MAI1740
C...           DIMENSIONALIZED WITH RESPECT TO THE CRITICAL SPEED   MAI1750
C...           OF SOUND                                             MAI1760
C...   M*------DIMENSIONLESS RATIO OF THE SPEED AT A POINT TO THE   MAI1770
C...           CRITICAL SPEED OF SOUND                              MAI1780
C...   THETA---ANGLE OF INCLINATION OF THE VELOCITY VECTOR FROM     MAI1790
C...           THE X-AXIS, THETA=ARCTAN(V/U)  (POSITIVE COUNTER-    MAI1800
C...           CLOCKWISE)                                           MAI1810
C...   M-------MACH NUMBER=DIMENSIONLESS RATIO OF THE SPEED AT A    MAI1820
C...           POINT TO THE SPEED OF SOUND AT THAT POINT            MAI1830
C...   P/PO----STATIC-TO-STAGNATION PRESSURE RATIO AT A POINT       MAI1840
C                                                                   MAI1850
C...ON INPUT THE DIMENSIONAL VARIABLES ARE AI,BI,RCI,AO,BO,         MAI1860
C...RCO,ZIMIN,ZIMAX,ZOMIN,ZOMAX, AND Z WHICH ALL HAVE DIMENSIONS    MAI1870
C...OF LENGTH.  THE UNITS USED FOR THESE INPUT PARAMETERS MUST      MAI1880
C...BE CONSISTENT AND ARE SIMPLY THE UNITS OF THE Z-R COORDINATE    MAI1890
C...SYSTEM.  ON OUTPUT THESE VARIABLES TOGETHER WITH ZI,RI,ZO,      MAI1900
C...RO, AND D WILL HAVE THE SAME UNITS AND ASTAR WILL HAVE THIS     MAI1910
C...UNIT SQUARED.                                                   MAI1920
C                                                                   MAI1930
      REAL MSCONT,MCONT,MSXPL,MXPL,MSZPL,MZPL                       MAI1940
      LOGICAL START                                                 MAI1950
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
      COMMON/BLKIN/G,ETA,ZIMIN,ZIMAX,ZOMIN,ZOMAX/BLKCIRC/NGEOM,
     $AI,BI,RCI,AO,BO,RCO/BLKGEOM/RI,ZI,RO,ZO,ASTAR,D,ZSTAR,BETA,
     $H1P,G1P,H2P,G2P/BLKPARM/YI,YO,EPS,H1,G1,H2,G2,BETA1
     $/BLKCONT/NSOLV,RCONT(53),ZCONT(53),UCONT(53),VCONT(53),
     $MSCONT(53),THCONT(53),MCONT(53),PPOCONT(53)/BLKXPL/YXPL(51),
     $UXPL(51),VXPL(51),MSXPL(51),THXPL(51),MXPL(51),PPOXPL(51),
     $U1XPL(51),V1XPL(51),U2XPL(51),V2XPL(51),U3XPL(51),V3XPL(51)
     $/BLKZPL/RZPL(51),UZPL(51),VZPL(51),MSZPL(51),THZPL(51),
     $MZPL(51),PPOZPL(51),U1ZPL(51),V1ZPL(51),U2ZPL(51),V2ZPL(51),
     $U3ZPL(51),V3ZPL(51)/BLKCALL/ICALL1,ICALL2,ICALL3
      DIMENSION TITLE(8)
      NAMELIST/PARAM/NGEOM,AI,BI,RCI,AO,BO,RCO,ZIMIN,ZIMAX,ZOMIN,
     $ZOMAX,G,ETA,NTERM/CONTROL/NCONT,START,NXPL,NZPL/NAMECON/
     $NVAR,VALUE,NPTS,NTERM/NAMEST/NPTS,NTERM/NAMEXPL/X,NPTS,
     $NTERM/NAMEZPL/Z,NPTS,NTERM
C
C...SET DEFAULT VALUES:
C
 10   NGEOM=1    $    G=1.4    $    ETA=2.0
      NTERM=3    $    NCONT=0    $    START=.FALSE.
      NXPL=0    $    NZPL=0    $    NVAR=1
      ICALL1=0    $    ICALL2=0    $    ICALL3=0
C
C...READ AND WRITE THE TITLE AND READ AND WRITE THE INPUT PARA-
C...METERS FROM NAMELISTS PARAM AND CONTROL:
C
      READ(5,900) (TITLE(I),I=1,8)
      IF(EOF(5)) 170,20
 20   WRITE(6,901) (TITLE(I),I=1,8)
      READ(5,PARAM)
      WRITE(6,902) NGEOM
      GO TO(30,40,50),NGEOM
 30   WRITE(6,903) AI,BI,RCI
      WRITE(6,904) AO,BO,RCO
      GO TO 60
 40   WRITE(6,905) AI,BI
      WRITE(6,904) AO,BO,RCO
      GO TO 60
 50   WRITE(6,903) AI,BI,RCI
      WRITE(6,906) AO,BO
 60   WRITE(6,907) ZIMIN,ZIMAX,ZOMIN,ZOMAX
      WRITE(6,908) G,ETA,NTERM
      READ(5,CONTROL)
      WRITE(6,909) NCONT,START,NXPL,NZPL
C
C...CALL SUBROUTINE ARMIN TO LOCATE THE THROAT PLANE AND CALCULATE
C...AND WRITE SOME INITIAL PARAMETERS:
C
      CALL ARMIN
      WRITE(6,910) ZI,RI,ZO,RO
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
      WRITE(6,911) ASTAR,D,BETA                                        MAI2460
      WRITE(6,912) YI,YO,EPS                                           MAI2470
C                                                                      MAI2480
C...CALL SUBROUTINE DISCO TO CALCULATE THE DISCHARGE COEFFICIENT        MAI2490
C...AND WRITE IT:                                                      MAI2500
C                                                                      MAI2510
      CALL DISCO(NTERM,FLOWCO)                                         MAI2520
      WRITE(6,913) FLOWCO                                              MAI2530
C                                                                      MAI2540
C...READ, CALCULATE, AND WRITE CONTOUR DATA:                           MAI2550
C                                                                      MAI2560
      IF(NCONT .EQ. 0) GO TO 120                                       MAI2570
      DO 110 J=1,NCONT                                                 MAI2580
      READ(5,NAMECON)                                                  MAI2590
      GO TO(70,80,90),NVAR                                             MAI2600
 70   VARIAB="MACH NO."   $   GO TO 100                                MAI2610
 80   VARIAB="MSTAR"   $   GO TO 100                                   MAI2620
 90   VARIAB="P/PO"                                                    MAI2630
 100  CALL CONTOUR(NVAR,VALUE,NPTS,NTERM)                              MAI2640
      WRITE(6,914) VARIAB,NVAR,VALUE,NTERM,NPTS,NSOLV                  MAI2650
      LIM=23                                                           MAI2660
      IF(NSOLV .LE. 23) LIM=NSOLV                                      MAI2670
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),     MAI2680
     $THCONT(I),MCONT(I),PPOCONT(I),I=1,LIM)                           MAI2690
      IF(LIM .EQ. NSOLV) GO TO 110                                     MAI2700
      LIM=49                                                           MAI2710
      IF((NSOLV-23) .LE. 26) LIM=NSOLV                                 MAI2720
      WRITE(6,916)                                                     MAI2730
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),     MAI2740
     $THCONT(I),MCONT(I),PPOCONT(I),I=24,LIM)                          MAI2750
      IF(LIM .EQ. NSOLV) GO TO 110                                     MAI2760
      WRITE(6,916)                                                     MAI2770
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),     MAI2780
     $THCONT(I),MCONT(I),PPOCONT(I),I=50,NSOLV)                        MAI2790
 110  CONTINUE                                                         MAI2800
C                                                                      MAI2810
C...READ, CALCULATE, AND WRITE STARTING LINE DATA:                     MAI2820
C                                                                      MAI2830
 120  IF(.NOT.(START)) GO TO 130                                       MAI2840
      READ(5,NAMEST)                                                   MAI2850
      CALL STLINE(NPTS,NTERM)                                          MAI2860
      WRITE(6,917) NPTS,NSOLV,NTERM                                    MAI2870
      LIM=23                                                           MAI2880
      IF(NSOLV .LE. 23) LIM=NSOLV                                      MAI2890
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),     MAI2900
     $THCONT(I),MCONT(I),PPOCONT(I),I=1,LIM)                           MAI2910
      IF(LIM .EQ. NSOLV) GO TO 130                                     MAI2920
      LIM=49                                                           MAI2930
      IF((NSOLV-23) .LE. 26) LIM=NSOLV                                 MAI2940
      WRITE(6,916)                                                     MAI2950
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),
     $THCONT(I),MCONT(I),PPOCONT(I),I=24,LIM)
      IF(LIM .EQ. NSOLV) GO TO 130
      WRITE(6,916)
      WRITE(6,915) (ZCONT(I),RCONT(I),UCONT(I),VCONT(I),MSCONT(I),
     $THCONT(I),MCONT(I),PPOCONT(I),I=50,NSOLV)
C
C...READ, CALCULATE, AND WRITE DATA ALONG PLANES OF CONSTANT X
C...COORDINATE:
C
 130  IF(NXPL .EQ. 0) GO TO 150
      DO 140 K=1,NXPL
      READ(5,NAMEXPL)
      CALL XPLANE(X,NPTS,NTERM)
      WRITE(6,918) X,NPTS,NTERM
      LIM=23
      IF(NPTS .LE. 23) LIM=NPTS
      WRITE(6,919) (YXPL(I),UXPL(I),VXPL(I),MSXPL(I),THXPL(I),
     $MXPL(I),PPOXPL(I),I=1,LIM)
      IF(LIM .EQ. NPTS) GO TO 140
      LIM=49
      IF((NPTS-23) .LE. 26) LIM=NPTS
      WRITE(6,916)
      WRITE(6,919) (YXPL(I),UXPL(I),VXPL(I),MSXPL(I),THXPL(I),
     $MXPL(I),PPOXPL(I),I=24,LIM)
      IF(LIM .EQ. NPTS) GO TO 140
      WRITE(6,916)
      WRITE(6,919) (YXPL(I),UXPL(I),VXPL(I),MSXPL(I),THXPL(I),
     $MXPL(I),PPOXPL(I),I=50,NPTS)
 140  CONTINUE
C
C...READ, CALCULATE, AND WRITE DATA ALONG PLANES OF CONSTANT Z
C...COORDINATE:
C
 150  IF(NZPL .EQ. 0) GO TO 10
      DO 160 L=1,NZPL
      READ(5,NAMEZPL)
      CALL ZPLANE(Z,NPTS,NTERM)
      WRITE(6,920) Z,NPTS,NTERM
      LIM=23
      IF(NPTS .LE. 23) LIM=NPTS
      WRITE(6,921) (RZPL(I),UZPL(I),VZPL(I),MSZPL(I),THZPL(I),
     $MZPL(I),PPOZPL(I),I=1,LIM)
      IF(LIM .EQ. NPTS) GO TO 160
      LIM=49
      IF((NPTS-23) .LE. 26) LIM=NPTS
      WRITE(6,916)
      WRITE(6,921) (RZPL(I),UZPL(I),VZPL(I),MSZPL(I),THZPL(I),
     $MZPL(I),PPOZPL(I),I=24,LIM)
      IF(LIM .EQ. NPTS) GO TO 160
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
      WRITE(6,916)
      WRITE(6,921) (RZPL(I),UZPL(I),VZPL(I),MSZPL(I),THZPL(I),
     $MZPL(I),PPOZPL(I),I=50,NPTS)
 160  CONTINUE
      GO TO 10
C
C...FORMAT STATEMENTS:
C
 900  FORMAT(8A10)
 901  FORMAT(1H1,///,20X,"RESULTS FROM THE TRANNOZ CODE FOR ANALY",
     $"ZING NOZZLE THROAT FLOWS--BY J.C. DUTTON",//,25X,8A10,//)
 902  FORMAT(20X,"THE GEOMETRY, NGEOM=",I1,", IS A SUPERSONIC ",
     $"NOZZLE WITH:",/)
 903  FORMAT(25X,"A CIRCULAR ARC INNER BOUNDARY SUCH THAT IN ",
     $"THE MERIDIONAL PLANE:",//,25X,"AI=ZCENTER=",G11.5,5X,
     $"BI=RCENTER=",G11.5,5X,"RCI=RADIUS=",G11.5,/)
 904  FORMAT(25X,"A CIRCULAR ARC OUTER BOUNDARY SUCH THAT IN ",
     $"THE MERIDIONAL PLANE:",//,25X,"AO=ZCENTER=",G11.5,5X,
     $"BO=RCENTER=",G11.5,5X,"RCO=RADIUS=",G11.5,//)
 905  FORMAT(25X,"A STRAIGHT INNER BOUNDARY SUCH THAT IN THE ",
     $"MERIDIONAL PLANE:",//,25X,"AI=SLOPE=",G11.5,7X,"BI=",
     $"INTERCEPT=",G11.5,/)
 906  FORMAT(25X,"A STRAIGHT OUTER BOUNDARY SUCH THAT IN THE ",
     $"MERIDIONAL PLANE:",//,25X,"AO=SLOPE=",G11.5,7X,"BO=",
     $"INTERCEPT=",G11.5,//)
 907  FORMAT(20X,"THE WINDOW FOR THE THROAT PLANE AND CONTOUR ",
     $"SEARCHES IS SET BY:",//,25X,"ZIMIN=",G11.5,10X,"ZIMAX=",
     $G11.5,/,25X,"ZOMIN=",G11.5,10X,"ZOMAX=",G11.5,//)
 908  FORMAT(20X,"THE VALUES OF OTHER, NON-GEOMETRICAL PARAME",
     $"TERS ARE:",//,25X,"G=GAMMA=",G11.5,8X,"ETA=",G11.5,12X,
     $"NTERM=",I2,//)
 909  FORMAT(20X,"THE VALUES OF THE CONTROL VARIABLES ARE:",//,
     $25X,"NCONT=",I2,19X,"START=",L2,/,25X,"NXPL=",I2,20X,
     $"NZPL=",I2,//)
 910  FORMAT(20X,"THE INNER AND OUTER WALL THROAT LOCATIONS ARE:",
     $//,25X,"ZI=",G11.5,13X,"RI=",G11.5,/,25X,"ZO=",G11.5,13X,
     $"RO=",G11.5,//)
 911  FORMAT(20X,"THE THROAT AREA, INNER WALL-TO-OUTER WALL ",
     $"THROAT SEPARATION DISTANCE,",/,20X,"AND ANGLE OF INCLINA",
     $"TION OF THE X-AXIS FROM THE Z-AXIS ARE:",//,25X,"ASTAR=",
     $G11.5,10X,"D=",G11.5,14X,"BETA=",G11.5,//)
 912  FORMAT(20X,"THE Y-COORDINATES OF THE INNER AND OUTER WALL ",
     $"THROAT LOCATIONS AND THE",/,20X,"VALUE OF THE EXPANSION ",
     $"PARAMETER ARE:",//,25X,"YI=",G11.5,13X,"YO=",G11.5,13X,
     $"EPS=",G11.5,//)
 913  FORMAT(20X,"THE VALUE OF THE NOZZLE DISCHARGE COEFFICIENT ",
     $"IS:",//,25X,"CD=",G11.5)
 914  FORMAT(1H1,////,42X,"DATA FOR A CONTOUR OF CONSTANT ",A8,
     $" (NVAR=",I1,")",//,51X,"VALUE=",G11.5,5X,"NTERM=",I2,/,
     $51X,"NPTS=",I3,14X,"NSOLV=",I3,//)
```

TRANNOZ CODE...PROGRAM MAIN (CONT.)

```
915  FORMAT(16X,"Z",13X,"R",13X,"U",13X,"V",13X,"M*",10X,"THETA",        MA13960
    $11X,"M",12X,"P/PO",/,(/,8X,8(3X,G11.5)))                             MA13970
916  FORMAT(1H1,///)                                                      MA13980
917  FORMAT(1H1,////,36X,"SUPERSONIC STARTING LINE DATA--",               MA13990
    $"CONSTANT MACH NUMBER CONTOUR",//,51X,"NPTS=",I3,14X,                MA14000
    $"NSOLV=",I3,/,51X,"NTERM=",I2,//)                                    MA14010
918  FORMAT(1H1,////,41X,"FLOWFIELD DATA ALONG A CONSTANT X-",            MA14020
    $"COORDINATE PLANE",//,51X,"X=",G11.5,9X,"NPTS=",I3,/,51X,            MA14030
    $"NTERM=",I2,//)                                                      MA14040
919  FORMAT(17X,"Y",15X,"U",15X,"V",15X,"M*",12X,"THETA",13X,             MA14050
    $"M",14X,"P/PO",/,(/,7X,7(5X,G11.5)))                                 MA14060
920  FORMAT(1H1,////,41X,"FLOWFIELD DATA ALONG A CONSTANT Z-",            MA14070
    $"COORDINATE PLANE",//,51X,"Z=",G11.5,9X,"NPTS=",I3,/,51X,            MA14080
    $"NTERM=",I2,//)                                                      MA14090
921  FORMAT(17X,"R",15X,"U",15X,"V",15X,"M*",12X,"THETA",13X,             MA14100
    $"M",14X,"P/PO",/,(/,7X,7(5X,G11.5)))                                 MA14110
C                                                                         MA14120
 170 STOP                                                                 MA14130
     END                                                                  MA14140
```

TRANNOZ CODE...FUNCTION IBND

```
      REAL FUNCTION IBND(Z)
C
C...FUNCTION IBND(Z) IS THE EQUATION OF THE INNER WALL CONTOUR
C...IN CYLINDRICAL COORDINATES IN THE FORM R=IBND(Z).  IF
C...NGEOM=2, THE INNER BOUNDARY IS A STRAIGHT LINE IN THE MERIDI-
C...ONAL PLANE.  OTHERWISE, IT IS A CIRCULAR ARC.
C
      COMMON/BLKCIRC/NGEOM,AI,BI,RCI,AO,BO,RCO
      IF(NGEOM .EQ. 2) GO TO 10
      IBND=BI+SQRT(RCI*RCI-(Z-AI)*(Z-AI))
      RETURN
 10   IBND=AI*Z+BI
      RETURN
      END
```

TRANNOZ CODE...FUNCTION OBND

```
      FUNCTION OBND(Z)
C
C...FUNCTION OBND(Z) IS THE EQUATION OF THE OUTER WALL CONTOUR
C...IN CYLINDRICAL COORDINATES IN THE FORM R=OBND(Z).  IF
C...NGEOM=3, THE OUTER BOUNDARY IS A STRAIGHT LINE IN THE MERIDI-
C...ONAL PLANE.  OTHERWISE, IT IS A CIRCULAR ARC.
C
      COMMON/BLKCIRC/NGEOM,AI,BI,RCI,AO,BO,RCO
      IF(NGEOM .EQ. 3) GO TO 10
      OBND=BO-SQRT(RCO*RCO-(Z-AO)*(Z-AO))
      RETURN
 10   OBND=AO*Z+BO
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE ARMIN

```
      SUBROUTINE ARMIN
C
C...SUBROUTINE ARMIN FINDS THE MINIMUM AREA CROSS-SECTION FOR
C...ANNULAR AXISYMMETRIC, SUPERSONIC NOZZLES GIVEN THE EQUATIONS
C...FOR THE INNER AND OUTER BOUNDARIES, R=IBND(Z) AND R=OBND(Z),
C...RESPECTIVELY.  ONCE THE MINIMUM AREA SECTION HAS BEEN FOUND,
C...EVALUATION OF SOME INITIAL PARAMETERS IN THE X-Y COORDINATES
C...OF THE TRANSONIC ANALYSIS ARE CARRIED OUT.
C
      REAL IBND
      COMMON/BLKIN/G,ETA,ZIMIN,ZIMAX,ZOMIN,ZOMAX/BLKGEOM/RI,
     $ZI,RO,ZO,ASTAR,D,ZSTAR,BETA,H1P,G1P,H2P,G2P/BLKPARM/YI,YO,EPS,
     $H1,G1,H2,G2,BETA1
      DATA PI,DX,DY,TOLER/3.1415926535898,0.001,0.01,1.0E-10/
      FAREA(RI,ZI,RO,ZO)=PI*(RO+RI)*SQRT((ZO-ZI)**2+(RO-RI)**2)
      CONV(OLD,NEW)=ABS((NEW-OLD)/NEW)
C
C...EVALUATE SOME INITIAL CONSTANTS AND PARAMETERS
C
      ZI=ZIMIN   $   ZO=ZOMIN
      RI=IBND(ZI)   $   RO=OBND(ZO)
      ARIM1=FAREA(RI,ZI,RO,ZO)
C
C...FIND THE MINIMUM AREA SECTION BY ALTERNATELY PIVOTING ON POINTS
C...ON THE UPPER AND LOWER BOUNDARIES
C
      DO 170 I=1,200
      IF(2*(I/2)-I) 10,20,20
 10   ZL=ZIMIN   $   ZR=ZIMAX   $   GO TO 30
 20   ZL=ZOMIN   $   ZR=ZOMAX
 30   DO 120 J=1,20
      DZ=(ZR-ZL)/20.
      DO 100 K=1,21
      ZK=ZL+FLOAT(K-1)*DZ
      IF(2*(I/2)-I) 40,50,50
 40   ARK=FAREA(IBND(ZK),ZK,RO,ZO)   $   GO TO 60
 50   ARK=FAREA(RI,ZI,OBND(ZK),ZK)
 60   IF(K-2) 90,80,70
 70   IF(ARK .GT. ARKM1) GO TO 110
 80   ZKM2=ZKM1   $   ARKM2=ARKM1
 90   ZKM1=ZK     $   ARKM1=ARK
 100  CONTINUE
      IF(I .NE. 1) CALL ERROR("ARMIN",1)
 110  IF(AMAX1(CONV(ARKM2,ARKM1),CONV(ARKM1,ARK),CONV(ARKM2,ARK))
     $.LT. TOLER/10.) GO TO 130
      ZL=ZKM2   $   ZR=ZK
 120  CONTINUE
      CALL ERROR("ARMIN",2)
 130  IF(2*(I/2)-I) 140,150,150
 140  ZI=ZKM1   $   RI=IBND(ZI)   $   GO TO 160
```

TRANNOZ CODE... SUBROUTINE ARMIN (CONT.)

```
 150  ZO=ZKM1    $    RO=OBND(ZO)                                        ARM 510
 160  ARI=ARKM1                                                          ARM 520
      IF((2*(I/2) .EQ. I) .AND. (CONV(ARI,ARIM1) .LT. TOLER)) GO TO 180  ARM 530
      ARIM1=ARI                                                          ARM 540
 170  CONTINUE                                                           ARM 550
      CALL ERROR("ARMIN",3)                                              ARM 560
C                                                                        ARM 570
C...THE MINIMUM AREA CROSS SECTION HAS BEEN FOUND.  EVALUATE SOME        ARM 580
C...INITIAL PARAMETERS FOR THE TRANSONIC ANALYSIS.                       ARM 590
C                                                                        ARM 600
 180  ASTAR=ARI                                                          ARM 610
      D=SQRT((RO-RI)**2+(ZO-ZI)**2)                                      ARM 620
      ZSTAR=ZO-RO*(ZO-ZI)/(RO-RI)                                        ARM 630
      IF(ABS(RI)-1.OE-4) 190,190,200                                     ARM 640
 190  BETA=0.    $    GO TO 210                                          ARM 650
 200  BETA=ATAN((ZSTAR-ZI)/RI)                                           ARM 660
 210  CALL TRRZXY(RI,ZI,XI,YI)                                           ARM 670
      CALL TRRZXY(RO,ZO,XO,YO)                                           ARM 680
C                                                                        ARM 690
C...ITERATE FOR THE VALUES Y=H(-DX),H(+DX),G(-DX),G(+DX) SO              ARM 700
C...THAT H'(O),H''(O),G'(O),G''(O) CAN BE DETERMINED.  SUBROUTINE        ARM 710
C...ITER IS USED.                                                        ARM 720
C                                                                        ARM 730
      DO 340 M=1,4                                                       ARM 740
      NIT=1    $    NTYPE=1                                              ARM 750
      GO TO(220,230,240,250),M                                           ARM 760
 220  XITER=-DX    $    YITER=YO-5.*DY    $    GO TO 260                 ARM 770
 230  XITER=+DX    $    YITER=YO-5.*DY    $    GO TO 260                 ARM 760
 240  XITER=-DX    $    YITER=YI-5.*DY    $    GO TO 260                 ARM 790
 250  XITER=+DX    $    YITER=YI-5.*DY                                   ARM 800
 260  CALL TRXYRZ(XITER,YITER,RITER,ZITER)                               ARM 810
      IF(M-2)270,270,280                                                 ARM 820
 270  DEP=RITER-OBND(ZITER)    $    GO TO 290                            ARM 830
 280  DEP=RITER-IBND(ZITER)                                              ARM 840
 290  CALL ITER(YITER,DY,TOLER,+1.0,DEP,0.0,TOLER,NIT,NTYPE,             ARM 850
     $XNEG,YNEG,XPOS,YPOS,NSIGN1,NSIGN2)                                 ARM 860
      IF((NIT .GT. 11 .AND. NTYPE .EQ. 1) .OR. NIT .GT. 100) CALL        ARM 870
     $ERROR("ARMIN",4)                                                   ARM 880
      IF(NTYPE .NE. 3) GO TO 260                                         ARM 890
      GO TO(300,310,320,330),M                                           ARM 900
 300  YOXM1=YITER    $    GO TO 340                                      ARM 910
 310  YOXP1=YITER    $    GO TO 340                                      ARM 920
 320  YIXM1=YITER    $    GO TO 340                                      ARM 930
 330  YIXP1=YITER                                                        ARM 940
 340  CONTINUE                                                           ARM 950
C                                                                        ARM 950
C...WITH THESE VALUES OF H AND G DETERMINED, EVALUATE THE REMAINING      ARM 970
C...PARAMETERS.  THE DERIVATIVES ARE APPROXIMATED AS SECOND ORDER        ARM 980
C...FINITE DIFFERENCES.                                                  ARM 990
C                                                                        ARM1000
```

TRANNOZ CODE...SUBROUTINE ARMIN (CONT.)

```
      H1P=(YOXP1-YOXM1)/(2.*DX)   $   G1P=(YIXP1-YIXM1)/(2.*DX)      ARM1010
      H2P=(YOXM1-2.*YO+YOXP1)/(DX**2)                                ARM1020
      G2P=(YIXM1-2.*YI+YIXP1)/(DX**2)                                ARM1030
      EPS=(H2P-G2P)/(2.+ETA*(H2P-G2P))                               ARM1040
      H1=H1P/(SQRT((G+1.)/2.)*EPS**1.5)                              ARM1050
      G1=G1P/(SQRT((G+1.)/2.)*EPS**1.5)                              ARM1060
      H2=2.*H2P/(H2P-G2P)   $   G2=2.*G2P/(H2P-G2P)                  ARM1070
      BETA1=TAN(BETA)/(SQRT((G+1.)/2.)*EPS**1.5)                     ARM1080
      RETURN                                                         ARM1090
      END                                                            ARM1100
```

TRANNOZ CODE...SUBROUTINE DISCO

```
      SUBROUTINE DISCO(NTERM,FLOWCO)
C
C...SUBROUTINE DISCO CALCULATES THE DISCHARGE (OR FLOW) COEFFICIENT,
C...FLOWCO, TO NTERM TERMS FOR A GIVEN NOZZLE CONFIGURATION.
C
      REAL MSTAR,M
      COMMON/BLKDEPV/U,V,MSTAR,THETA,M,PPO,CD
      CALL AATRANS(0.0,0.0,NTERM,.T.)
      FLOWCO=CD
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE CONTOUR

```
      SUBROUTINE CONTOUR(NVAR,VALUE,NPTS,NTERM)
C
C...SUBROUTINE CONTOUR FINDS THE R-Z COORDINATES OF A MAXIMUM OF
C...53 POINTS ON THE CONSTANT M,MSTAR, OR P/PO CONTOURS IN THE
C...TRANSONIC REGION WINDOWED BY (ZIMIN,ZIMAX) AND (ZOMIN,ZOMAX)
C...ON THE INNER AND OUTER BOUNDARIES, RESPECTIVELY.  NPTS IS THE
C...NUMBER OF POINTS REQUESTED ON THE CONTOUR AND NSOLV IS THE
C...NUMBER ACTUALLY FOUND, SINCE THE CONTOUR MAY PASS OUT OF THE
C...WINDOW AREA.  IF NVAR=1, THE DEPENDENT VARIABLE IS MACH NUMBER,
C...FOR NVAR=2 IT IS MSTAR, AND FOR NVAR=3 IT IS P/PO.  VALUE IS
C...THE VALUE OF THE DEPENDENT VARIABLE AND NTERM IS THE NUMBER OF
C...TERMS FROM THE EXPANSION SOLUTION TO BE INCLUDED.  THE CONTOUR
C...INFORMATION IS STORED IN ARRAYS RCONT-PPOCONT.
C
      REAL IBND,IVAR,MSTAR,M,MSCONT,MCONT
      COMMON/BLKIN/G,ETA,ZIMIN,ZIMAX,ZOMIN,ZOMAX/BLKPARM/YI,YO,
     $EPS,H1,G1,H2,G2,BETA1/BLKCONT/NSOLV,RCONT(53),ZCONT(53),UCONT(53),
     $VCONT(53),MSCONT(53),THCONT(53),MCONT(53),PPOCONT(53)/BLKDEPV/U,
     $V,MSTAR,THETA,M,PPO,CD
C
C...SET INITIAL VALUES
C
      NSOLV=0   $   DY=(YO-YI)/FLOAT(NPTS-3)   $   YIM1=2.*YO
      CALL TRRZXY(IBND(ZIMIN),ZIMIN,XIMIN,YIMIN)
      CALL TRRZXY(IBND(ZIMAX),ZIMAX,XIMAX,YIMAX)
      CALL TRRZXY(OBND(ZOMIN),ZOMIN,XOMIN,YOMIN)
      CALL TRRZXY(OBND(ZOMAX),ZOMAX,XOMAX,YOMAX)
C
C...SET UP DO LOOP TO FIND POINTS ON CONTOURS
C
      DO 90 I=1,NPTS
      IF(I .EQ. 1) GO TO 10
      IF(I .EQ. NPTS) GO TO 20
      YITER=YO-FLOAT(I-2)*DY
      IVAR=XITER=XOMIN+(XIMIN-XOMIN)/(YIMIN-YOMIN)*(YITER-YOMIN)
      XMAX=XOMAX+(XIMAX-XOMAX)/(YIMAX-YOMAX)*(YITER-YOMAX)
      DIVAR=(XMAX-XITER)/20.
      GO TO 30
 10   IVAR=ZOMIN   $   DIVAR=(ZOMAX-ZOMIN)/20.
      GO TO 30
 20   IVAR=ZIMIN   $   DIVAR=(ZIMAX-ZIMIN)/20.
C
C...INITIALIZE QUANTITIES FOR AND CALL SUBROUTINE ITER
C
 30   NIT=1   $   NTYPE=1
 40   IF(I .EQ. 1) CALL TRRZXY(OBND(IVAR),IVAR,XITER,YITER)
      IF(I .EQ. NPTS) CALL TRRZXY(IBND(IVAR),IVAR,XITER,YITER)
      IF(I .NE. 1 .AND. I .NE. NPTS) XITER=IVAR
      CALL AATRANS(XITER,YITER,NTERM,.F.)
      CALL VARSOR(NVAR,DEP)
```

TRANNOZ CODE...SUBROUTINE CONTOUR (CONT.)

```
      DVAR=(DEP-VALUE)/VALUE
      CALL ITER(IVAR,DIVAR,1.0E-6,+1.0,DVAR,0.0,1.0E-6,NIT,NTYPE,
     $XNEG,YNEG,XPOS,YPOS,NSIGN1,NSIGN2)
      IF(NIT .GT. 21 .AND. NTYPE .EQ. 1) GO TO 90
      IF(NIT .GT. 100) CALL ERROR("CONTOUR",5)
      IF(NTYPE .NE. 3) GO TO 40
C
C...THE SOLUTION POINT HAS BEEN FOUND.  CHECK TO MAKE SURE THAT THE
C...POINT IS WITHIN THE REGION OF INTEREST, AND IF SO, STORE THE
C...R-Z COORDINATES OF THE POINT AND VARIOUS PROPERTIES (U,V,M*,
C...THETA,M,P/PO) IN CORRESPONDING ARRAYS.
C
      IF(I .NE. 1) GO TO 50
      RSOLN=OBND(IVAR)    $    ZSOLN=IVAR
      CALL TRRZXY(RSOLN,ZSOLN,XITER,YITER)
      GO TO 70
 50   IF(I .NE. NPTS) GO TO 60
      RSOLN=IBND(IVAR)    $    ZSOLN=IVAR
      CALL TRRZXY(RSOLN,ZSOLN,XITER,YITER)
      IF(ABS(YITER-YIM1) .LE. 0.001) GO TO 80
      GO TO 70
 60   XITER=IVAR
      CALL TRXYRZ(XITER,YITER,RSOLN,ZSOLN)
      IF(ABS(YITER-YIM1) .LE. 0.001) GO TO 90
      IF(I .GT. 3) GO TO 65
      IF(RSOLN .GT. OBND(ZSOLN)) GO TO 90
 65   IF(I .LT. NPTS-2) GO TO 70
      IF(RSOLN .LT. IBND(ZSOLN)) GO TO 90
 70   YIM1=YITER    $    NSOLV=NSOLV+1
 80   RCONT(NSOLV)=RSOLN    $    ZCONT(NSOLV)=ZSOLN
      CALL AATRANS(XITER,YITER,NTERM,.F.)
      UCONT(NSOLV)=U    $    VCONT(NSOLV)=V
      MSCONT(NSOLV)=MSTAR    $    THCONT(NSOLV)=THETA
      MCONT(NSOLV)=M    $    PPOCONT(NSOLV)=PPO
 90   CONTINUE
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE STLINE

```
      SUBROUTINE STLINE(NPTS,NTERM)
C
C...SUBROUTINE STLINE CALCULATES A SUPERSONIC INITIAL VALUE LINE
C...FOR USE IN STARTING METHOD OF CHARACTERISTICS (OR SIMILAR)
C...CALCULATIONS FOR ANNULAR SUPERSONIC NOZZLES.  THE CONSTANT
C...MACH NUMBER LINE FROM THE THROAT WALL LOCATION WITH THE HIGHER
C...MACH NUMBER IS USED.  NPTS IS THE NUMBER OF POINTS ON THE
C...STARTING LINE (MAXIMUM=53) AND NTERM SPECIFIES THE NUMBER OF
C...TERMS FROM THE ANALYSIS TO BE USED.
C
      REAL MSTART,MSTAR,M,MSCONT,MCONT
      COMMON/BLKPARM/YI,YO,EPS,H1,G1,H2,G2,BETA1/BLKDEPV/U,V,MSTAR,
     $THETA,M,PPO,CD/BLKCONT/NSOLV,RCONT(53),ZCONT(53),UCONT(53),
     $VCONT(53),MSCONT(53),THCONT(53),MCONT(53),PPOCONT(53)
C
C...CHECK THE MACH NUMBERS AT THE INNER AND OUTER THROAT WALL
C...LOCATIONS
C
      CALL AATRANS(0.0,YI,NTERM,.F.)
      MSTART=M
      CALL AATRANS(0.0,YO,NTERM,.F.)
      IF(M .GT. MSTART) MSTART=M
      IF(MSTART .LE. 1.0) CALL ERROR("STLINE",6)
C
C...GENERATE THE INITIAL VALUE LINE.  COORDINATES AND CORRE-
C...SPONDING FLOW PROPERTIES ALONG THE LINE ARE STORED IN THE
C...ARRAYS RCONT-PPOCONT.
C
      NTEMP=NPTS+1
      DO 10 I=1,2
      CALL CONTOUR(1,MSTART,NTEMP,NTERM)
      IF(NSOLV .EQ. NPTS) RETURN
 10   NTEMP=NTEMP+NPTS-NSOLV
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE XPLANE

```
      SUBROUTINE XPLANE(XPL,NPTS,NTERM)
C
C...SUBROUTINE XPLANE EVALUATES THE DEPENDENT VARIABLES U,V,M*,
C...THETA,M,P/PO AND PERTURBATION VELOCITY COMPONENTS U1,V1,U2,
C...V2,U3,V3 AT NPTS POINTS FROM YI TO YO ALONG THE PLANE X=XPL
C...IN THE NOZZLE THROAT.  A MAXIMUM OF NPTS=51 POINTS IS ALLOWED.
C...NTERM TERMS IN THE SERIES SOLUTION ARE USED.  THE RESULTS ARE
C...RETURNED IN ARRAYS YXPL-V3XPL.
C
      REAL MSXPL,MXPL,MSTAR,M
      COMMON/BLKPARM/YI,YO,EPS,H1,G1,H2,G2,BETA1/BLKXPL/YXPL(51),
     $UXPL(51),VXPL(51),MSXPL(51),THXPL(51),MXPL(51),PPOXPL(51),
     $U1XPL(51),V1XPL(51),U2XPL(51),V2XPL(51),U3XPL(51),V3XPL(51)
     $/BLKDEPV/U,V,MSTAR,THETA,M,PPO,CD/BLKCOMP/U1,V1,U2,V2,U3,V3
C
C...CALL AATRANS TO EVALUATE THE VARIOUS QUANTITIES:
C
      DY=(YO-YI)/FLOAT(NPTS-1)
      DO 10 I=1,NPTS
      YXPL(I)=YI+FLOAT(I-1)*DY
      CALL AATRANS(XPL,YXPL(I),NTERM,.F.)
      UXPL(I)=U   $   VXPL(I)=V
      MSXPL(I)=MSTAR   $   THXPL(I)=THETA
      MXPL(I)=M   $   PPOXPL(I)=PPO
      U1XPL(I)=U1   $   V1XPL(I)=V1
      IF(NTERM .EQ. 1) GO TO 10
      U2XPL(I)=U2   $   V2XPL(I)=V2
      IF(NTERM .EQ. 2) GO TO 10
      U3XPL(I)=U3   $   V3XPL(I)=V3
   10 CONTINUE
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE ZPLANE

```
      SUBROUTINE ZPLANE(ZPL,NPTS,NTERM)
C
C...SUBROUTINE ZPLANE EVALUATES THE DEPENDENT VARIABLES U,V,M*
C...THETA,M,P/PO AND PERTURBATION VELOCITY COMPONENTS U1,V1,U2,
C...V2,U3,V3 AT NPTS POINTS FROM THE INNER TO THE OUTER WALL
C...ALONG THE PLANE Z=ZPL (PERPENDICULAR TO THE AXIS OF SYMMETRY).
C...A MAXIMUM OF NPTS=51 POINTS IS ALLOWED.  NTERM TERMS IN THE
C...SERIES SOLUTION ARE USED.  THE RESULTS ARE RETURNED IN ARRAYS
C...RZPL-V3ZPL.
C
      REAL IBND,MSZPL,MZPL,MSTAR,M
      COMMON/BLKZPL/RZPL(51),UZPL(51),VZPL(51),MSZPL(51),THZPL(51),
     $MZPL(51),PPOZPL(51),U1ZPL(51),V1ZPL(51),U2ZPL(51),V2ZPL(51),
     $U3ZPL(51),V3ZPL(51)/BLKDEPV/U,V,MSTAR,THETA,M,PPO,CD/BLKCOMP/
     $U1,V1,U2,V2,U3,V3
C
C...CALL AATRANS TO EVALUATE THE VARIOUS QUANTITIES:
C
      RIN=IBND(ZPL)   $   ROUT=OBND(ZPL)
      DR=(ROUT-RIN)/FLOAT(NPTS-1)
      DO 10 I=1,NPTS
      RZPL(I)=RIN+FLOAT(I-1)*DR
      CALL TRRZXY(RZPL(I),ZPL,X,Y)
      CALL AATRANS(X,Y,NTERM,.F.)
      UZPL(I)=U   $   VZPL(I)=V
      MSZPL(I)=MSTAR   $   THZPL(I)=THETA
      MZPL(I)=M   $   PPOZPL(I)=PPO
      U1ZPL(I)=U1   $   V1ZPL(I)=V1
      IF(NTERM .EQ. 1) GO TO 10
      U2ZPL(I)=U2   $   V2ZPL(I)=V2
      IF(NTERM .EQ. 2) GO TO 10
      U3ZPL(I)=U3   $   V3ZPL(I)=V3
 10   CONTINUE
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE TRRZXY

```
      SUBROUTINE TRRZXY(R,Z,X,Y)
C
C...SUBROUTINE TRRZXY CARRIES OUT THE TRANSFORMATION FOR A POINT
C...WITH CYLINDRICAL COORDINATES (R,Z) TO THE (X,Y) COORDINATES
C...OF THE TRANSONIC ANALYSIS.  D IS THE NON-DIMENSIONALIZING
C...DISTANCE, ZSTAR IS THE DISPLACEMENT OF THE X-Y ORIGIN FROM
C...THE R-Z ORIGIN, AND BETA IS THE ANGLE OF INCLINATION OF THE
C...X-AXIS WITH RESPECT TO THE Z-AXIS.
C
      COMMON/BLKGEOM/RI,ZI,RO,ZO,ASTAR,D,ZSTAR,BETA,H1P,G1P,H2P,G2P
      X=(Z-ZSTAR)/D*COS(BETA)+R/D*SIN(BETA)
      Y=-(Z-ZSTAR)/D*SIN(BETA)+R/D*COS(BETA)
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE TRXYRZ

```
      SUBROUTINE TRXYRZ(X,Y,R,Z)
C
C. .SUBROUTINE TRXYRZ CARRIES OUT THE TRANSFORMATION FOR A POINT
C...WITH COORDINATES (X,Y) OF THE TRANSONIC ANALYSIS TO CYLINDRI-
C...CAL COORDINATES (R,Z).  D IS THE NON-DIMENSIONALIZING DISTANCE,
C...ZSTAR IS THE DISPLACEMENT OF THE X-Y ORIGIN FROM THE R-Z ORIGIN,
C...AND BETA IS THE ANGLE OF INCLINATION OF THE X-AXIS WITH RESPECT
C...TO THE Z-AXIS.
C
      COMMON/BLKGEOM/RI,ZI,RO,ZO,ASTAR,D,ZSTAR,BETA,H1P,G1P,H2P,G2P
      R=X*D*SIN(BETA)+Y*D*COS(BETA)
      Z=ZSTAR+X*D*COS(BETA)-Y*D*SIN(BETA)
      RETURN
      END
```

TRANNOZ CODE...SUBROUTINE ITER

```
      SUBROUTINE ITER(X,DX,ERRORX,SIGN,Y,YGIVEN,ERRORY,NIT,NTYPE,
     $XNEG,YNEG,XPOS,YPOS,NSIGN1,NSIGN2)
C
C...SUBROUTINE ITER PERFORMS AN ITERATION TO FIND X SUCH THAT THE
C...ABSOLUTE VALUE OF (Y-YGIVEN) IS LESS THAN OR EQUAL TO ERRORY
C...OR THE ABSOLUTE VALUE OF (X(I+1)-X(I)) IS LESS THAN OR EQUAL
C...TO ERRORX.
C
C...VARIABLES:
C
C...   X      = INDEPENDENT VARIABLE
C...   DX     = INCREMENT IN INDEPENDENT VARIABLE
C...   ERRORX = MAXIMUM VALUE OF ABS(X(I+1)-X(I)) FOR SOLN
C...   SIGN   = +1.0 OR -1.0, DEFINES INCREMENTING FROM X INITIAL
C...   Y      = DEPENDENT VARIABLE
C...   YGIVEN = GIVEN VALUE OF DEPENDENT VARIABLE
C...   ERRORY = MAXIMUM VALUE OF ABS(Y-YGIVEN)
C...   NIT    = INCREMENT NUMBER
C...   NTYPE  = 1--INCREMENT, 2--INTERPOLATION, 3--SOLUTION
C
      DY=Y-YGIVEN
      IF(ABS(DY)-ERRORY) 90,90,10
 10   IF(DY) 20,90,30
C
 20   NSIGN2=-1
      XNEG=X   $   YNEG=Y
      GO TO 40
C
 30   NSIGN2=+1
      XPOS=X   $   YPOS=Y
 40   IF(NTYPE .EQ. 2) GO TO 80
 50   IF(NIT-1) 70,70,60
 60   NSIGN=NSIGN1*NSIGN2
      IF(NSIGN) 80,80,70
 70   NSIGN1=NSIGN2   $   NIT=NIT+1
C
C...INCREMENT TO FIND SOLUTION INTERVAL
C
      X=X+SIGN*DX
      GO TO 100
C
C...INTERPOLATION FOR SOLUTION
C
 80   NTYPE=2   $   NIT=NIT+1
      XSAVE=X   $   RATIO=(XPOS-XNEG)/(YPOS-YNEG)
      X=XNEG+RATIO*(YGIVEN-YNEG)
      IF(ABS(X-XSAVE)-ERRORX) 90,90,100
 90   NTYPE=3
 100  RETURN
      END
```

TRANNOZ CODE...SUBROUTINE VARSOR

```
      SUBROUTINE VARSOR(NVAR,DEP)
C
C...SUBROUTINE VARSOR PUTS THE VALUE OF M, MSTAR, OR P/PO INTO
C...DEP DEPENDING ON THE VALUE OF NVAR.
C...FOR:              NVAR=1,   DEP=M
C...                  NVAR=2,   DEP=MSTAR
C...                  NVAR=3,   DEP=P/PO
C
      REAL MSTAR,M
      COMMON/BLKDEPV/U,V,MSTAR,THETA,M,PPO,CD
      GO TO(10,20,30),NVAR
 10   DEP=M   $   RETURN
 20   DEP=MSTAR   $   RETURN
 30   DEP=PPO   $   RETURN
      END
```

TRANNOZ CODE...SUBROUTINE ERROR

```
      SUBROUTINE ERROR(ROUT,IER)
C
C...SUBROUTINE ERROR WRITES DIAGNOSTIC MESSAGES FOR ERROR CON-
C...DITIONS ENCOUNTERED IN OTHER SUBROUTINES.  ROUT NAMES THE
C...SUBROUTINE WHERE THE ERROR OCCURRED AND IER IS THE ERROR
C...NUMBER.
C
      WRITE(6,900) ROUT
      GO TO(10,20,30,40,50,60),IER
 10   WRITE(6,901) IER    $   GO TO 100
 20   WRITE(6,902) IER    $   GO TO 100
 30   WRITE(6,903) IER    $   GO TO 100
 40   WRITE(6,904) IER    $   GO TO 100
 50   WRITE(6,905) IER    $   GO TO 100
 60   WRITE(6,906) IER
 100  WRITE(6,910)
C
C...FORMAT STATEMENTS
C
 900  FORMAT(1H1,//,27X,"AN ERROR OCCURRED WHILE COMPUTATIONS ",
     $"WERE BEING CARRIED OUT IN SUBROUTINE ",A7,//,52X,"THE ",
     $"DIAGNOSIS OF THE PROBLEM IS:",//)
 901  FORMAT(28X,"ERROR NO. ",I2,": AREA NOT FOUND TO INCREASE ",
     $"IN INNER LOOP OF MINIMIZING ITERATIONS")
 902  FORMAT(19X,"ERROR NO. ",I2,": CONVERGENCE FOR MINIMUM AREA ",
     $"WITH A GIVEN PIVOT POINT DID NOT OCCUR IN 20 ITERATIONS")
 903  FORMAT(14X,"ERROR NO. ",I2,": CONVERGENCE FOR MINIMUM AREA ",
     $"NOT OBTAINED FOR 100 PIVOTS EACH ON THE UPPER AND LOWER ",
     $"BOUNDARIES")
 904  FORMAT(27X,"ERROR NO. ",I2,": ITERATIONS FOR H(-DX),H(+DX)",
     $",G(-DX), OR G(+DX) DID NOT CONVERGE")
 905  FORMAT(19X,"ERROR NO. ",I2,": ITERATIONS FOR COORDINATES OF ",
     $"CONSTANT M,M*, OR P/PO CONTOUR POINTS DID NOT CONVERGE")
 906  FORMAT(35X,"ERROR NO. ",I2,": MACH NUMBER FOR INITIAL VALUE ",
     $"LINE IS NOT SUPERSONIC")
 910  FORMAT(//,58X,"EXECUTION TERMINATED")
      END
```

TRANNOZ CODE...SUBROUTINE AATRANS

```
      SUBROUTINE AATRANS(XS,YS,NTERM,FCOEF)
C
C...SUBROUTINE AATRANS COMPUTES THE TRANSONIC FLOWFIELD IN THE
C...THROAT REGION OF INCLINED, ANNULAR AXISYMMETRIC, SUPERSONIC
C...NOZZLES.  THE METHOD USED IS EVALUATION OF A PERTURBATION
C...SERIES SOLUTION SIMILAR TO THOSE OF HALL AND THOMPSON AND
C...FLACK.  THE QUANTITIES RETURNED ARE U,V,M*,THETA,M,P/PO, AND
C...CD
C
      IMPLICIT DOUBLE PRECISION(A-H,M,O-Z)
      LOGICAL FCOEF
      REAL XS,YS,GS,ETAS,ZIMIN,ZIMAX,ZOMIN,ZOMAX,YIS,YOS,EPSS,
     $H1S,G1S,H2S,G2S,BETA1S,US,VS,MSTARS,THETAS,MS,PPOS,CDS,U1S,
     $V1S,U2S,V2S,U3S,V3S
      COMMON/BLKIN/GS,ETAS,ZIMIN,ZIMAX,ZOMIN,ZOMAX/BLKPARM/
     $YIS,YOS,EPSS,H1S,G1S,H2S,G2S,BETA1S/BLKDEPV/US,VS,MSTARS,
     $THETAS,MS,PPOS,CDS/BLKCOMP/U1S,V1S,U2S,V2S,U3S,V3S
     $/BLKCALL/ICALL1,ICALL2,ICALL3
C
C...CALCULATE SOME INITIAL CONSTANTS:
C
      ICALL1=ICALL1+1
      IF(ICALL1 .GT. 1) GO TO 10
      ETA=DBLE(ETAS)   $   EPS=DBLE(EPSS)   $   YI=DBLE(YIS)
      YO=DBLE(YOS)   $   G1=DBLE(G1S)   $   G2=DBLE(G2S)
      H1=DBLE(H1S)   $   H2=DBLE(H2S)   $   BETA1=DBLE(BETA1S)
      G=DBLE(GS)   $   GP1=G+1.   $   GM1=G-1.
      CVT=DSQRT(GP1*.5*EPS)
      CM=GP1*.5   $   CPPO=(2./GP1)**(G/GM1)
      CCD=GP1*EPS*EPS/(YO*YO-YI*YI)   $   CDS=1.0
      U2S=0.0   $   V2S=0.0
      U3S=0.0   $   V3S=0.0
C
C...CALCULATE THE REQUIRED QUANTITIES FOR THE FIRST ORDER SOLUTION.
C...FIRST THE VARIOUS YI AND YO CONSTANTS:
C
      YOE2=YO*YO   $   YIE2=YI*YI
      YOE3=YOE2*YO   $   YIE3=YIE2*YI
      YOE4=YOE2*YOE2   $   YIE4=YIE2*YIE2
      YOE5=YOE2*YOE3   $   YIE5=YIE2*YIE3
      YOE6=YOE3*YOE3   $   YIE6=YIE3*YIE3
      YOCO=DLOG(YO)   $   YICO=DLOG(YI)
      YOC1=YO*YOCO   $   YIC1=YI*YICO
      YOC2=YOC1*YOC1   $   YIC2=YIC1*YIC1
      YOC3=YOE4*YOCO   $   YIC3=YIE4*YICO
      YOC4=YOE2*YOCO   $   YIC4=YIE2*YICO
C
C...CALCULATE THE "B" CONSTANTS:
C
      B2=-(H2*YI-G2*YO)*YO*YI/(YOE2-YIE2)   $   B2E2=B2*B2
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      B1=DSQRT(H2*YO-B2)/YO   $   B1E2=B1*B1
      B1E3=B1E2*B1   $   B1E4=B1E2*B1E2
      B4=B1E3*YOE3*.25+B1*B2*YOC1-B1*B2*YO*.5-BETA1
      B5=B1E3*YIE3*.25+B1*B2*YIC1-B1*B2*YI*.5-BETA1
      B3=-(H1*YI-G1*YO-B4*YI+B5*YO)*YO*YI/(YOE2-YIE2)
      BO=(H1*YO-B4*YO-B3)/(B1*YOE2)   $   BOE2=BO*BO
      B6=BO*B1-B1*B2*.5
C
C...CALCULATE X,Y,Z, THE Y CONSTANTS, AND THE "A" FUNCTIONS:
C
 10   IF(FCOEF) GO TO 20
      X=DBLE(XS)   $   Y=DBLE(YS)
      Z=X/DSQRT(GP1*.5*EPS)
      YE2=Y*Y   $   YE3=YE2*Y
      YCO=DLOG(Y)   $   YC1=Y*YCO
      A1P=B1E2*Y+B2/Y
      A1=B1E2*YE2*.5+B2*YCO
      AOP=B1E3*YE3*.25+B1*B2*YC1-B1*B2*Y*.5-BETA1+BO*B1*Y+B3/Y
C
C...CALCULATE THE DESIRED QUANTITIES TO FIRST ORDER:
C
      U1=A1+BO+B1*Z   $   V1=AOP+A1P*Z
      U=1.+U1*EPS   $.  V=CVT*V1*EPS
      MSTAR=U   $   THETA=V
      M=1.+CM*U1*EPS   $   PPO=CPPO*(1.-G*U1*EPS)
      U1S=SNGL(U1)   $   V1S=SNGL(V1)
      US=SNGL(U)   $   VS=SNGL(V)
      MSTARS=SNGL(MSTAR)   $   THETAS=SNGL(THETA)
      MS=SNGL(M)   $   PPOS=SNGL(PPO)
      GO TO 30
C
C...IF DESIRED, CALCULATE THE DISCHARGE COEFFICIENT:
C
 20   CD4=BO*B1E2*.25-B1E2*B2/16.
      CD5=BOE2*.5+B2E2*.25-BO*B2*.5
      CD6=BO*B2-B2E2*.5
      CD1=B1E4*(YOE6-YIE6)/24.+CD4*(YOE4-YIE4)+CD5*(YOE2-YIE2)+B2E2*.5
     $*(YOC2-YIC2)+B1E2*B2*.25*(YOC3-YIC3)+CD6*(YOC4-YIC4)
      CD=1.-CCD*CD1
      CDS=SNGL(CD)
 30   IF(NTERM .EQ. 1) RETURN
C
C...CALCULATE THE REQUIRED QUANTITIES FOR THE SECOND ORDER SOLUTION.
C...FIRST THE VARIOUS B,YI,YO CONSTANTS:
C
      ICALL2=ICALL2+1
      IF(ICALL2 .GT. 1) GO TO 40
      B1E5=B1E2*B1E3   $   B1E6=B1E3*B1E3
      BOE3=BO*BOE2   $   B2E3=B2*B2E2
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      B3E2=B3*B3   $   B6E2=B6*B6                                       AAT1000
      BETA1E2=BETA1*BETA1                                               AAT1010
      YOE7=YOE3*YOE4   $   YIE7=YIE3*YIE4                               AAT1020
      YOE8=YOE4*YOE4   $   YIE8=YIE4*YIE4                               AAT1030
      YOC5=YOCO/YO   $   YIC5=YICO/YI                                   AAT1040
      YOC6=YO*YOCO*YOCO   $   YIC6=YI*YICO*YICO                         AAT1050
      YOC7=YOE3*YOCO   $   YIC7=YIE3*YICO                               AAT1060
      YOC8=YOC4*YOC4   $   YIC8=YIC4*YIC4                               AAT1070
      YOC9=YOE6*YOCO   $   YIC9=YIE6*YICO                               AAT1080
      YOC10=YOC2*YOCO   $   YIC10=YIC2*YICO                             AAT1090
C                                                                       AAT1100
C...CALCULATE THE "D" CONSTANTS:                                        AAT1110
C                                                                       AAT1120
      D3=B1E2*YOE2*.5+B2*YOCO+BO                                        AAT1130
      D4=H1*D3                                                          AAT1140
      D5=H2*ETA+H2*D3+H1*B1                                             AAT1150
      D6=H2*B1                                                          AAT1160
      D7=B1E2*YIE2*.5+B2*YICO+BO                                        AAT1170
      D8=G1*D7                                                          AAT1180
      D9=G2*ETA+G1*B1+G2*D7                                             AAT1190
      D10=G2*B1                                                         AAT1200
      D11=(D10*YO-D6*YI)*YO*YI/(YOE2-YIE2)                              AAT1210
      D2=(D6*YO-(2.*G-1.)*.5*B1E3*YOE2-D11)/(3.*B1*YOE2)                AAT1220
      D12=(2.*G-1.)*.5*B1E3+3.*B1*D2                                    AAT1230
      D13=4.*B1*D12+2.*B1E2*D2+(2.*G+1.)*B1E4                           AAT1240
      D14=8.*B1*D11+4.*B2*D2+(4.*G-2.)*B1E2*B2                          AAT1250
      D15=4.*B1E2*B2+4.*BO*D2+(4.*G-2.)*BO*B1E2                         AAT1260
      D17=D13*YOE3*.25+(D15*.5-D14*.25)*YO+D14*.5*YOC1+2.*B2E2*YOC5-    AAT1270
     $BETA1*B1                                                          AAT1280
      D18=D13*YIE3*.25+(D15*.5-D14*.25)*YI+D14*.5*YIC1+2.*B2E2*YIC5-    AAT1290
     $BETA1*B1                                                          AAT1300
      D16=(D9*YO-D5*YI-D18*YO+D17*YI)*YI*YO/(YOE2-YIE2)                 AAT1310
      D1=(D5*YO-D17*YO-D16)/(2.*B1*YOE2)                                AAT1320
      D19=D15*.5-D14*.25+2.*B1*D1                                       AAT1330
      D20=D19*.5-D14/8.                                                 AAT1340
      D21=B1E2*D12+B1*D13/8.+(2.*G+1.)*.25*B1E5                         AAT1350
      D22=2.*BO*D12+B1E2*D1+(2.*G-1.)*BO*B1E3+2.*B1*D20+2.*B1E2*B6+     AAT1360
     $B1E3*B2*.5                                                        AAT1370
      D23=-4.5*BETA1*B1E2                                               AAT1380
      D24=-2.*BETA1*B2-BETA1*BO                                         AAT1390
      D25=4.*B2*D11+(2.*G+1.)*B1*B2E2                                   AAT1400
      D26=2.*B2*D12+2.*B1E2*D11+B1*D14*.5+(2.*G+1.)*B1E3*B2             AAT1410
      D27=4.*BO*D11+2.*B2*D1+(4.*G-2.)*BO*B1*B2+2.*B1*D16+2.*B1*B2E2    AAT1420
      D28=2.*BO*D1+(2.*G-1.)*BOE2*B1+2.*B1E2*B3+2.*B2*B6                AAT1430
      D30=D21*YOE5/6.+(D22*.25-D26/16.)*YOE3+D23*YOE2/3.+(D25*.25-D27   AAT1440
     $*.25+D28*.5)*YO+D25*YOC6*.5+D26*YOC7*.25+(D27*.5-D25*.5)*YOC1-    AAT1450
     $BETA1*B2*YOCO+2.*B2*B3*YOC5+D24+BETA1*B2                          AAT1460
      D31=D21*YIE5/6.+(D22*.25-D26/16.)*YIE3+D23*YIE2/3.+(D25*.25-D27   AAT1470
     $*.25+D28*.5)*YI+D25*YIC6*.5+D26*YIC7*.25+(D27*.5-D25*.5)*YIC1-    AAT1480
     $BETA1*B2*YICO+2.*B2*B3*YIC5+D24+BETA1*B2                          AAT1490
      D29=(D8*YO-D4*YI-D31*YO+D30*YI)*YI*YO/(YOE2-YIE2)                 AAT1500
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      D0=(D4*Y0-D30*Y0-D29)/(B1*YOE2)
      D32=D22*.25-D26/16.
      D33=D25*.25-D27*.25+D28*.5+B1*D0
      D34=D27*.5-D25*.5
      D35=D24+BETA1*B2
C
C...CALCULATE THE Y CONSTANTS AND THE "C" FUNCTIONS:
C
 40   IF(FCOEF) GO TO 50
      YE4=YE2*YE2   $   YE5=YE2*YE3
      YC3=YC0/Y   $   YC4=YC0*YC0
      YC5=YE2*YC0   $   YC6=Y*YC4
      YC7=YE3*YC0
      C2P=D12*Y+D11/Y
      C2=D12*YE2*.5+D11*YC0
      C1P=D13*YE3*.25+D19*Y+D16/Y+D14*YC1*.5+2.*B2E2*YC3-BETA1*B1
      C1=D13*YE4/16.+D20*YE2-BETA1*B1*Y+B2E2*YC4+D14*YC5*.25+D16*YC0
      C0P=D21*YE5/6.+D32*YE3+D23*YE2/3.+D33*Y+D29/Y+D25*YC6*.5+D26*
     $YC7*.25+D34*YC1-BETA1*B2*YC0+2.*B2*B3*YC3+D35
C
C...CALCULATE THE DESIRED QUANTITIES TO SECOND ORDER:
C
      ZE2=Z*Z   $   EPSE2=EPS*EPS
      U2=C1+D0+(2.*C2+D1)*Z+D2*ZE2
      V2=C0P+C1P*Z+C2P*ZE2
      U=U+U2*EPSE2   $   V=V+CVT*V2*EPSE2
      MSTAR=U   $   THETA=THETA+CVT*(V2-U1*V1)*EPSE2
      M=M+CM*(U2+0.75*GM1*U1*U1)*EPSE2
      PP0=PP0-CPP0*G*U2*EPSE2
      U2S=SNGL(U2)   $   V2S=SNGL(V2)
      US=SNGL(U)   $   VS=SNGL(V)
      MSTARS=SNGL(MSTAR)   $   THETAS=SNGL(THETA)
      MS=SNGL(M)   $   PP0S=SNGL(PP0)
      GO TO 60
C
C...IF DESIRED, CALCULATE THE DISCHARGE COEFFICIENT:
C
 50   CD10=B1E3*B6/24.-B1E4*B2/144.
      CD11=B1E3*B3/16.+B6E2/8.-B1*B2*B6/16.+B1E2*B2E2/64.
      CD12=BETA1*B1*B2/9.-BETA1*B6/3.
      CD13=B3*B6*.5+BETA1E2*.25-B1*B2*B3*.25
      CD14=B1*B2*B6*.25-B1E2*B2E2/16.
      CD7A=B1E6/256.*(YOE8-YIE8)+CD10*(YOE6-YIE6)-BETA1*B1E3/20.*(YOE5-
     $YIE5)+CD11*(YOE4-YIE4)+CD12*(YOE3-YIE3)+CD13*(YOE2-YIE2)-BETA1*
     $B3*(YO-YI)
      CD7B=B1E2*B2E2/8.*(YOC8-YIC8)+B1E4*B2/24.*(YOC9-YIC9)+CD14
     $*(YOC3-YIC3)-BETA1*B1*B2/3.*(YOC7-YIC7)+B1*B2*B3*.5*(YOC4-YIC4)+
     $B3E2*.5*(YOC0-YIC0)
      CD7=CD7A+CD7B
      CD15=B1E2*D20/6.+B0*D13/48.-B1E2*D14/144.-B2*D13/288.
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      CD16=B1E2*D0*.25+B0*D20*.5+B1E2*B2E2/32.+B2*D14/64.-B1E2*D16/16.-  AAT2010
     $B2*D20/8.-B0*D14/32.                                                AAT2020
      CD17=2./9.*BETA1*B1*B2-2./3.*BETA1*B0*B1                            AAT2030
      CD18=B0*D0-0.75*B2E3+B2*D16*.5+B0*B2E2*.5-B2*D0*.5-B0*D16*.5       AAT2040
      CD19=B1E2*B2E2*.25+B2*D14/8.                                        AAT2050
      CD20=B2*D16+B0*B2E2-1.5*B2E3                                        AAT2060
      CD21=B1E2*D14/24.+B2*D13/48.                                        AAT2070
      CD22=B1E2*D16*.25+B2*D20*.5+B0*D14/8.-B1E2*B2E2/8.-B2*D14/16.      AAT2080
      CD23=1.5*B2E3-B2*D16-B0*B2E2+B2*D0+B0*D16                           AAT2090
      CD8A=B1E2*D13/128.*(YOE8-YIE8)+CD15*(YOE6-YIE6)-BETA1*B1E3/5.*    AAT2100
     $(YOE5-YIE5)+CD16*(YOE4-YIE4)+CD17*(YOE3-YIE3)+CD18*(YOE2-YIE2)    AAT2110
      CD8B=B2E3*(YOC10-YIC10)+CD19*(YOC8-YIC8)+CD20*(YOC2-YIC2)+CD21*   AAT2120
     $(YOC9-YIC9)+CD22*(YOC3-YIC3)-2./3.*BETA1*B1*B2*(YOC7-YIC7)+CD23*  AAT2130
     $(YOC4-YIC4)                                                         AAT2140
      CD8=CD8A+CD8B                                                       AAT2150
      CD24=B0*B1E4/8.-B1E4*B2/48.                                         AAT2160
      CD25=3./8.*B0E2*B1E2+3./64.*B1E2*B2E2-3./16.*B0*B1E2*B2            AAT2170
      CD26=B0E3*.5-0.75*B0E2*B2+0.75*B0*B2E2-3./8.*B2E3                  AAT2180
      CD27=1.5*B0*B2E2-0.75*B2E3                                          AAT2190
      CD28=0.75*B0*B1E2*B2-3./16.*B1E2*B2E2                               AAT2200
      CD29=0.75*B2E3-1.5*B0*B2E2+1.5*B0E2*B2                              AAT2210
      CD9A=B1E6/64.*(YOE8-YIE8)+CD24*(YOE6-YIE6)+CD25*(YOE4-            AAT2220
     $YIE4)+CD26*(YOE2-YIE2)+B2E3*.5*(YOC10-YIC10)+3./8.*B1E2*           AAT2230
     $B2E2*(YOC8-YIC8)                                                    AAT2240
      CD9B=CD27*(YOC2-YIC2)+B1E4*B2/8.*(YOC9-YIC9)+CD28*(YOC3-          AAT2250
     $YIC3)+CD29*(YOC4-YIC4)                                              AAT2260
      CD9=(2.*G-3.)/3.*(CD9A+CD9B)                                        AAT2270
      CD2=CD7+CD8+CD9                                                     AAT2280
      CD=CD-CCD*CD2*EPS                                                   AAT2290
      CDS=SNGL(CD)                                                        AAT2300
 60   IF(NTERM .EQ. 2) RETURN                                             AAT2310
C                                                                         AAT2320
C...CALCULATE THE REQUIRED QUANTITIES FOR THE THIRD ORDER SOLUTION.      AAT2330
C...FIRST THE VARIOUS B,D,YI,YO CONSTANTS:                                AAT2340
C                                                                         AAT2350
      ICALL3=ICALL3+1                                                     AAT2360
      IF(ICALL3 .GT. 1) GO TO 70                                          AAT2370
      ETAE2=ETA*ETA   $   B0E4=B0E2*B0E2                                  AAT2380
      B1E7=B1E3*B1E4   $   B1E8=B1E4*B1E4                                 AAT2390
      B2E4=B2E2*B2E2   $   D0E2=D0*D0                                     AAT2400
      D1E2=D1*D1   $   D2E2=D2*D2                                         AAT2410
      D11E2=D11*D11   $   D12E2=D12*D12                                   AAT2420
      D13E2=D13*D13   $   D14E2=D14*D14                                   AAT2430
      D16E2=D16*D16   $   D20E2=D20*D20                                   AAT2440
      YOE10=YOE5*YOE5   $   YIE10=YIE5*YIE5                               AAT2450
      YOC11=YOC6/YO   $   YIC11=YIC6/YI                                   AAT2460
      YOC12=YOC11/YO   $   YIC12=YIC11/YI                                 AAT2470
      YOC13=YOC10/YO   $   YIC13=YIC10/YI                                 AAT2480
      YOC14=YOC8/YO   $   YIC14=YIC8/YI                                   AAT2490
      YOC15=YO*YOC3   $   YIC15=YI*YIC3                                   AAT2500
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      YOC16=YOC3*YOC11    $    YIC16=YIC3*YIC11
      YOC17=YOE2*YOC8    $   YIC17=YIE2*YIC8
      YOC18=YOE2*YOC9    $   YIC18=YIE2*YIC9
      YOC19=YOC10*YOCO    $    YIC19=YIC10*YICO
C
C...CALCULATE THE "F" CONSTANTS:
C
      F4=H1*(D13*YOE4/16.+D20*YOE2-BETA1*B1*YO+B2E2*YOC11+D14*YOC4*.25
     $+D16*YOCO+DO)
      F5A=H2*ETAE2+H2*ETA*(B1E2*YOE2*.5+B2*YOCO+BO)+H2*(D13*YOE4/16.+
     $D20*YOE2-BETA1*B1*YO+B2E2*YOC11+D14*YOC4*.25+D16*YOCO+DO)
      F5B=H1*(D12*YOE2+2.*D11*YOCO+D1)-GP1*.5*H1*(0.75*B1E3*YOE2+
     $B6+B1*B2*YOCO+B1*B2-B3/YOE2)
      F5=F5A+F5B
      F6=H2*ETA*B1+H1*D2+H2*(D12*YOE2+2.*D11*YOCO+D1)-GP1*.5*H1*
     $(B1E2-B2/YOE2)-GP1*.25*H2*(0.75*B1E3*YOE2+B6+B1*B2*YOCO+
     $B1*B2-B3/YOE2)
      F7=H2*D2-GP1*.25*H2*(B1E2-B2/YOE2)
      F8=G1*(D13*YIE4/16.+D20*YIE2-BETA1*B1*YI+B2E2*YIC11+D14*YIC4*.25
     $+D16*YICO+DO)
      F9A=G2*ETAE2+G2*ETA*(B1E2*YIE2*.5+B2*YICO+BO)+G1*(D12*YIE2+2.*
     $D11*YICO+D1)+G2*(D13*YIE4/16.+D20*YIE2-BETA1*B1*YI+B2E2*YIC11+
     $D14*YIC4*.25+D16*YICO+DO)
      F9B=-GP1*.5*G1*(0.75*B1E3*YIE2+B6+B1*B2*YICO+B1*B2-B3/YIE2)
      F9=F9A+F9B
      F10=G2*ETA*B1+G1*D2+G2*(D12*YIE2+2.*D11*YICO+D1)-GP1*.5*
     $G1*(B1E2-B2/YIE2)-GP1*.25*G2*(0.75*B1E3*YIE2+B6+B1*B2*YICO+
     $B1*B2-B3/YIE2)
      F11=G2*D2-GP1*.25*G2*(B1E2-B2/YIE2)
      F12=2.*GM1*B1*D12+2.*GM1*B1E2*D2+GM1*B1E4+4.*D2E2+4.*
     $B1E2*D2
      F13=(F11*YO-F7*YI)*YI*YO/(YOE2-YIE2)
      F3=(F7*YO-F12*YOE2*.5-F13)/(4.*B1*YOE2)
      F14=F12*.5+4.*B1*F3
      F15=3.*B1E2*F3+(G+2.)*B1E3*D2+9.*B1*F14+6.*D2*D12+3.*(G+2.)*
     $B1E2*D12+2.*G*B1E5+GM1*B1*D13
      F16=GP1*.5*BETA1*B1E2-BETA1*D2
      F17=(5.*G-1.)*.5*B1*B2E2+6.*B2*D11
      F18=GP1*.5*BETA1*B2
      F19=6.*B2*F3+2.*(G+2.)*B1*B2*D2+18.*B1*F13+12.*D2*D11+2.*(2.*G+
     $1.)*B1E2*D11+2.*GM1*B2*D12+GM1*B1*D14+3.*GM1*B1E3*B2
      F20A=(3.*G+5.)*.5*B1E3*B2+6.*B1E2*D11+6.*B2*D12+2.*GM1*BO*D12
     $+2.*GM1*B1*D19+GM1*.5*B1*D14+2.*GM1*B6*D2+GM1*B1E2*
     $B6
      F20B=GM1*B1*B2*D2+(2.*G+1.)*B1E2*D1+2.*GM1*BO*B1E3+6.*BO*F3+
     $6.*D1*D2+6.*BO*B1*D2
      F20=F20A+F20B
      F22=F15*YOE3*.25+F16+F17*YOC5-F18/YOE2+F19*(YOC1*.5-YO*.25)+F20*
     $YO*.5
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      F23=F15*YIE3*.25+F16+F17*YIC5-F18/YIE2+F19*(YIC1*.5-YI*.25)+F20*   AAT3000
     $YI*.5                                                              AAT3010
      F21=(F10*YO-F6*YI-F23*YO+F22*YI)*YI*YO/(YOE2-YIE2)                 AAT3020
      F2=(F6*YO-F21-F22*YO)/(3.*B1*YOE2)                                 AAT3030
      F24=F20*.5-F19*.25+3.*B1*F2                                        AAT3040
      F25=F24*.5-F19/8.                                                  AAT3050
      F26=3.*B1E2*F14+B1*F15*.5+2.*D12E2+D2*D13*.25+(5.*G+4.)/8.*B1E2*   AAT3060
     $D13+(G+2.)*B1E3*D12+B1E4*D2*.5+(2.*G+1.)*.5*B1E6+GM1*B1*D21        AAT3070
      F27A=2.*B1E2*F2+GP1*B1E3*D1+2.*B0*B1E2*D2+6.*B0*F14+8.*B1*F25+     AAT3080
     $4.*D1*D12+4.*B0*B1*D12+4.*D2*D20+2.*G*B1E2*D20+2.*G*B1E3*B6+(3.*   AAT3090
     $G+7.)*.25*B1E4*B2                                                  AAT3100
      F27B=(G+3.)*B1E2*D19+B2*D13+2.*G*B0*B1E4+2.*GP1*B6*D12             AAT3110
     $+B1E3*D11+GM1*.25*B1E2*D14+GM1*B0*D13+4.*GM1*B1*                   AAT3120
     $D32+GM1*.25*B1*D26+GM1*B1*B2*D12                                   AAT3130
      F27=F27A+F27B                                                      AAT3140
      F28=8.*B1*F16-4.*BETA1*B1*D2-(19.*G+43.)/8.*BETA1*B1E3-5.*BETA1*   AAT3150
     $D12+GM1*B1*D23                                                     AAT3160
      F29=8.*B1*F18-2.*(G+2.)*BETA1*B1*B2-4.*BETA1*D11+GM1*BETA1*B0      AAT3170
     $*B1+GM1*B1*D35-BETA1*D1+GP1*.5*BETA1*B6                            AAT3180
      F30=(3.*G-1.)*B1*B2*B3+4.*B2*D16+2.*G*B0*B2E2+4.*B3*D11            AAT3190
      F31=GP1*.5*BETA1*B3                                                AAT3200
      F32=12.*B2*F13+4.*B1*F17+8.*D11E2+6.*B2E2*D2+(5.*G-3.)*B1E2*B2E2   AAT3210
     $+4.*GP1*B1*B2*D11+GM1*B2*D14+GM1*B1*D25                            AAT3220
      F33=6.*B1E2*F13+6.*B2*F14+2.*B1*F19+8.*D11*D12+D2*D14+(2.*G+3.)*   AAT3230
     $.5*B1E2*D14+2.*GP1*B1E3*D11+2.*(G+3.)*B1*B2*D12+2.*B1E2*B2*D2+     AAT3240
     $4.*G*B1E4*B2+GM1*B2*D13+GM1*B1*D26                                 AAT3250
      F34A=4.*B2*F2+2.*GP1*B1*B2*D1+4.*B0*B2*D2+12.*B0*F13+8.*B1*F21+    AAT3260
     $8.*D1*D11+8.*B0*B1*D11+4.*D2*D16+2.*G*B1E2*D16+2.*(G+6.)*B1E2*     AAT3270
     $B2E2                                                               AAT3280
      F34B=(G+3.)*.5*B2*D14+2.*GP1*B1*B2*D11+2.*GM1*B2*D19+GM1           AAT3290
     $*B0*D14+GM1*B1*D25+2.*GM1*B1*D34+4.*GM1*B6*D11+4.*GM1              AAT3300
     $*B0*B1E2*B2+2.*GM1*B1*B2*B6                                        AAT3310
      F34=F34A+F34B                                                      AAT3320
      F35=GP1*.5*BETA1*B1*B2-2.*BETA1*D11                                AAT3330
      F36=2.*(G+4.)*B2E3                                                 AAT3340
      F37A=GP1*B1E3*B3+GP1*B1*B2*B6+4.*B1E2*D16+4.*B2*D19+G*B1E2*        AAT3350
     $B2E2+(G+3.)*B0*B1E2*B2+4.*B3*D12+4.*B6*D11+2.*GM1*B0*D19+GM1       AAT3360
     $*.5*B0*D14                                                         AAT3370
      F37B=2.*GM1*B1*D33+GM1*B1*D34+2.*GM1*B6*D1+2.*                     AAT3380
     $GM1*B0*B1*B6+GM1*B1*B2*D1+2.*G*B1E2*D0+GM1*B0E2*B1E2+              AAT3390
     $4.*B0*F2+2.*D1E2+4.*D0*D2+4.*B0*B1*D1+2.*B0E2*D2                   AAT3400
      F37=F37A+F37B                                                      AAT3410
      F39=F26*YOE5/6.+F27*YOE3*.25+F28*YOE2/3.+F29+F30*YOC5-F31/YOE2+    AAT3420
     $F32*(YOC6*.5-YOC1*.5+YO*.25)+F33*(YOC7*.25-YOE3/16.)+F34*(YOC1*.5- AAT3430
     $YO*.25)+F35*(YOCO-1.)+F36*YOC12*.5+F37*YO*.5                       AAT3440
      F40=F26*YIE5/6.+F27*YIE3*.25+F28*YIE2/3.+F29+F30*YIC5-F31/YIE2+    AAT3450
     $F32*(YIC6*.5-YIC1*.5+YI*.25)+F33*(YIC7*.25-YIE3/16.)+F34*(YIC1*.5- AAT3460
     $YI*.25)+F35*(YICO-1.)+F36*YIC12*.5+F37*YI*.5                       AAT3470
      F38=(F9*YO-F5*YI-F40*YO+F39*YI)*YI*YO/(YOE2-YIE2)                  AAT3480
      F1=(F5*YO-F39*YO-F38)/(2.*B1*YOE2)                                 AAT3490
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      F41=F27*.25-F33/16.                                               AAT3500
      F42=F32*.25-F34*.25+F37*.5+2.*B1*F1                               AAT3510
      F43=F34*.5-F32*.5                                                 AAT3520
      F44=F29-F35                                                       AAT3530
      F45=F41*.25-F33/64.                                               AAT3540
      F46=F42*.5+F32/8.-F43*.25                                         AAT3550
      F47=F44-F35                                                       AAT3560
      F48=F43*.5-F32*.25                                                AAT3570
      F49=B1E2*F15/8.+B1*F26/18.+D12*D13/8.+B1E4*D12*.25+(G+2.)/16.*B1E3 AAT3580
     $*D13+(5.*G+3.)/32.*B1E7+(3.*G-1.)/6.*B1E2*D21                     AAT3590
      F50A=2.*B1E2*F25+B0*F15*.25+2.*B1*F45+2.*D12*D20+D1*D13/8.+B0*B1* AAT3600
     $D13/8.+B0*B1E2*D12+B1E4*D1*.25+G*B1E3*D20+GP1*.5*B1E4*B6+2.*G*    AAT3610
     $B1E2*D32                                                          AAT3620
      F50B=B2*D21/3.+GP1/8.*B1E5*B2+G*.5*B0*B1E5+B1E3*D19*.5+           AAT3630
     $(G+3.)/8.*B6*D13+GM1/8.*B1E2*D26+GM1*B0*D21+GM1/16.*B1*           AAT3640
     $B2*D13                                                            AAT3650
      F50=F50A+F50B                                                     AAT3660
      F51=2.*B1E2*F16+2./9.*B1*F28-2.*BETA1*B1*D12-(2.*G+3.)*.5*BETA1*  AAT3670
     $B1E4+(3.*G+1.)/6.*B1E2*D23-9./16.*BETA1*D13                       AAT3680
      F52A=B1E2*F1+B0*B1E2*D1+G*B1E3*D0+4.*B0*F25+2.*B1*F46+2.*D0*D12+  AAT3690
     $B0E2*D12+2.*D1*D20+2.*B0*B1*D20+(G+3.)*.25*B1E4*B3+GM1*.5*B1*     AAT3700
     $B6E2                                                              AAT3710
      F52B=GP1*B1E2*D33+2.*B2*D32+B1E2*B2*B6+GP1*B0*B1E2*B6+G*          AAT3720
     $.5*B0*B1E3*B2+B1E3*D16*.5+2.*B6*D19+B3*D13*.5+GM1*.5*B1E2*        AAT3730
     $D34                                                               AAT3740
      F52C=4.*GM1*B0*D32+GM1*.25*B0*D26+2.*GM1*B6*D20+GM1*              AAT3750
     $B1*B2*D20+GM1*.5*B0E2*B1E3                                        AAT3760
      F52=F52A+F52B+F52C                                                AAT3770
      F53=2.*B1E2*F18+4.*B0*F16+2.*B1*F47-2.*BETA1*B1*D1+(G-5.)*BETA1*  AAT3780
     $B0*B1E2-(3.*G-1.)*BETA1*B1*B6+(G+3.)*.5*B1E2*D35+2./3.*B2*D23-    AAT3790
     $(3.*G-1.)*.5*BETA1*B1E2*B2-2.*BETA1*D19+GM1*B0*D23-BETA1*D20      AAT3800
      F54=4.*B0*F18+2.*B1*F31-GP1*BETA1*B1*B3+2.*B2*D35-GP1*            AAT3810
     $BETA1*B0*B2-2.*BETA1*D16+GM1*B0*D35-BETA1*D0+GM1*BETA1*           AAT3820
     $B0E2                                                              AAT3830
      F55=GM1*.5*B1*B3E2+2.*B2*D29+2.*G*B0*B2*B3+2.*B3*D16              AAT3840
      F56=2.*B2*F17+B1*F36/3.+6.*B2E2*D11+(3.*G-1.)*B1*B2E3+GM1*B2*     AAT3850
     $D25                                                               AAT3860
      F57=B1E2*F17+B2*F19+B1*F32*.5+3.*B2E2*D12+D11*D14+2.*B1E2*B2*D11+ AAT3870
     $3.*G*B1E3*B2E2+(G+2.)*.5*B1*B2*D14+GP1*.5*B1E2*D25+GM1*B2*        AAT3880
     $D26                                                               AAT3890
      F58=4.*B2*F21+2.*B0*F17+B1*F30+4.*D11*D16+3.*B2E2*D1+2.*G*B0*B1*  AAT3900
     $B2E2+4.*B0*B2*D11+2.*G*B1*B2*D16+G*B2*D25+3.*(G+3.)*.5*B1*B2E3+   AAT3910
     $2.*GM1*B2*D34+GM1*B0*D25+3.*GM1*B2E2*B6                           AAT3920
      F59=-BETA1*B2E2                                                   AAT3930
      F60=B1E2*F19*.5+B2*F15*.25+B1*F33/8.+D12*D14*.5+D11*D13*.25+B1E2* AAT3940
     $B2*D12+B1E4*D11*.5+GP1*.25*B1E3*D14+(G+4.)/8.*B1*B2*D13+(2.*G+    AAT3950
     $1.)*.5*B1E5*B2+G*.5*B1E2*D26+GM1*B2*D21                           AAT3960
      F61A=2.*B1E2*F21+4.*B2*F25+B0*F19+2.*B1*F48+2.*D12*D16+4.*D11*    AAT3970
     $D20+D1*D14*.5+B0*B1*D14*.5+2.*B0*B1E2*D11+2.*B0*B2*D12+B1E2*B2*   AAT3980
     $D1                                                                AAT3990
```

TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

```
      F61B=G*B1E3*D16+2.*G*B1*B2*D20+2.*G*B1E2*B2*B6+GP1*B1E2*D34+     AAT4000
     $GP1*.25*B2*D26+(G+4.)*.5*B1E3*B2E2+2.*G*B0*B1E3*B2+GP1*.5*       AAT4010
     $B6*D14                                                           AAT4020
      F61C=2.*B1*B2*D19+GM1*.5*B1E2*D25+4.*GM1*B2*D32+GM1*             AAT4030
     $B0*D26+GM1*.25*B1*B2*D14                                         AAT4040
      F61=F61A+F61B+F61C                                               AAT4050
      F62=4.*B2*F16+2.*B1*F35-4.*BETA1*B1*D11-(5.*G+11.)*.5*BETA1*B1E2 AAT4060
     $*B2-1.25*BETA1*D14+GM1*B2*D23                                    AAT4070
      F63A=2.*B2*F1+2.*B0*B2*D1+2.*G*B1*B2*D0+4.*B0*F21+2.*B1*F36+4.*  AAT4080
     $D0*D11+2.*B0E2*D11+2.*D1*D16+2.*B0*B1*D16+(G+5.)*B1E2*B2*B3+     AAT4090
     $GP1*B2*D34                                                       AAT4100
      F63B=6.*B2E2*B6+GP1*B0*B1*B2E2+GP1*B1*B2*D16+B3*D14              AAT4110
     $+2.*GM1*B2*D33+GM1*B0*D25+2.*GM1*B0*D34+2.*GM1*                  AAT4120
     $B6*D16+GM1*B0E2*B1*B2+2.*GM1*B0*B2*B6                            AAT4130
      F63=F63A+F63B                                                    AAT4140
      F64=4.*B2*F18-(G+7.)*BETA1*B2E2+GM1*B2*D35+GM1*BETA1*B0*         AAT4150
     $B2-BETA1*D16                                                     AAT4160
      F65=2.*(G+4.)*B2E2*B3                                            AAT4170
      F66A=GM1*B1*B3*B6+(G+5.)*.5*BETA1E2*B1+2.*B1E2*D29+2.*B2*D33+    AAT4180
     $G*B1E2*B2*B3+2.*B0*B1E2*B3+2.*B0*B2*B6+2.*B6*D16+2.*B3*D19+2.*   AAT4190
     $GM1*B0*D33                                                       AAT4200
      F66B=GM1*B0*D34+2.*GM1*B6*D0+GM1*B0E2*B6+GM1*B1                  AAT4210
     $*B2*D0+GM1*.5*B0E2*B1*B2+2.*B0*F1+2.*D0*D1+B0E2*D1+2.*B0*        AAT4220
     $B1*D0                                                            AAT4230
      F66=F66A+F66B                                                    AAT4240
      F68=F50/6.-F60/36.                                               AAT4250
      F69=F52*.25+F57/32.-F61/16.                                      AAT4260
      F70=F53/3.-F62/9.                                                AAT4270
      F71=F58*.25-3./8.*F56-F63*.25+F66*.5                             AAT4280
      F72=F58*.5-0.75*F56                                              AAT4290
      F73=F61*.25-F57/8.                                               AAT4300
      F74=0.75*F56-F58*.5+F63*.5                                       AAT4310
      F75=F64-2.*F59                                                   AAT4320
      F76=F54+2.*F59-F64                                               AAT4330
      F77=F49*Y0E7/8.+F68*Y0E5+F51*Y0E4/5.+F69*Y0E3+F70*Y0E2+F71*Y0+   AAT4340
     $F56*Y0C13*.5+F57*Y0C14*.25+F72*Y0C6+F59*Y0C11+F65*Y0C12*.5+F60*  AAT4350
     $Y0C15/6.+F73*Y0C7+F62*Y0C4/3.+F74*Y0C1+F75*Y0C0+F55*Y0C5+F76     AAT4360
      F78=F49*YIE7/8.+F68*YIE5+F51*YIE4/5.+F69*YIE3+F70*YIE2+F71*YI+   AAT4370
     $F56*YIC13*.5+F57*YIC14*.25+F72*YIC6+F59*YIC11+F65*YIC12*.5+F60*  AAT4380
     $YIC15/6.+F73*YIC7+F62*YIC4/3.+F74*YIC1+F75*YIC0+F55*YIC5+F76     AAT4390
      F67=(F8*Y0-F4*YI-F78*Y0+F77*YI)*YI*Y0/(Y0E2-YIE2)                AAT4400
      F0=(F4*Y0-F77*Y0-F67)/(B1*Y0E2)                                  AAT4410
      F79=F71+B1*F0                                                    AAT4420
C                                                                      AAT4430
C...CALCULATE THE Y CONSTANTS AND THE "E" FUNCTIONS:                   AAT4440
C                                                                      AAT4450
 70   IF(FCOEF) GO TO 80                                               AAT4460
      YE6=YE3*YE3    $    YE7=YE3*YE4                                  AAT4470
      YC8=YC4/Y    $    YC9=YC4*YC0                                    AAT4430
      YC10=Y*YC6    $    YC11=Y*YC7                                    AAT4490
```

TRANWZ CODE...SUBROUTINE AATRANS (CONT.)

```
      YC12=Y*YC9    $    YC13=Y*YC10                                    AAT4500
      YC14=Y*YC11                                                       AAT4510
      E3P=F14*Y+F13/Y                                                   AAT4520
      E3=F14*YE2*.5+F13*YC0                                             AAT4530
      E2P=F15*YE3*.25+F24*Y+F21/Y-F18/YE2+F19*YC1*.5+F17*YC3+F16        AAT4540
      E2=F15*YE4/16.+F25*YE2+F16*Y+F18/Y+F17*YC4*.5+F19*YC8*.25+F21*YC0 AAT4550
      E1P=F26*YE5/6.+F41*YE3+F28*YE2/3.+F42*Y+F38/Y-F31/YE2+F32*YC8*.5  AAT4560
     $+F36*YC8*.5+F33*YC7*.25+F43*YC1+F35*YC0+F30*YC3+F44               AAT4570
      E1=F26*YE6/36.+F45*YE4+F28*YE3/9.+F46*YE2+F47*Y+F31/Y+F36*YC8/6.  AAT4580
     $+F32*YC10*.25+F30*YC4*.5+F33*YC11/16.+F48*YC5+F35*YC1+F38*YC0     AAT4590
      E0P=F49*YE7/8.+F68*YE5+F51*YE4/5.+F69*YE3+F70*YE2+F79*Y+F67/Y+    AAT4600
     $F56*YC12*.5+F57*YC13*.25+F72*YC6+F58*YC4+F65*YC8*.5+F60*YC14/6.+  AAT4610
     $F73*YC7+F62*YC5/3.+F74*YC1+F75*YC0+F55*YC3+F76                    AAT4620
C                                                                       AAT4630
C...CALCULATE THE DESIRED QUANTITIES TO THIRD ORDER:                    AAT4640
C                                                                       AAT4650
      ZE3=Z*ZE2    $    EPSE3=EPS*EPSE2                                 AAT4660
      U3=E1+F0+(2.*E2+F1)*Z+(3.*E3+F2)*ZE2+F3*ZE3                       AAT4670
      V3=E0P+E1P*Z+E2P*ZE2+E3P*ZE3                                      AAT4680
      U=U+U3*EPSE3    $    V=V+CVT*V3*EPSE3                             AAT4690
      MSTAR=MSTAR+(U3+GP1*.25*V1*V1)*EPSE3                              AAT4700
      THETA=THETA+CVT*(V3-U1*V2-U2*V1+U1*U1*V1)*EPSE3                   AAT4710
      M=M+CM*(U3+GP1*.25*V1*V1+1.5*GM1*U1*U2+(5.*G*G-8.*G+3.)/          AAT4720
     $8.*U1*U1*U1)*EPSE3                                                AAT4730
      PPO=PPO-CPPO*G*(U3+GP1*.25*V1*V1-GP1/6.*U1*U1*U1)*EPSE3           AAT4740
      U3S=SNGL(U3)    $    V3S=SNGL(V3)                                 AAT4750
      US=SNGL(U)    $    VS=SNGL(V)                                     AAT4760
      MSTARS=SNGL(MSTAR)    $    THETAS=SNGL(THETA)                     AAT4770
      MS=SNGL(M)    $    PPOS=SNGL(PPO)                                 AAT4780
      RETURN                                                            AAT4790
C                                                                       AAT4800
C...IF DESIRED, CALCULATE THE DISCHARGE COEFFICIENT:                    AAT4810
C                                                                       AAT4820
 80   CD36=B1E3*D32*.25+B6*D21/6.                                       AAT4830
      CD37=B1E3*D23/12.-BETA1*D21/6.                                    AAT4840
      CD38=B1E3*D33*.25+B6*D32+B3*D21/6.                                AAT4850
      CD39=B1E3*D35*.25+B6*D23/3.-BETA1*D32                             AAT4860
      CD40=B1E3*D29*.25+B6*D33+B3*D32-BETA1*D23/3.                      AAT4870
      CD41=B6*D35+B3*D23/3.-BETA1*D33                                   AAT4880
      CD42=B6*D29+B3*D33-BETA1*D35                                      AAT4890
      CD43=B3*D35-BETA1*D29                                             AAT4900
      CD44=B1E3*D25/8.+B1*B2*D26*.25                                    AAT4910
      CD45=B6*D25*.5+B1*B2*D34                                          AAT4920
      CD46=-BETA1*B1*B2E2-BETA1*D25*.5                                  AAT4930
      CD47=2.*B1*B2E2*B3+B3*D25*.5                                      AAT4940
      CD48=B1E3*D26/16.+B1*B2*D21/6.                                    AAT4950
      CD49=B1E3*D34*.25+B6*D26*.25+B1*B2*D32                            AAT4960
      CD50=B1*B2*D23/3.-BETA1*B1E3*B2*.25-BETA1*D26*.25                 AAT4970
      CD51=B1E3*B2*B3*.5+B6*D34+B1*B2*D33+B3*D26*.25                    AAT4980
      CD52=-BETA1*B2*B6+B1*B2*D35-BETA1*D34                             AAT4990
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TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

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      CD53=2.*B2*B3*B6+B1*B2*D29+B3*D34+BETA1E2*B2
      CD54=CD36/8.-CD48/64.
      CD55=CD38/6.+CD44/108.-CD49/36.
      CD56=CD39/5.-CD50/25.
      CD57=CD40*.25-3./256.*B1*B2*D25+CD45/32.-CD51/16.
      CD58=CD41/3.+2./27.*CD46-CD52/9.
      CD59=CD42*.5+CD47*.25-CD53*.25
      CD60=CD43+3.*BETA1*B2*B3
      CD61=CD45*.25-3./32.*B1*B2*D25
      CD62=CD49/6.-CD44/18.
      CD63=3./64.*B1*B2*D25-CD45/8.+CD51*.25
      CD64=CD52/3.-2./9.*CD46
      CD65=CD53*.5-CD47*.5
      CD30A=B1E3*D21/240.*(YOE10-YIE10)+CD54*(YOE8-YIE8)+CD37/7.*(YOE7-
     $YIE7)+CD55*(YOE6-YIE6)+CD56*(YOE5-YIE5)+CD57*(YOE4-YIE4)+CD58*
     $(YOE3-YIE3)
      CD30B=CD59*(YOE2-YIE2)+CD60*(YO-YI)+B1*B2*D25/8.*(YOC16-
     $YIC16)+CD44/6.*(YOC17-YIC17)+CD61*(YOC8-YIC8)+CD46/3.*(YOC14-
     $YIC14)
      CD30C=CD47*.5*(YOC2-YIC2)+B2*B3E2*(YOC11-YIC11)+CD48/8.*(YOC18-
     $YIC18)+CD62*(YOC9-YIC9)+CD50/5.*(YOC15-YIC15)+CD63*(YOC3-YIC3)+
     $CD64*(YOC7-YIC7)
      CD30D=CD65*(YOC4-YIC4)-3.*BETA1*B2*B3*(YOC1-YIC1)+B3*D29*
     $(YOCO-YICO)
      CD30=CD30A+CD30B+CD30C+CD30D
      CD66=B1E5*B6*.25+B0*B1E6/16.
      CD67=B1E5*B3*.25+B1E2*B6E2*.5+B0*B1E3*B6*.5
      CD68=-BETA1*B1E2*B6-BETA1*B0*B1E3*.5
      CD69=B1E2*B3*B6+BETA1E2*B1E2*.5+B0*B1E3*B3*.5+B0*B6E2
      CD70=-BETA1*B1E2*B3-2.*BETA1*B0*B6
      CD71=2.*B0*B3*B6+BETA1E2*B0+B1E2*B3E2*.5
      CD72=2.*B1*B2E2*B6+B0*B1E2*B2E2
      CD73=1.5*B1E3*B2*B6+B0*B1E4*B2*.5
      CD74=1.5*B1E3*B2*B3+B2*B6E2+2.*B0*B1*B2*B6
      CD75=-2.*BETA1*B2*B6-2.*BETA1*B0*B1*B2
      CD76=2.*B2*B3*B6+BETA1E2*B2+2.*B0*B1*B2*B3
      CD77=CD66/8.-5./1024.*B1E6*B2
      CD78=CD67/6.+B1E4*B2E2/108.-CD73/36.
      CD79=CD68/5.+3./50.*BETA1*B1E3*B2
      CD80=CD69*.25-3./128.*B1E2*B2E3+CD72/32.-CD74/16.
      CD81=CD70/3.-4./27.*BETA1*B1*B2E2-CD75/9.
      CD82=CD71*.5+B1*B2E2*B3*.5-CD76*.25
      CD83=2.*BETA1*B2*B3-2.*BETA1*B0*B3
      CD84=CD72*.25-3./16.*B1E2*B2E3
      CD85=CD73/6.-B1E4*B2E2/18.
      CD86=3./32.*B1E2*B2E3-CD72/8.+CD74*.25
      CD87=4./9.*BETA1*B1*B2E2+CD75/3.
      CD88=CD76*.5-B1*B2E2*B3
      CD31A=B1E8/320.*(YOE10-YIE10)+CD77*(YOE8-YIE8)-BETA1*B1E5/
     $28.*(YOE7-YIE7)+CD78*(YOE6-YIE6)+CD79*(YOE5-YIE5)+CD80*
     $(YOE4-YIE4)
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TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

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      CD31B=CD81*(YOE3-YIE3)+CD82*(YOE2-YIE2)+CD83*(YO-YI)+B1E2*        AAT5510
     $B2E3*.25*(YOC16-YIC16)+B1E4*B2E2/6.*(YOC17-YIC17)+CD84*(YOC8-YIC8) AAT5520
      CD31C=-2./3.*BETA1*B1*B2E2*(YOC14-YIC14)+B1*B2E2*B3*(YOC2-YIC2)+B2 AAT5530
     $*B3E2*.5*(YOC11-YIC11)+5./128.*B1E6*B2*(YOC18-YIC18)+CD85*(YOC9-  AAT5540
     $YIC9)                                                              AAT5550
      CD31D=-3./10.*BETA1*B1E3*B2*(YOC15-YIC15)+CD86*(YOC3-YIC3)+CD87*  AAT5560
     $(YOC7-YIC7)+CD88*(YOC4-YIC4)-2.*BETA1*B2*B3*(YOC1-YIC1)+B0*B3E2*  AAT5570
     $(YOC0-YIC0)                                                        AAT5580
      CD31=GM1*.5*(CD31A+CD31B+CD31C+CD31D)                              AAT5590
      CD89=B1E2*F45*.5+B0*F26/36.                                        AAT5600
      CD90=B1E2*F46*.5+B0*F45                                            AAT5610
      CD91=B1E2*F47*.5+B0*F28/9.                                         AAT5620
      CD92=B1E2*F0*.5+B0*F46                                             AAT5630
      CD93=B1E2*F31*.5+B0*F47                                            AAT5640
      CD94=B1E2*F36/12.+B2*F32*.25                                       AAT5650
      CD95=B2*F30*.5+B0*F36/6.                                           AAT5660
      CD96=B1E2*F32/8.+B2*F33/16.                                        AAT5670
      CD97=B1E2*F30*.25+B2*F48+B0*F32*.25                                AAT5680
      CD98=B2*F38+B0*F30*.5                                              AAT5690
      CD99=B1E2*F33/32.+B2*F26/36.                                       AAT5700
      CD100=B1E2*F48*.5+B2*F45+B0*F33/16.                                AAT5710
      CD101=B1E2*F35*.5+B2*F28/9.                                        AAT5720
      CD102=B1E2*F38*.5+B2*F46+B0*F48                                    AAT5730
      CD103=B2*F47+B0*F35                                                AAT5740
      CD104=B2*F0+B0*F38                                                 AAT5750
      CD105=CD89/8.-CD99/64.                                             AAT5760
      CD106=CD90/6.+CD96/108.-CD100/36.                                  AAT5770
      CD107=CD91/5.-CD101/25.                                            AAT5780
      CD108=CD92*.25+CD97/32.-CD102/16.-3./128.*CD94                     AAT5790
      CD109=CD93/3.+2./27.*B2*F35-CD103/9.                               AAT5800
      CD110=B0*F0*.5+B2*F36/8.-3./8.*CD95+CD98*.25-CD104*.25             AAT5810
      CD111=B0*F31-B2*F31                                                AAT5820
      CD112=CD95*.5-B2*F36/6.                                            AAT5830
      CD113=CD97*.25-3./16.*CD94                                         AAT5840
      CD114=B2*F36*.25-0.75*CD95+CD98*.5                                 AAT5850
      CD115=CD100/6.-CD96/18.                                            AAT5860
      CD116=CD102*.25-CD97/8.+3./32.*CD94                                AAT5870
      CD117=CD103/3.-2./9.*B2*F35                                        AAT5880
      CD118=0.75*CD95-B2*F36*.25-CD98*.5+CD104*.5                        AAT5890
      CD32A=B1E2*F26/720.*(YOE10-YIE10)+CD105*(YOE8-YIE8)+B1E2*F28/     AAT5900
     $126.*(YOE7-YIE7)+CD106*(YOE6-YIE6)+CD107*(YOE5-YIE5)+CD108*(YOE4  AAT5910
     $-YIE4)                                                             AAT5920
      CD32B=CD109*(YOE3-YIE3)+CD110*(YOE2-YIE2)+CD111*(YO-YI)+B2*F36/   AAT5930
     $12.*(YOC19-YIC19)+CD94*.25*(YOC16-YIC16)+CD96/6.*(YOC17-YIC17)+   AAT5940
     $CD113*(YOC8-YIC8)                                                  AAT5950
      CD32C=B2*F35/3.*(YOC14-YIC14)+CD114*(YOC2-YIC2)+CD99/8.*         AAT5960
     $(YOC18-YIC18)+CD115*(YOC9-YIC9)+CD101/5.*(YOC15-YIC15)+CD116      AAT5970
     $*(YOC3-YIC3)                                                       AAT5980
      CD32D=CD117*(YOC7-YIC7)+CD118*(YOC4-YIC4)+B2*F31*(YOC1-YIC1)      AAT5990
     $+CD112*(YOC10-YIC10)                                               AAT6000
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TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

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      CD32=2.*(CD32A+CD32B+CD32C+CD32D)                                  AAT6010
      CD119=D0*D13/8.+D20E2                                              AAT6020
      CD120=2.*D0*D20+BETA1E2*B1E2                                       AAT6030
      CD121=B2E2*D13/8.+D14E2/16.                                        AAT6040
      CD122=2.*B2E2*D20+D14*D16*.5                                       AAT6050
      CD123=2.*B2E2*D0+D16E2                                             AAT6060
      CD124=D13*D16/8.+D14*D20*.5                                        AAT6070
      CD125=2.*D16*D20+D0*D14*.5                                         AAT6080
      CD126=D13*D20/64.-D13*D14/2048.                                    AAT6090
      CD127=CD119/6.+CD121/108.-CD124/36.                                AAT6100
      CD128=BETA1*B1*D14/50.-2./5.*BETA1*B1*D20                          AAT6110
      CD129=CD120*.25-3./256.*B2E2*D14+CD122/32.-CD125/16.               AAT6120
      CD130=2./9.*BETA1*B1*D16-2./3.*BETA1*B1*D0-4./27.*BETA1*B1*B2E2    AAT6130
      CD131=D0E2*.5+0.75*B2E4-0.75*B2E2*D16+CD123*.25-D0*D16*.5          AAT6140
      CD132=B2E2*D16-B2E4                                                AAT6150
      CD133=CD122*.25-3./32.*B2E2*D14                                    AAT6160
      CD134=1.5*B2E4-1.5*B2E2*D16+CD123*.5                               AAT6170
      CD135=CD124/6.-CD121/18.                                           AAT6180
      CD136=3./64.*B2E2*D14-CD122/8.+CD125*.25                           AAT6190
      CD137=4./9.*BETA1*B1*B2E2-2./3.*BETA1*B1*D16                       AAT6200
      CD138=1.5*B2E2*D16-1.5*B2E4-CD123*.5+D0*D16                        AAT6210
      CD33A=D13E2/2560.*(YOE10-YIE10)+CD126*(YOE8-YIE8)-BETA1*B1*D13/56. AAT6220
     $*(YOE7-YIE7)+CD127*(YOE6-YIE6)+CD128*(YOE5-YIE5)+CD129*(YOE4-YIE4) AAT6230
     $+CD130*(YOE3-YIE3)                                                 AAT6240
      CD33B=CD131*(YOE2-YIE2)+B2E4*.5*(YOC19-YIC19)+B2E2*D14/8.          AAT6250
     $*(YOC16-YIC16)+CD132*(YOC10-YIC10)+CD121/6.*(YOC17-YIC17)+         AAT6260
     $CD133*(YOC8-YIC8)                                                  AAT6270
      CD33C=-2./3.*BETA1*B1*B2E2*(YOC14-YIC14)+CD134*(YOC2-YIC2)         AAT6280
     $+D13*D14/256.*(YOC18-YIC18)+CD135*(YOC9-YIC9)-BETA1*B1*D14/        AAT6290
     $10.*(YOC15-YIC15)                                                  AAT6300
      CD33D=CD136*(YOC3-YIC3)+CD137*(YOC7-YIC7)+CD138*(YOC4-YIC4)        AAT6310
      CD33=CD33A+CD33B+CD33C+CD33D                                       AAT6320
      CD139=B1E4*D20*.25+B0*B1E2*D13/16.                                 AAT6330
      CD140=B1E4*D0*.25+B0*B1E2*D20+B0E2*D13/16.                         AAT6340
      CD141=B0*B1E2*D0+B0E2*D20                                          AAT6350
      CD142=B1E2*B2E3+B2E2*D14*.25                                       AAT6360
      CD143=B2E2*D16+2.*B0*B2E3                                          AAT6370
      CD144=B1E4*B2E2*.25+B1E2*B2*D14*.25+B2E2*D13/16.                   AAT6380
      CD145=B1E2*B2*D16+B2E2*D20+B0*B1E2*B2E2+B0*B2*D14*.5               AAT6330
      CD146=B2E2*D0+2.*B0*B2*D16+B0E2*B2E2                               AAT6400
      CD147=B1E4*D14/16.+B1E2*B2*D13/16.                                 AAT6410
      CD148=B1E4*D16*.25+B1E2*B2*D20+B0*B1E2*D14*.25+B0*B2*D13/8.        AAT6420
      CD149=B1E2*B2*D0+B0*B1E2*D16+2.*B0*B2*D20+B0E2*D14*.25             AAT6430
      CD150=2.*B0*B2*D0+B0E2*D16                                         AAT6440
      CD151=CD139/8.-CD147/64.                                           AAT6450
      CD152=CD140/6.+CD144/108.-CD148/36.                                AAT6460
      CD153=BETA1*B1E3*B2/25.-BETA1*B0*B1E3/5.                           AAT6470
      CD154=CD141*.25-3./128.*CD142+CD145/32.-CD149/16.                  AAT6480
      CD155=2./9.*BETA1*B0*B1*B2-BETA1*B0E2*B1/3.-2./27.*BETA1*B1*B2E2   AAT6490
      CD156=B0E2*D0*.5+0.75*B2E4-3./8.*CD143+CD146*.25-CD150*.25         AAT6500
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TRANNOZ CODE...SUBROUTINE AATRANS (CONT.)

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      CD157=CD143*.5-B2E4                                               AAT6510
      CD158=CD145*.25-3./16.*CD142                                      AAT6520
      CD159=1.5*B2E4-0.75*CD143+CD146*.5                                AAT6530
      CD160=CD148/6.-CD144/18.                                          AAT6540
      CD161=3./32.*CD142-CD145/8.+CD149*.25                             AAT6550
      CD162=2./9.*BETA1*B1*B2E2-2./3.*BETA1*B0*B1*B2                    AAT6560
      CD163=0.75*CD143-1.5*B2E4-CD146*.5+CD150*.5                       AAT6570
      CD34A=B1E4*D13/640.*(Y0E10-YIE10)+CD151*(Y0E8-YIE8)-BETA1         AAT6580
     $*B1E5/28.*(Y0E7-YIE7)+CD152*(Y0E6-YIE6)+CD153*(Y0E5-YIE5)+        AAT6590
     $CD154*(Y0E4-YIE4)                                                 AAT6600
      CD34B=CD155*(Y0E3-YIE3)+CD156*(Y0E2-YIE2)+B2E4*.5*(Y0C19          AAT6610
     $-YIC19)+CD142*.25*(Y0C16-YIC16)+CD157*(Y0C10-YIC10)+CD144/6.      AAT6620
     $*(Y0C17-YIC17)                                                    AAT6630
      CD34C=CD158*(Y0C8-YIC8)-BETA1*B1*B2E2/3.*(Y0C14-YIC14)+           AAT6640
     $CD159*(Y0C2-YIC2)+CD147/8.*(Y0C18-YIC18)+CD160*(Y0C9-YIC9)-BETA1  AAT6650
     $*B1E3*B2/5.*(Y0C15-YIC15)                                         AAT6660
      CD34D=CD161*(Y0C3-YIC3)+CD162*(Y0C7-YIC7)+CD163*(Y0C4-YIC4)       AAT6670
      CD34=(2.*G-3.)*(CD34A+CD34B+CD34C+CD34D)                          AAT6680
      CD164=B0*B1E6/16.-B1E6*B2/128.                                    AAT6690
      CD165=B0E2*B1E4*.25+B1E4*B2E2/72.-B0*B1E4*B2/12.                  AAT6700
      CD166=B0E3*B1E2*.5-3./64.*B1E2*B2E3+3./16.*B0*B1E2*B2E2-3./8.*    AAT6710
     $B0E2*B1E2*B2                                                      AAT6720
      CD167=B0E4*.5+0.75*B2E4-1.5*B0*B2E3+1.5*B0E2*B2E2-B0E3*B2         AAT6730
      CD168=2.*B0*B2E3-B2E4                                             AAT6740
      CD169=1.5*B0*B1E2*B2E2-3./8.*B1E2*B2E3                            AAT6750
      CD170=1.5*B2E4-3.*B0*B2E3+3.*B0E2*B2E2                            AAT6760
      CD171=B0*B1E4*B2*.5-B1E4*B2E2/12.                                 AAT6770
      CD172=3./16.*B1E2*B2E3-0.75*B0*B1E2*B2E2+1.5*B0E2*B1E2*B2         AAT6780
      CD173=3.*B0*B2E3-1.5*B2E4-3.*B0E2*B2E2+2.*B0E3*B2                 AAT6790
      CD35A=B1E8/160.*(Y0E10-YIE10)+CD164*(Y0E8-YIE8)+CD165             AAT6800
     $*(Y0E6-YIE6)+CD166*(Y0E4-YIE4)+CD167*(Y0E2-YIE2)+B2E4*.5          AAT6810
     $*(Y0C19-YIC19)                                                    AAT6820
      CD35B=B1E2*B2E3*.5*(Y0C16-YIC16)+CD168*(Y0C10-YIC10)+B1E4         AAT6830
     $*B2E2*.25*(Y0C17-YIC17)+CD169*(Y0C8-YIC8)+CD170*(Y0C2-YIC2)+      AAT6840
     $B1E6*B2/16.*(Y0C18-YIC18)                                         AAT6850
      CD35C=CD171*(Y0C9-YIC9)+CD172*(Y0C3-YIC3)+CD173*(Y0C4-YIC4)       AAT6860
      CD35=(2.*G*G-5.*G+2.)*.25*(CD35A+CD35B+CD35C)                     AAT6870
      CD3=CD30+CD31+CD32+CD33+CD34+CD35                                 AAT6880
      CD=CD-CCD*CD3*EPS*EPS                                             AAT6890
      CDS=SNGL(CD)                                                      AAT6900
      RETURN                                                            AAT6910
      END                                                               AAT6920
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