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COMPUTER PROGRAM FOR QUASI-ONE-DIMENSIONAL COMPRESSIBLE FLOW WITH AREA CHANGE AND FRICTION - APPLICATION TO GAS FILM SEALS

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16. Abstract

A computer program is presented for compressible fluid flow with friction and area change. The program carries out a quasi-one-dimensional flow analysis which is valid for laminar and turbulent flows under both subsonic and choked flow conditions. The program was written to be applied to gas film seals. The area-change analysis should prove useful for choked flow conditions with small mean film thickness, as well as for face seals where radial area change is significant. The program is written in FORTRAN IV.

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SUMMARY

The computer program, AREAX, presented in this report calculates the properties of compressible fluid flow with friction and area change. The program carries out a quasi-one-dimensional flow analysis which is valid for laminar and turbulent flows under both subsonic and choked flow conditions. The program was written to be applied to gas film seals. The area-change analysis should prove useful for choked flow conditions with a small mean film thickness, as well as for face seals where radial area change is significant.

The program requires the seal geometry, the reservoir conditions, and the gas properties as input. It will then calculate seal mass leakage and volume leakage; force; center of pressure; and distributions of pressure, temperature, density, mean friction factor, Reynolds number, friction parameter, velocity, and Mach number across the seal for both laminar and turbulent flow regimes and for choked and subsonic flow.

The program is written in FORTRAN IV. Input, internal calculations, and output can be in either the International System of Units (SI) or the U. S. customary system.

This report includes a description of the program, a summary of the mathematical model on which the program is based, a complete description of the input variables, and sample input and output.

INTRODUCTION

Shaft seals in advanced rotating machinery, such as in advanced aircraft turbine engines, will operate at higher speeds, temperatures, and pressures than shaft seals in current use. Because of these severe operating conditions, a positive face separation (no rubbing contact) is required for long life and reliability (ref. 1). However, seal-face deformation is very likely to occur.

These deformations may be caused by various distortions (thermal, centrifugal, pressure, etc.). Seal-face distortions become more pronounced under severe operating conditions and are usually detrimental to seal performance. Hence, prediction of these face deformation effects on gas-film-seal performance is of paramount importance. This report presents an analysis and computer program to enable prediction of gas-film-face-seal performance when face deformations and/or radial area change is significant. The analysis is especially useful for choked flow conditions.

The computer program presented in this report, AREAX, calculates the properties of compressible fluid flow with friction and area change across shaft face seals. It extends the capabilities of the program QUASC (ref. 2) to account for the change in flow properties resulting from radial area change and face deformations represented by linear distortions of the seal faces. The mathematical model for this analysis is given in the next section. The analysis includes viscous friction, fluid inertia, area change, and entrance losses. Rotational effects and body forces are neglected. The model is valid for subsonic flow and for choked flow. It is also valid for both laminar and turbulent flow regimes.

Computer programs have proven useful in seal design, where much of the physical information of interest is difficult to determine experimentally. The program QUASC has proven to be a good model for most applications. It rapidly evaluates physical quantities of interest. However, QUASC is valid only for parallel sealing surfaces and constant-area flow. The program presented here should be used when the effects of seal-face distortions are desired and when the radial area change is significant.

Some of the physical parameters of interest in designing a seal are the leakage, the pressure distribution across the seal, and the opening (separating) force. These and other parameters are determined by the program AREAX for specified seal geometries (flow length, gap, surface deformation), reservoir pressures and temperatures, and gas properties. The program also requires two additional parameters. One of these is the variation of a mean Fanning friction factor with Reynolds number. The other is the entrance loss coefficient. The program input and output format are almost identical to QUASC (except for the accounting of the face deformation and radial area change).

This report is intended to serve three purposes: (1) to give a summary of the quasi-one-dimensional analysis of compressible flow with friction and area change, (2) to give a detailed description of the computer program AREAX which performs this analysis, and (3) to serve as a user's guide for AREAX.

QUASI-ONE-DIMENSIONAL FLOW ANALYSIS

The program AREAX is based on a mathematical model for sealing surfaces separated by a narrow gap. One surface may be tilted with respect to the other. The model is valid for both rectangular strip surfaces and coaxial ring surfaces. A pressure difference exists across the sealing dam. The cavities on either side of the sealing dam are assumed to be constant-pressure reservoirs.

The flow is assumed to be quasi-one-dimensional. It has been shown that the effects of rotation for a circular ring seal geometry are negligible for most gas film sealing applications (ref. 3). It is assumed that the rectangular surfaces do not slide with respect to one another.

The flow analysis can be separated into two parts. The first is the flow in the passage itself, where the flow is assumed to behave as adiabatic flow with friction and area change. The second part is flow in the entrance region. These two parts are discussed separately.

Seal Leakage Passage Flow

It is assumed that the flow in the seal leakage flow region behaves as a variable-area adiabatic flow with friction. A quasi-one-dimensional approximation is made wherein it is assumed that the flow properties can be described in terms of their cross-sectional averages.

The following assumptions have been made in the analysis: (1) the effects of rotation are negligible; (2) the flow is adiabatic; (3) no shaft work is done on or by the system; (4) no potential energy gradient is present, such as caused by evaluation difference, etc; (5) the fluid behaves as a perfect gas. In addition to these assumptions, a simplification to the area change is made in the momentum equation where $P\,dA$ and $A\,dP \gg dA\,dP$, or $A \gg dA$. This assumption should be satisfactory for most sealing applications.

The control volume is shown in figure 1. The governing equations with area changes reduce to the following differential forms (all symbols are defined in appendix A):

Conservation of mass:

$$\frac{d\rho}{\rho} + \frac{1}{2}\frac{du^2}{u^2} + \frac{dA}{A} = 0 \qquad (1)$$

Conservation of energy:

$$\frac{dT}{T} + \frac{\gamma - 1}{2} M^2 \frac{du^2}{u^2} = 0 \qquad (2)$$

Equation of state:

$$\frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dT}{T} \tag{3}$$

Conservation of momentum (for a <u>small</u> area change):

$$-A\ dP - \tau_w\ dA_w = \dot{M}\ du \tag{4}$$

With the introduction of the mean Fanning friction factor $\bar{f}$ and the hydraulic diameter D

$$\bar{f} = \frac{\frac{dP}{dx}}{\frac{2\rho u^2}{D}} = \bar{f}(x) \qquad \text{for radial flow}$$

$$D = \frac{4A}{\mathscr{P}_w} = 2h \qquad \text{for radial flow between parallel disks and plates}$$

equations (1) to (4) can be combined into a single equation (5)

$$\frac{dM^2}{M^2} = \frac{-2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2} \frac{dA}{A} + \left[\frac{\gamma M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2}\right] \frac{4\bar{f}\ dx}{D} \tag{5}$$

Equation (5) will be referred to as the Mach number equation. This equation is identical to the equation obtained from the Table of Influence Coefficients for generalized one-dimensional flow in references 4 and 5.

The other dependent variables can be found in a similar way and are

$$\frac{du}{u} = \frac{-1}{1 - M^2} \frac{dA}{A} + \frac{\gamma M^2}{2(1 - M^2)} \frac{4\bar{f}\ dx}{D} \tag{6}$$

$$\frac{dT}{T} = \frac{(\gamma - 1)M^2}{1 - M^2}\frac{dA}{A} - \frac{\gamma(\gamma - 1)M^4}{2(1 - M^2)}\frac{4\bar{f}\,dx}{D} \tag{7}$$

$$\frac{d\rho}{\rho} = \frac{M^2}{1 - M^2}\frac{dA}{A} - \frac{\gamma M^2}{2(1 - M^2)}\frac{4\bar{f}\,dx}{D} \tag{8}$$

$$\frac{dP}{P} = \frac{\gamma M^2}{1 - M^2}\frac{dA}{A} - \frac{\gamma M^2\left[1 + (\gamma - 1)M^2\right]}{2(1 - M^2)}\frac{4\bar{f}\,dx}{D} \tag{9}$$

Solving equation (5) for $4\bar{f}\,dx/D$ and substituting that into equations (6) to (9) give

$$\frac{du}{u} = \frac{dM^2}{2M^2\left(1 + \frac{\gamma - 1}{2}M^2\right)} \tag{10}$$

$$\frac{dT}{T} = \frac{-(\gamma - 1)}{2}\frac{dM^2}{1 + \frac{\gamma - 1}{2}M^2} \tag{11}$$

$$\frac{d\rho}{\rho} = -\frac{dA}{A} - \frac{dM^2}{2M^2\left(1 + \frac{\gamma - 1}{2}M^2\right)} \tag{12}$$

$$\frac{dP}{P} = -\frac{dA}{A} - \frac{dM^2\left[1 + (\gamma - 1)M^2\right]}{2M^2\left(1 + \frac{\gamma - 1}{2}M^2\right)} \tag{13}$$

Equations (10) to (13) can be integrated directly from the point of interest (M_x, A_x) to the point of choking $(M^* = 1, A^*)$ since the variables are separable. The integration gives the following equations:

$$\frac{u^*}{u} = \frac{1}{M}\sqrt{\frac{1 + \frac{\gamma - 1}{2}M^2}{\frac{1}{2}(\gamma + 1)}} \tag{14}$$

$$\frac{T^*}{T} = \frac{1 + \frac{\gamma - 1}{2} M^2}{\frac{1}{2}(\gamma + 1)} \tag{15}$$

$$\frac{\rho^*}{\rho} = \frac{AM}{A^*} \sqrt{\frac{\frac{1}{2}(\gamma + 1)}{1 + \frac{\gamma - 1}{2} M^2}} \tag{16}$$

$$\frac{P^*}{P} = \frac{AM}{A^*} \sqrt{\frac{1 + \frac{\gamma - 1}{2} M^2}{\frac{1}{2}(\gamma + 1)}} \tag{17}$$

Hence, once the Mach number distribution is known, the physical quantities of interest can be found.

With the introduction of the definition of the flow area A, the radius r, and the film thickness h

$$\left.\begin{aligned} A &= 2\pi rh \quad \text{for the coaxial ring geometry} \\ A &= Wh \quad \text{for the rectangular plate geometry} \end{aligned}\right\} \tag{18}$$

$$r = R_1 \pm x \tag{19}$$

$$h = h_1 + x \sin \alpha \tag{20}$$

equation (5) can be written as

$$\frac{dM^2}{dx} = \frac{2M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{h(1 - M^2)} \left\{\gamma M^2 \bar{f}(x) - \frac{\left[h + F(x)\sin \alpha\right]}{F(x)}\right\} \tag{21}$$

where

$$F(x) = \begin{cases} x & \text{for flow with no radial expansion} \\ R_1 + x & \text{for radial outward flow} \\ R_2 - x & \text{for radial inward flow} \end{cases}$$

and $x = 0$ is defined as the flow entrance whether the flow is radially inward or outward. The mean friction factor varies with Reynolds number according to the relation (ref. 6)

$$\bar{f} = \frac{k}{Re^n} \tag{22}$$

Consequently, $\bar{f}$ is an implicit function of x. Equation (21) can be integrated numerically from the point of interest (x, M) to the point of choking $(x^*, M^* = 1)$.

Other equations that are needed are those for Reynolds number and Mach number:

$$Re = \frac{\rho u D}{\mu} \tag{23}$$

$$M = \frac{u}{c} = \frac{u}{\sqrt{\gamma \mathscr{R} T}} \tag{24}$$

Entrance Flow

The entrance flow region can be assumed to be an isentropic and adiabatic expansion (ref. 6). Since real entrance flows are not isentropic because of viscous friction, turning losses, and so forth, the entrance loss is accounted for by introducing an empirically determined entrance velocity loss coefficient C_L into the isentropic equations. The resulting entrance equations for temperature and pressure become

$$\frac{T_1}{T_0} = \frac{1}{1 + \frac{\gamma - 1}{2}\left(\frac{M_1}{C_L}\right)^2} \tag{25}$$

and

$$\frac{P_1}{P_0} = \frac{1}{\left[1 + \frac{\gamma - 1}{2}\left(\frac{M_1}{C_L}\right)^2\right]^{\frac{\gamma}{\gamma - 1}}} \tag{26}$$

When $C_L = 1$, the flow is isentropic. When C_L is large (e.g., 30), the entrance losses become negligible.

SOLUTION OF EQUATIONS

The equations developed in the preceding sections, plus the equation of state written as

$$\frac{P}{\rho} = \mathscr{R}T \tag{27}$$

must now be solved. The independent variable is chosen to be x, the distance across the seal face (fig. 2), with the x origin always located at the flow entrance. The known parameters are

P_0 sealed-gas pressure (upstream reservoir pressure)

P_3 ambient pressure (downstream reservoir pressure)

T_0 sealed-gas temperature (upstream reservoir temperature, also the stagnation temperature)

C_L entrance velocity loss coefficient

ΔR distance across face of sealing dam

h(x) film thickness distribution

k, n constants in friction factor - Reynolds number relation

These two constants (k, n) apply to laminar flow ($Re \le Re_l$) and turbulent flow ($Re \ge Re_t$), respectively. For flow in the transition region ($Re_l < Re < Re_t$), variation of the friction factor with Reynolds number is determined by an interpolation method which is described in appendix B of reference 2.

There are two types of flow that must be considered: (1) choked flow, when the exit Mach number is 1 and the exit pressure is greater than the ambient pressure; and (2) subsonic flow, when the exit Mach number is less than 1 and the exit pressure equals the ambient pressure. The method of solution is the same for both types of flow. However, the boundary conditions are different. (The lengths and stations used in the analysis are illustrated for the subsonic-flow case in fig. 3.)

In both cases, equation (21), the Mach number equation which relates Mach number, flow distance, and friction is a differential equation which must be solved numerically. The fourth-order Runge-Kutta method is used. Since equation (21) is a first-order differential equation in x and M^2, one boundary condition on M^2 is needed. The only known condition is at $x = x^*$, $M^2 = 1$. Equation (21) is solved by guessing a value M_1^2 for M^2 at $x = 0$ and integrating until $M^2 = 1$. The final value of x is x^*. Since the Mach number is known to vary rapidly as x approaches x^*, the interval of integration is divided into small subintervals in that region.

For choked flow, the solution of the equations for this case is as follows: a value of M_1^2 is guessed, the Mach number equation is solved, and x^* is noted. If $x^* = \Delta R$, the solution is complete. If $x^* \neq \Delta R$, new values of M_1^2 are guessed until the condition $x^* = \Delta R$ is satisfied.

For subsonic flow, the solution of the equations for this case is as follows: a value of M_1^2 is guessed, the Mach number equation is solved, and x^* is noted. If x^* is less than ΔR, new values of M_1^2 are guessed until the solution of the Mach number gives a value of x^* greater than ΔR. When a satisfactory x^* is found, P_2 is calculated. If P_2 and P_3 are equal, the solution is complete. If P_2 and P_3 are not equal, new values of M_1^2 are guessed until the condition $P_2 = P_3$ is satisfied.

COMPUTER PROGRAM

The program AREAX which performs the analysis of quasi-one-dimensional flow with friction and area change across shaft face seals is written in FORTRAN IV for the IBM 7094II/7044 direct couple computer at the Lewis Research Center.

The program must be supplied with the geometry of the seal, the gas properties, the reservoir conditions, the constants for determining the variation of mean friction factor with Reynolds number, and certain logical variables which control output. Input and output can be in either the International System (SI) or the U.S. customary system of units.

In general, AREAX performs the following operations in analyzing the flow across a seal: It reads the input data and checks that these data are consistent. For instance, there are three input variables which can determine the flow length. Since only two are necessary, the third must be made consistent with the other two. When the input data have been read, AREAX analyzes the flow for each combination of film thickness and tilt angle.

The program first solves the Mach number equation and determines the Mach number distribution across the seal face. AREAX then determines the distributions across the seal face of pressure; temperature; density; velocity; mean friction factor; Reynolds number; mass and volume flow rates; Knudsen number; seal opening force; center of pressure; and where appropriate, rotational Reynolds number, variables associated with power dissipation, and axial film stiffness.

When these data have been calculated, the Mach number distribution across the seal face is punched on cards. Since the running time of the program can be fairly long, it is convenient to restart it and not have to rerun the cases that are complete. When all the data for all the film thicknesses have been calculated, AREAX writes the output data with appropriate labels and headings.

To increase program efficiency and to facilitate program writing, AREAX includes a number of subprograms. Figure 4 shows the heirarchy of the subprogram calls. Variables are transmitted between the main program and the subprograms through labeled COMMON storage. A more detailed description of AREAX and descriptions of the subprograms are given in appendix B. Since the programs AREAX and QUASC are so similar, the numerical methods described in reference 2 apply to both programs.

The formulas for the parameters calculated by AREAX are listed in table I. When the flow is in either the transitional or turbulent flow regime, the power loss due to rotation is not calculated. Also, there is no Reynolds number criterion for determining turbulence due to rotation. A complete list of the variable names used by the program is given in the program listing in appendix C. Flow charts of AREAX and the subprograms are also in appendix C.

Input Data

Input to AREAX is by punched cards. The NAMELIST feature of FORTRAN IV is used to read the data. This feature allows the individual variables to be named and eliminates complicated card formats.

The first card required by AREAX is a title card. The title identifies the data and uses columns 1 to 72 of one card. It is read by format (12A6).

The next cards required by AREAX contain the parameters in NAMELIST/SEAL/. These parameters define the seal geometry, the gas properties, and the logical variables. The variables in /SEAL/ are listed in table II. The next cards required contain the parameters in NAMELIST/HDATA/ which define the gap. These parameters are listed in table III. The last cards required contain the parameters in NAMELIST/RESDAT/ which define the reservoir properties. These variables are listed in table IV.

Output

Computer output consists of the input data and calculated parameters. If input is in SI units, output is also in SI units. If input is in U.S. units, output is also in U.S. units. The printed output parameters are identified, and the units of each are also printed. A sample of the output data appears in appendix D.

The first page of the output contains the title which identifies the data; the input data as they are read from cards; the checked input data; the calculated parameters - mean flow width and gas constant; and a list of what optional parameters will be calculated, namely power, normalized center of pressure, pressure profile factor, and distributions across the seal face. The key at the bottom of the page identifies the flow regime associated with a particular film thickness. The key is as follows:

/ choked flow

\+ flow in laminar-turbulent transitional regime

T flow in turbulent regime

The second page contains lists of parameters that vary only with mean film thickness. These parameters are mass flow rate, standard volume flow rate, mean Knudsen number, mean free path of the gas molecules, axial film stiffness, sealing dam force, center of pressure, normalized center of pressure, pressure profile factor, rotational flow Reynolds number, choking pressure, choking distance, power, heat generation due to viscous shearing, apparent temperature rise due to power dissipation, and torque. Power and parameters based on power dissipation are not printed for the transitional or turbulent flow regimes since they are not calculated.

The third and following pages contain lists of parameters that vary with radial distance as well as with mean film thickness. These parameters are film thickness, Mach number, velocity, density, pressure, temperature, Reynolds number, and mean friction factor. The maximum and minimum film thicknesses, the mean film thickness, the relative area change, the area change with respect to radial distance, and the tilt angle for each film thickness are printed above each set of lists.

SAMPLE PROBLEM

An example of the use of the computer program is given here with the following conditions: Air at 45 N/cm^2 abs (65.0 psia) is to be sealed from ambient air at 10.3 N/cm^2 abs (15.0 psia) by a coaxial ring seal operating in the externally pressurized mode. The mean temperature of the pressurized air is 311 K (100° F). The sealing dam outside diameter is 16.84 centimeters (6.630 in.), and the inside diameter is

16.58 centimeters (6.530 in.). The seal faces are separated by a negative linear tilt of 1 milliradian. (The smallest gap is located at the outer radius.) The design surface speed is 61 meters per second (200 ft/sec).

It is desired to find a design film thickness which is large enough so that power dissipation and viscous heating temperature rise are sufficiently low, yet small enough so that the mass leakage is tolerable. From our experience, the best method is to try mean film thickness inputs of 7.62 to 25.4 micrometers (0.3 to 1.0 mil) in increments of 2.54 micrometers (0.1 mil). However, to give a sample output for transitional flow and turbulent flow, the range of film thicknesses has been increased to 40.64 micrometers (1.6 mils). For this study, isentropic entrance conditions are assumed. Thus, the program input will include

Mean rotational velocity, V, m/sec (ft/sec)	61 (200)
Molecular weight of gas, m	28.9660
Reservoir temperature, T_0, K (^{o}F)	311 (100)
Reservoir pressure (highest pressure), P_0, N/cm^2 abs (psia)	45 (65.0)
Ambient pressure (lowest pressure), P_3, N/cm^2 abs (psia)	10.3 (15.0)
Specific heat at constant pressure, c_p, J/kg-K (Btu/lbm-^{o}R)	10^3 (0.24)
Film thickness (increase in increments of 2.54 μm (0.1 mil)), h, μm (mil)	7.62 to 40.64 (0.3 to 1.6)
Tilt angle, α, rad	-0.001
Inner radius, R_1, cm (in.)	8.300 (3.265)
Flow length, ΔR, cm (in.)	0.127 (0.050)
Specific-heat ratio, γ	1.4
Numerical constant in laminar friction factor - Reynolds number relation, k_l	24
Exponent in laminar friction factor - Reynolds number relation, n_l	1.00
Numerical constant in turbulent friction factor - Reynolds number relation, k_t	0.079
Exponent in turbulent friction factor - Reynolds number relation, n_t	0.25
Loss coefficient, C_L	1.00

The input data sheet for this sample problem is given in table V, in both SI and U.S. units. Plots of profiles of pressure, temperature, density, Mach number, Reynolds number, and mean friction factor for a mean film thickness of 12.7 micrometers (0.5 mil) are shown in figure 5.

REGION OF VALIDITY AND USAGE AND PROGRAM EFFICIENCY

Results obtained using the AREAX computer program are compared with known solutions to check their validity. The first case considered is a parallel-film seal with a relatively large radial area change.

Figure 6 shows both the pressure distribution for pure radial viscous flow found from this variable-area analysis (AREAX) and the analytical solution obtained from the classical viscous flow model (ref. 3), which is

$$P_x = P_1 \left\{ 1 + \left[\left(\frac{P_2}{P_1} \right)^2 - 1 \right] \frac{\ln\left(\frac{R_1}{r} \right)}{\ln\left(\frac{R_1}{R_2} \right)} \right\}^{1/2} \tag{28}$$

The conditions are representative of aircraft idle operation: $P_0 = 45\ \mathrm{N/cm^2}$ abs (65 psia), $P_3 = 10.3\ \mathrm{N/cm^2}$ abs (15 psia), $T_0 = 311\ \mathrm{K}$ (100° F), $R_1 = 5.880$ centimeters (2.315 in.), and $R_2 = 8.410$ centimeters (3.315 in.) ($\Delta A/A = 0.43$). The parallel-surface case of 12.7-micrometer (0.5-mil) film thickness was solved. The variable-area analysis shows excellent agreement with the analytical solution. Also shown in figure 6 is the pressure profile obtained when a constant friction factor calculated at the mean radius is used. This constant-friction-factor approach slightly underestimates the pressure along the seal passage length.

Figure 7 compares the pressure profiles obtained by using the area expansion analysis with those from the viscous flow solution for the case of a positive linear tilt of 1 milliradian. The pressure profile predicted by the viscous compressible flow solution is (ref. 7)

$$P = P_1 \left\{ 1 + \frac{\left[\left(\frac{P_2}{P_1} \right)^2 - 1 \right] x h_2^2 (2h_1 + \alpha x)}{(R_2 - R_1) 2h_m \left(h_1 + \alpha x \right)^2} \right\}^{1/2} \tag{29}$$

The conditions are the same as for the case shown in figure 6, except that R_1 equals 8.300 centimeters (3.265 in.). Hence, the radial area change is negligible.

At a mean film thickness of 5.1 micrometers (0.2 mil) and a positive linear tilt of 1 milliradian, there is excellent agreement between the present analysis and the small-tilt analysis of reference 7. Also shown in figure 7 is the corresponding case of a negative linear tilt of 1 milliradian but a mean film thickness of 4.4 micrometers (0.175 mil). Again, excellent agreement is found.

Figure 8 shows pressure distribution results obtained from the present analysis for a divergent tilt of 2 milliradians. Distributions for mean film thicknesses of 2.5, 5.1, 7.6, and 12.7 micrometers (0.1, 0.2, 0.3, and 0.5 mil) are presented. The other conditions were $P_0 = 148\ N/cm^2$ abs (215 psia), $P_3 = 10.3\ N/cm^2$ abs (15 psia), $T_0 = 700$ K (800^o F), $R_1 = 8.300$ centimeters (3.265 in.), and $R_2 = 8.410$ centimeters (3.315 in.). These conditions are representative of advanced aircraft cruise conditions (ref. 1). These conditions represent subcritical (subsonic), critical ($P_2 = P_3$ and $M_2 = 1$), and supercritical (choked) flow conditions. Also shown is the parallel-film pressure profile for 2.5-micrometer (0.1-mil) film thickness. This is the classical parabolic profile for viscous compressible flow. In addition, figure 8 shows a supercritical flow pressure profile for parallel sealing surfaces and for a film thickness of 12.7 micrometers (0.5 mil) which was obtained using the constant-area analysis (QUASC) of reference 2. The present analysis shows excellent agreement with this parallel-film profile with a 12.7-micrometer (0.5-mil) film thickness. Similar results were found for the case of 2-milliradian convergent tilt.

Experience has shown that QUASC (ref. 2) performs each film-thickness case six to ten times faster than AREAX. Hence, for parallel surfaces, QUASC is more efficient and should be used. The small-seal-face-deformation cases using AREAX on the IBM 7094/7044 direct couple computer required about 0.16 minute for each film thickness where the flow was choked and about 0.5 minute for each film thickness where the flow was subsonic.

For small face deformations and subsonic flow conditions, the analytical solution (ref. 6) should be used. For deformed surfaces with a relatively large mean film thickness and choked flow, QUASC (ref. 2) may give satisfactory results (faster computer solution time). For a more complete solution, AREAX should prove useful for choked flow conditions with a relatively small mean film thickness, as well as for face seals where radial area change is significant.

CONCLUDING REMARKS

A summary of the quasi-one-dimensional analysis of compressible flow with friction and area change has been presented. Also, a detailed description of the computer program AREAX, which performs this analysis, is given. This program has proven useful in extending the capabilities of the computer program QUASC by including the area change due to (1) change in radius and (2) deformed seal faces represented by a small linear tilt. Results obtained using AREAX showed excellent agreement with analytical solutions for pure radial viscous flow and for viscous flow with a small tilt of the sealing surfaces. Favorable agreement was also found between AREAX and QUASC (ref. 2) for a parallel film under choked flow conditions. An example mainshaft seal problem is also given.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 7, 1973,
501-24.

APPENDIX A

SYMBOLS

A	area
C_L	entrance velocity loss coefficient
c	speed of sound
c_p	specific heat at constant pressure
D	hydraulic diameter ($D = 2h$ for coaxial rings and narrow slots)
F	seal opening force
$\overline{F}$	dimensionless seal-opening-force pressure profile factor
$\overline{f}$	mean Fanning friction factor
H	shear heat
h	film thickness (gap)
Kn	mean Knudsen number, λ/h_m
k	numerical constant in friction factor - Reynolds number relation
M	Mach number, $u/\sqrt{\gamma \mathscr{R} T}$
$\dot{M}$	mass flow
m	molecular weight of gas
n	exponent in friction factor - Reynolds number relation
P	pressure
$\mathscr{P}_w$	wetted perimeter
Q	volume leakage flow rate
R_1	inner radius
R_2	outer radius
ΔR	sealing dam radial width (physical flow length), $R_2 - R_1$
$\mathscr{R}$	gas constant (universal gas constant/molecular weight)
$\mathscr{R}_u$	universal gas constant
Re	Reynolds number
Re(p)	Reynolds number of leakage flow

Re(r)	Reynolds number of rotational flow
r	radius
S	axial film stiffness
T	temperature
u	leakage flow mean velocity (x-direction)
V	mean rotational velocity
W	flow width
x	flow direction coordinate
x_c	center of pressure
$\overline{x}_c$	dimensionless center of pressure
α	relative inclination angle of surface (positive α designates $h_2 > h_1$)
γ	specific-heat ratio
λ	mean free path of gas molecules
μ	absolute (dynamic) viscosity
ρ	density
τ	shear stress

Subscripts:

l	laminar flow
m	mean
max	maximum
t	turbulent flow
w	wetted surface area or wall
x	location along flow leakage length from entrance
0	sealed (reservoir) conditions
1	flow entrance conditions
2	flow exit conditions
3	ambient sump conditions

Superscript:

*	critical flow condition

APPENDIX B

DETAILED DESCRIPTION OF PROGRAM

This appendix contains details regarding checking the consistency of the input data, traps for invalid data, and the subprograms. The variables mentioned in this appendix are defined and listed either in the main-text section Input Data or in the program listings (appendix C). Further details of numerical methods and subroutines that are used by both AREAX and QUASC can be found in reference 2.

Main Program AREAX

The main program AREAX controls the complete quasi-one-dimensional analysis. It defines the labeled COMMON storage for transmission of data among the subprograms. It defines some constants and labels for the output. It reads the input data, checks that these data are consistent, and rejects cases for which the input data are invalid. It calls subprograms to solve the Mach number equation and to determine the distributions across the seal face of pressure, temperature, density, velocity, mean friction factor, and Reynolds number. It calculates the other parameters associated with the flow, such as mass flow rate, and writes the output. AREAX then transfers to read new input data.

The labeled COMMON storage defined by AREAX contains constants needed by the subprograms and the output data. Most of the variables in the COMMON blocks are listed in tables VI to IX. The COMMON blocks not described contain variables which are useful in the operation of the program but are not necessary for the analysis. The variable names and the array names are not listed because the names are not the same in all the subprograms.

There are two kinds of parameters in the COMMON block /ARRAYS/ (table VI): one is the distributions across the face of the seal, the other is the integrated flow parameters that vary only with mean film thickness. The arrays are dimensioned for 20 film thicknesses and 11 points across the seal face.

The parameters in COMMON block /CONSTS/ (table VII) are constants needed by the program for internal calculations. The array CNVT has dimension (11,2). The first column of the array contains constants for calculations in SI units. The second column of the array contains constants for calculations in U.S. customary units. The variable NSI is 1 for SI units and 2 for U.S. units. Table VIII lists the parameters for which each element of CNVT is used.

The arrays in COMMON block /TRAYS/ (table IX) contain the parameters used in the solution of the Mach number equation for the film thickness under consideration.

COMMON blocks /CTITLE/ and /PRNT/ contain the title, which identifies the data, and the labels for identifying which parameters are calculated. COMMON block /LOGICL/ contains logical variables.

The program AREAX first reads the input data and checks that these data are consistent. One parameter it checks for consistency is the flow length, RDIF. There are three input variables that can be used to determine RDIF. These variables are RINNER, ROUTER, and RDIFIN. Since only two are necessary, the third must be made consistent with the other two. The check is made as follows: If RINNER $\neq$ 0 and ROUTER $\neq$ 0, AREAX sets R1 = RINNER and R2 = ROUTER and then calculates RDIF = R2 - R1. If RINNER $\neq$ 0, ROUTER = 0, and RDIFIN $\neq$ 0, AREAX sets R1 = RINNER and RDIF = RDIFIN and then calculates R2 = R1 + RDIF. If RINNER = 0, ROUTER $\neq$ 0, and RDIFIN $\neq$ 0, AREAX sets R2 = ROUTER and RDIF = RDIFIN and then calculates R1 = R2 - RDIF. These three conditions are for the coaxial ring geometry. The variable WIDTH is calculated as $2\pi\overline{R}$. If RINNER = 0, ROUTER = 0, and RDIFIN $\neq$ 0, the geometry is for the rectangular plate. Then AREAX sets RDIF = RDIFIN, and WIDTH must be nonzero. Any other combination of RINNER, ROUTER, RDIFIN, and WIDTH is considered an error since there is not enough information available to determine a nonzero flow length and flow width. If this error condition exists, AREAX writes a message and transfers to read new data from NAMELIST/SEAL/.

The second parameter that is checked for consistency is the pressure ratio. Three input variables are available for determining the pressure ratio, but only two are necessary. The check is made the same way as the check for flow length. If P1IN $\neq$ 0 and P2IN $\neq$ 0, AREAX sets P1 = P1IN and P2 = P2IN and then calculates PRAT = P1/P2. If P1IN $\neq$ 0, P2IN = 0, and PRIN $\neq$ 0, AREAX sets P1 = P1IN and PRAT = PRIN and then calculates P2 = P1/PRAT. If P1IN = 0, P2IN $\neq$ 0, and PRIN $\neq$ 0, AREAX sets P2 = P2IN and PRAT = PRIN and then calculates P1 = PRAT $\times$ P2. Any other combination of P1IN, P2IN, and PRIN is considered an error. In that case, AREAX writes an error message and transfers to read new data according to the input code. Since the flow may be radially inward or outward for the coaxial ring geometry. AREAX chooses the larger value of P1 and P2 to be the sealed-gas pressure P0 and the smaller value to be the ambient pressure P3.

The third parameter that must be checked for consistency is the rotational velocity. If SPEED $\neq$ 0, CAPV is calculated from SPEED. If CAPV $\neq$ 0 and SPEED = 0, SPEED is calculated from CAPV. If both are 0, the system is considered static, and the logical variable PWRSKP is set to .TRUE. to omit calculations involving power.

For each film thickness and tilt angle combination, AREAX calls subroutine NCFLOW to solve the Mach number equation for the given film thickness. Subroutine NCFLOW also punches the solution of the Mach number equation on cards for restarting the program if it runs out of time. AREAX then calls subroutine DISTS to calculate the distributions across the seal face. Function subprogram SIMPS1 is used for the numerical integrations in the calculation of force and center of pressure. When all the data for all the film thicknesses have been calculated, AREAX call subroutine STFNSS to determine the axial film stiffness.

When all the calculations are complete, AREAX writes the input data, the "checked" input data, and the output data with appropriate headings and labels. The final command in the program is a transfer to read new input data.

Subprogram NCFLOW

Subprogram NCFLOW controls the solution of the Mach number equation, for any given film thickness and tilt angle combination. The subprogram calls subprogram RK1 to solve the Mach number equation. NCFLOW iterates first on the boundary condition $x^* \geq \Delta R$. If $x^* > \Delta R$, NCFLOW then iterates on the boundary condition $P_2 = P_3$. When the solution for each film thickness is complete, NCFLOW punches the x distribution and the Mach number distribution on cards for restarting the program.

Subprogram DISTS

Subprogram DISTS determines the distributions across the seal face of pressure, temperature, Mach number, density, velocity, Reynolds number, and mean friction factor. It uses a three-point Lagrange interpolation on the data from the solution of the Mach number equation to get the Mach number distribution at the given x grid points. It then calculates the other parameters as follows: temperature from equation (15), velocity from the definition of Mach number, density from the continuity equation, pressure from the equation of state, Reynolds number from the definition of Reynolds number, and mean friction factor from the friction factor - Reynolds number relation.

Subprogram PRESS

Function subprogram PRESS uses a three-point Lagrange interpolation to determine the Mach number and film thickness at distance x across the seal face. Then pressure is calculated from equation (17).

Subprogram RK1

Subprogram RK1 solves the Mach number equation by the fourth order Runge-Kutta solution. Since the flow must remain subsonic, there are traps built into the subprogram to ensure that the Mach number remains less than 1. The initial guess for M_1 is supplied by the calling program. The equation is considered solved when the final M is 1.0. All variables and operations in this subprogram are in double precision.

Subprogram SIMPS1

Function subprogram SIMPS1 uses Simpson's rule to evaluate the integrals in the force and center-of-pressure equations. Reference 2 provides a detailed description of this subprogram.

Subprogram STFNSS

Subprogram STFNSS performs a numerical differentiation to determine the axial film stiffness. Reference 2 provides a detailed description of the numerical technique used.

Subprogram FRFUNC

Function subprogram FRFUNC determines the mean friction factor for a given Reynolds number. FRFUNC examines the Reynolds number to determine whether the flow is laminar, turbulent, or transitional. It then uses the input constants to determine $\bar{f}$. If the flow is transitional, FRFUNC calculates $\bar{f}$ by an interpolation formula developed in reference 2.

Subprograms FFUNC and XCFUNC

Function subprograms FFUNC and XCFUNC evaluate the integrands in the force and center-of-pressure integrals. Both FFUNC and XCFUNC call subroutine PRESS, which evaluates the pressure at any given x.

Subprogram SORTXY

Subprogram SORTXY rearranges the ordered pairs of numbers (X(1), Y(1)), (X(2), Y(2)), . . . , (X(N), Y(N)), which are stored in arrays X and Y, in order of ascending X. The (X, Y) pairing is preserved.

Subprogram GRAFIC

Subprogram GRAFIC makes the following plots:

(1) Power against mean film thickness
(2) Center of pressure against mean film thickness
(3) Force against mean film thickness
(4) Pressure against x
(5) Temperature against x
(6) Density against x
(7) Mach number against x
(8) Reynolds number against x
(9) Mean friction factor against x

The subprogram presented here is a dummy routine to satisfy the call to GRAFIC from the main program. Each user must write his own plotting subroutine, using the dummy subprogram and the flow chart as a guide, that is appropriate to the plotting devices available.

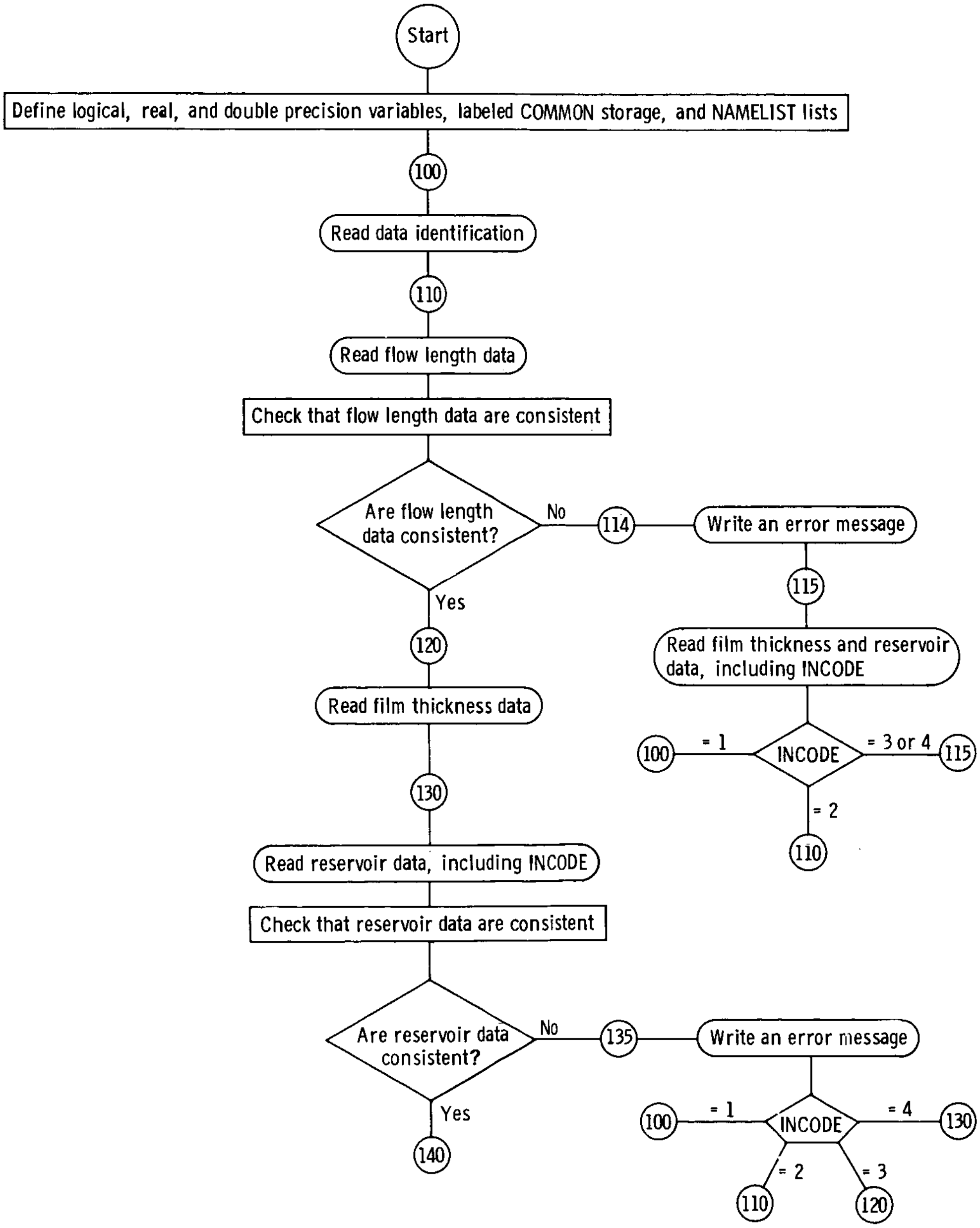
Subprogram BLOCK

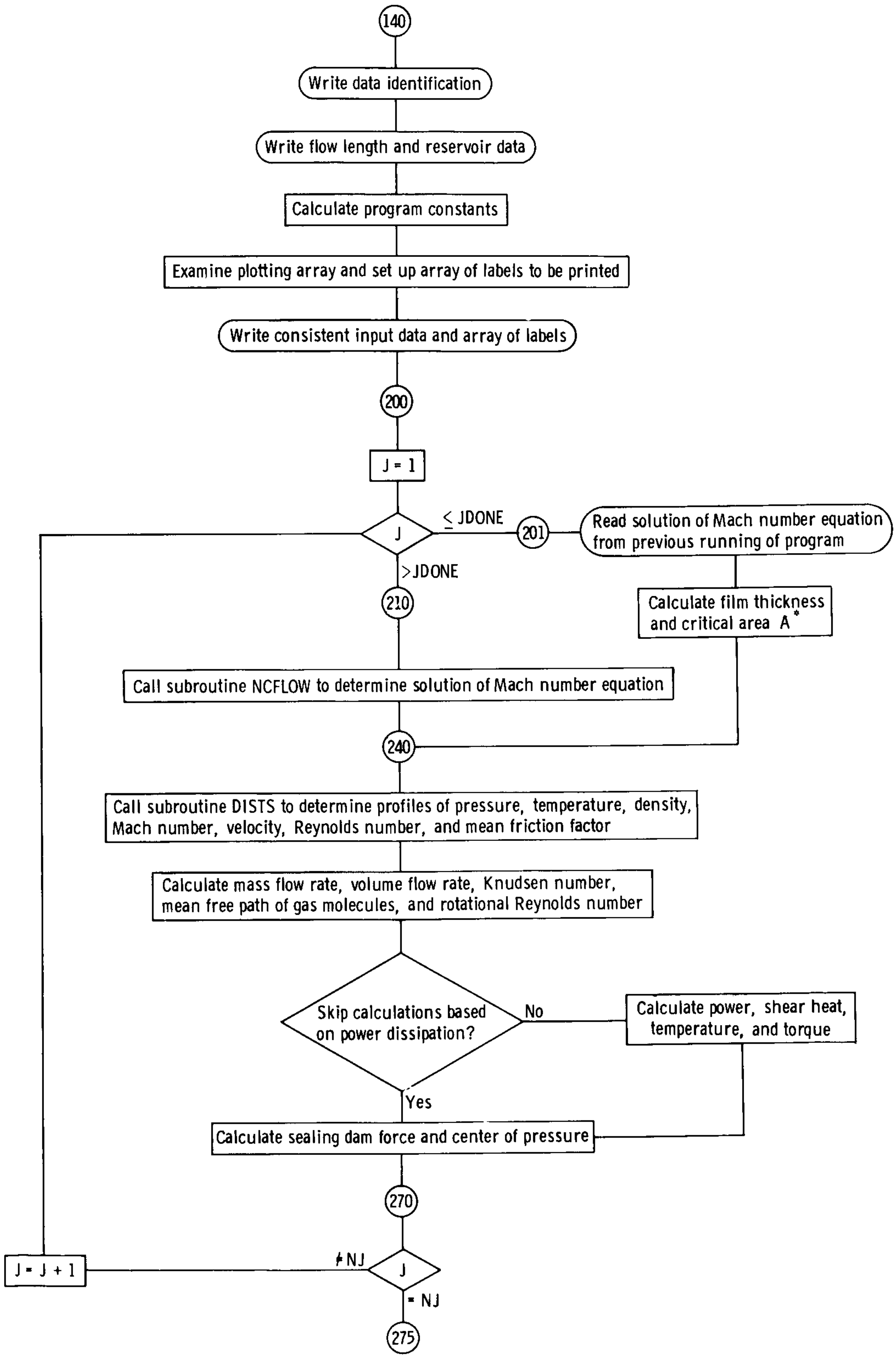
Subprogram BLOCK is a block data subprogram to load constants into labeled COMMON.

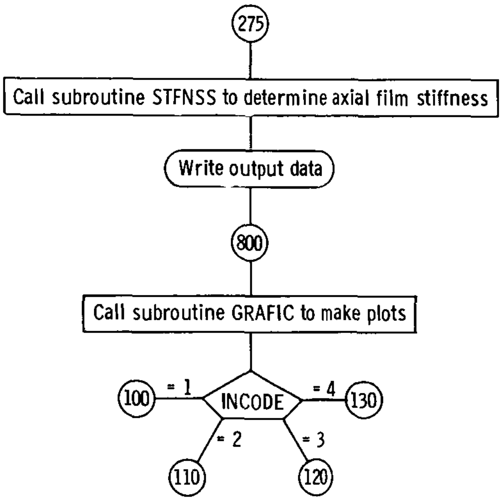
APPENDIX C

FLOW CHARTS AND PROGRAM LISTING

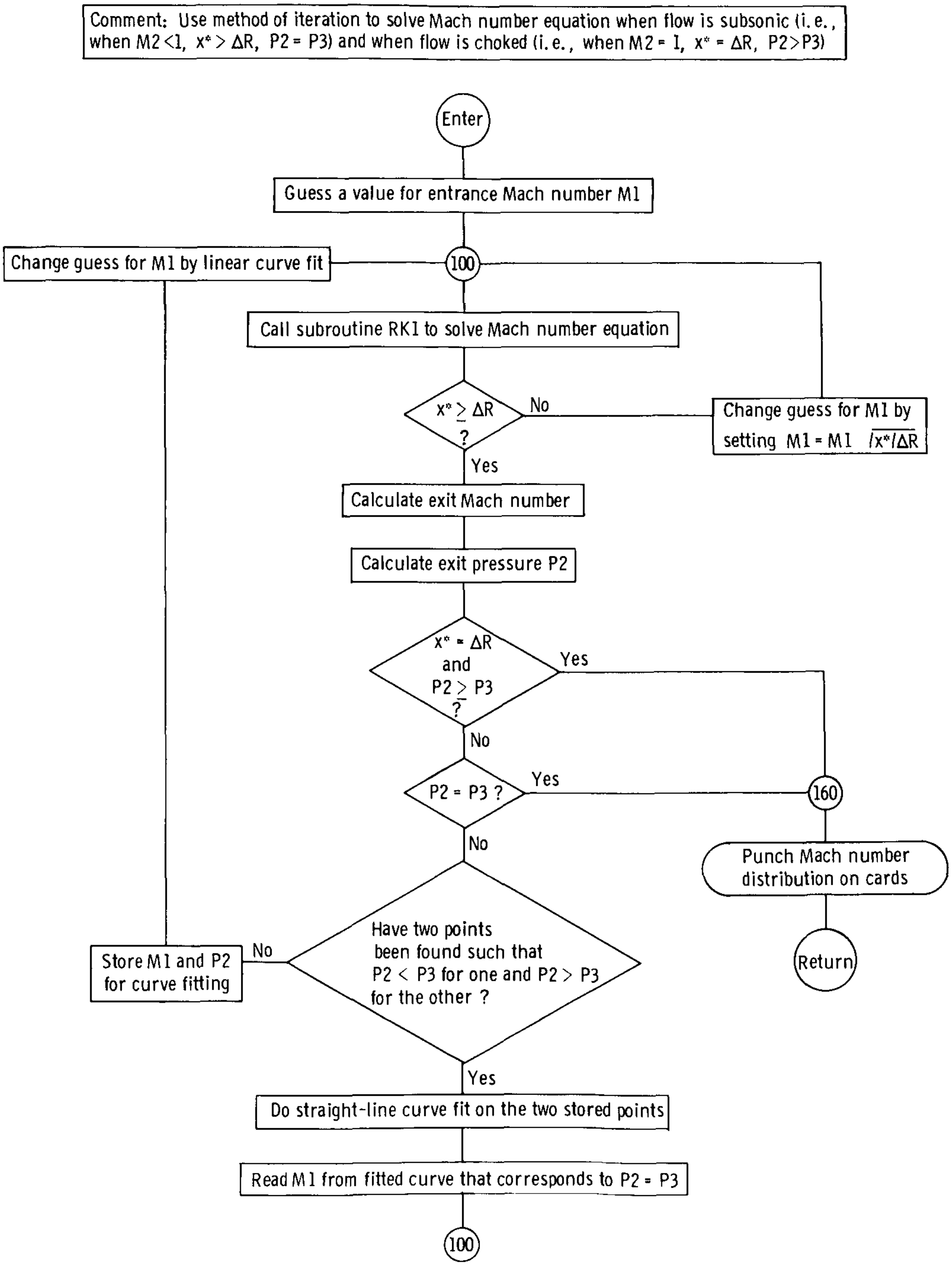
AREAX



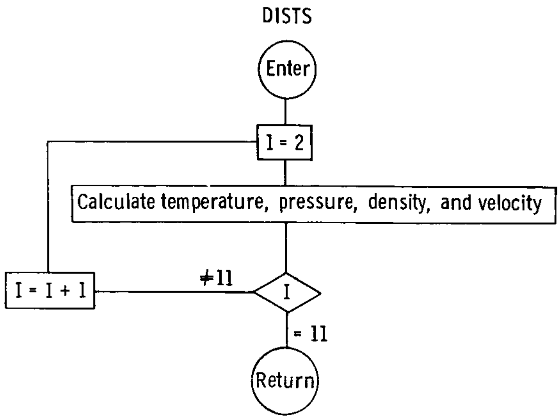

140
Write data identification
Write flow length and reservoir data
Calculate program constants
Examine plotting array and set up array of labels to be printed
Write consistent input data and array of labels
200
J = 1
J
≤ JDONE
201
Read solution of Mach number equation from previous running of program
Calculate film thickness and critical area A*
> JDONE
210
Call subroutine NCFLOW to determine solution of Mach number equation
240
Call subroutine DISTS to determine profiles of pressure, temperature, density, Mach number, velocity, Reynolds number, and mean friction factor
Calculate mass flow rate, volume flow rate, Knudsen number, mean free path of gas molecules, and rotational Reynolds number
Skip calculations based on power dissipation?
No
Calculate power, shear heat, temperature, and torque
Yes
Calculate sealing dam force and center of pressure
270
J = J + 1
≠ NJ
J
= NJ
275

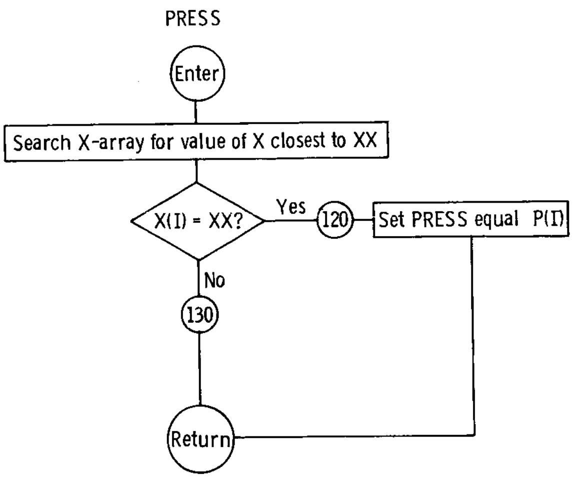

275
Call subroutine STFNSS to determine axial film stiffness
Write output data
800
Call subroutine GRAFIC to make plots
INCODE
= 1
100
= 2
110
= 3
120
= 4
130

NCFLOW

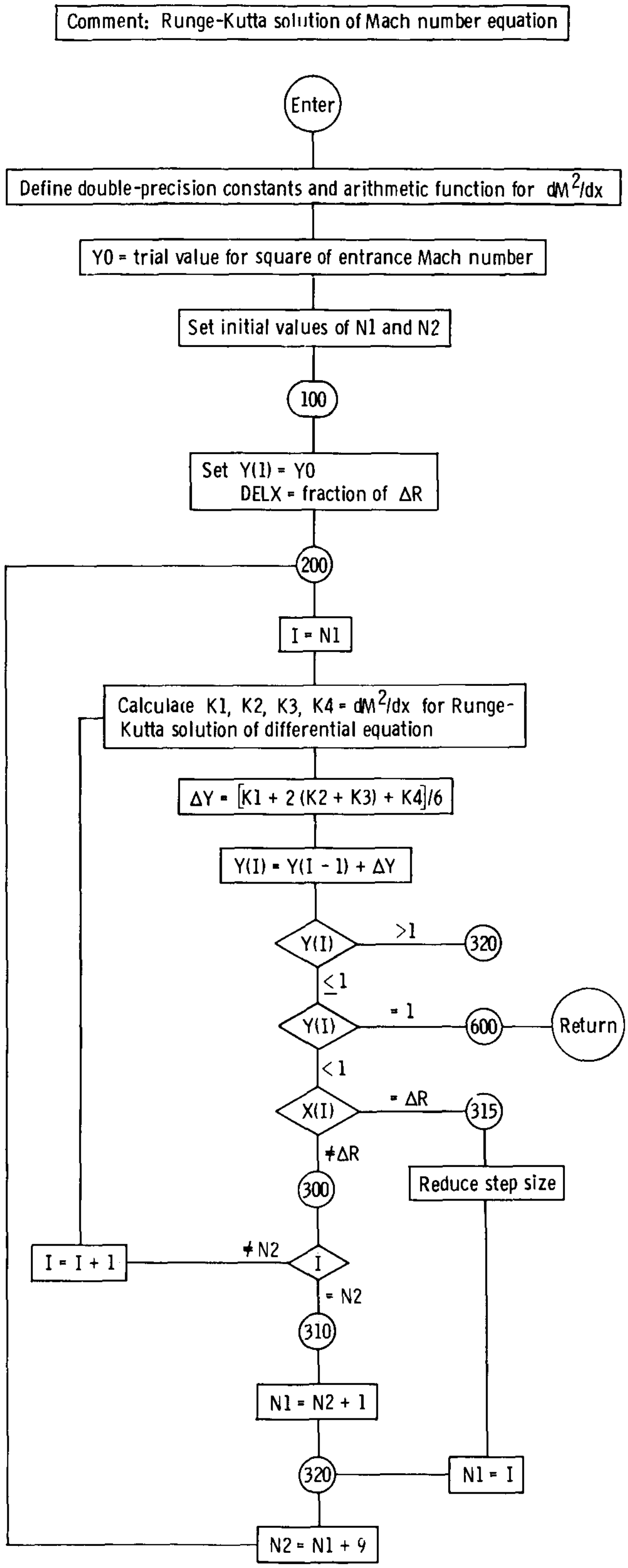


Comment: Use method of iteration to solve Mach number equation when flow is subsonic (i.e., when M2<1, x* > ΔR, P2 = P3) and when flow is choked (i.e., when M2 = 1, x* = ΔR, P2>P3)
Enter
Guess a value for entrance Mach number M1
Change guess for M1 by linear curve fit
100
Call subroutine RK1 to solve Mach number equation
x* ≥ ΔR ?
No
Change guess for M1 by setting M1 = M1 √x*/ΔR
Yes
Calculate exit Mach number
Calculate exit pressure P2
x* = ΔR and P2 ≥ P3 ?
Yes
No
P2 = P3 ?
Yes
160
No
Punch Mach number distribution on cards
Return
Store M1 and P2 for curve fitting
No
Have two points been found such that P2 < P3 for one and P2 > P3 for the other ?
Yes
Do straight-line curve fit on the two stored points
Read M1 from fitted curve that corresponds to P2 = P3
100


DISTS
Enter
I = 2
Calculate temperature, pressure, density, and velocity
I = I + 1
≠11
I
= 11
Return

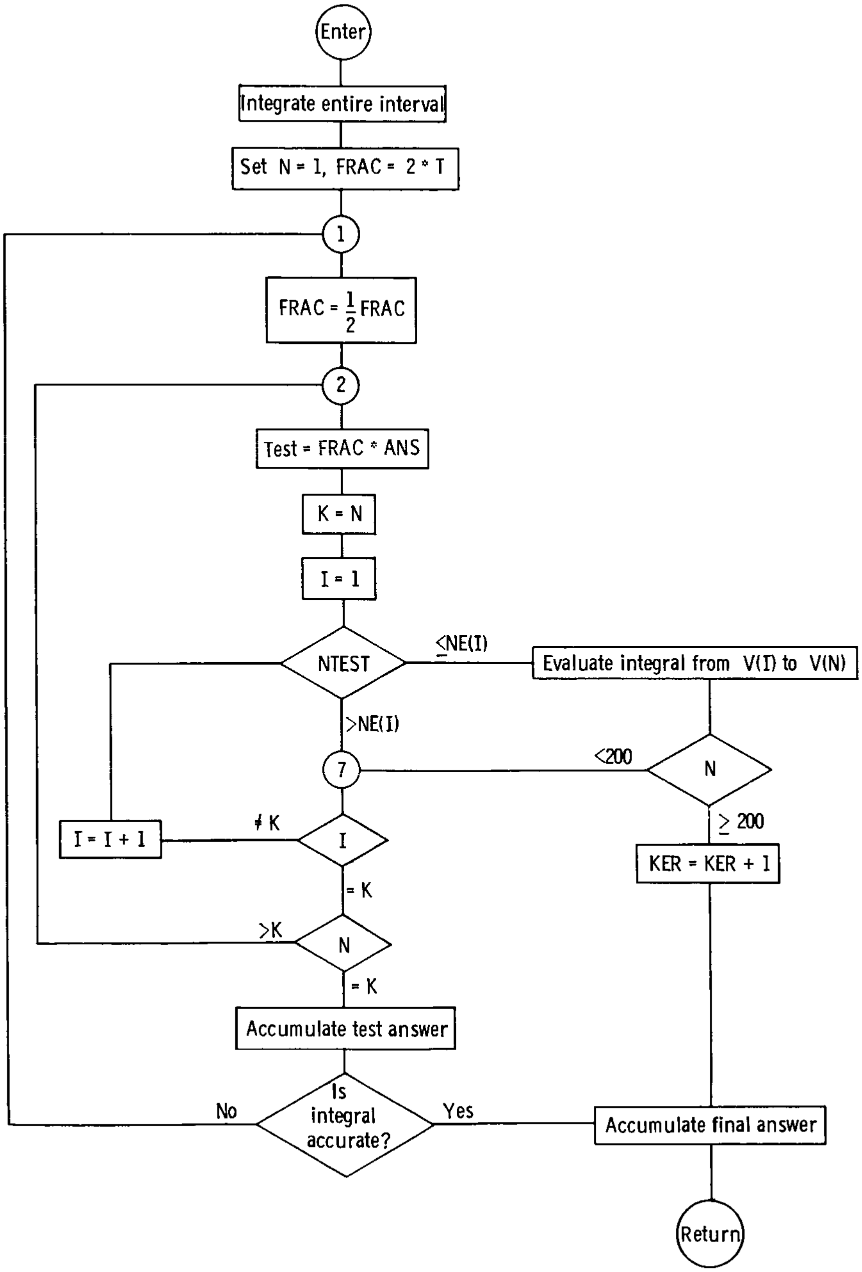

PRESS
Enter
Search X-array for value of X closest to XX
X(I) = XX?
Yes
120
Set PRESS equal P(I)
No
130
Return

RK1

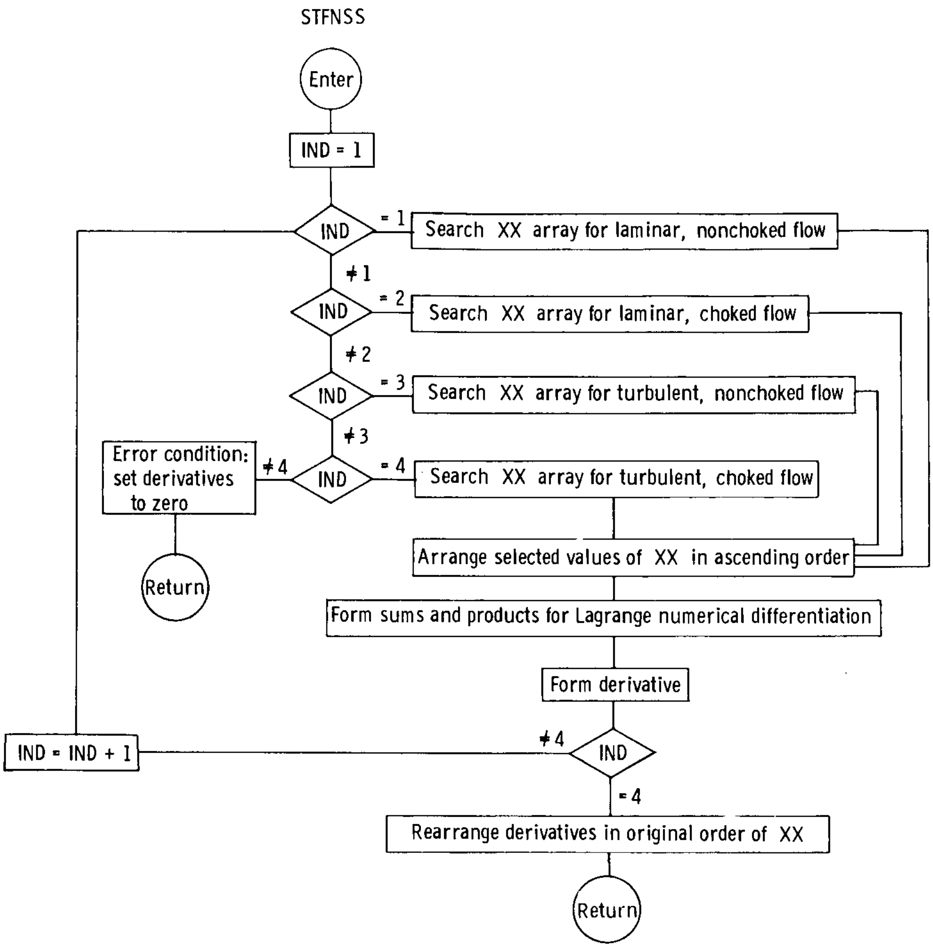


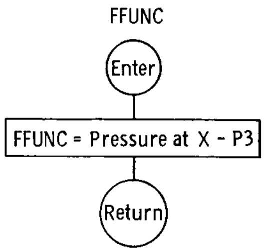
Comment: Runge-Kutta solution of Mach number equation
Enter
Define double-precision constants and arithmetic function for dM²/dx
Y0 = trial value for square of entrance Mach number
Set initial values of N1 and N2
100
Set Y(1) = Y0
DELX = fraction of ΔR
200
I = N1
Calculate K1, K2, K3, K4 = dM²/dx for Runge-Kutta solution of differential equation
ΔY = [K1 + 2 (K2 + K3) + K4]/6
Y(I) = Y(I - 1) + ΔY
Y(I)
>1
320
≤1
Y(I)
= 1
600
Return
< 1
X(I)
= ΔR
315
Reduce step size
≠ΔR
300
I = I + 1
≠N2
I
= N2
310
N1 = N2 + 1
320
N1 = I
N2 = N1 + 9

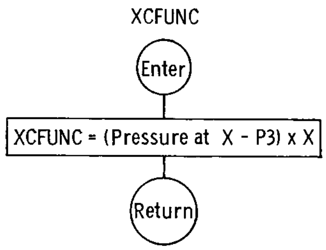
SIMPS1

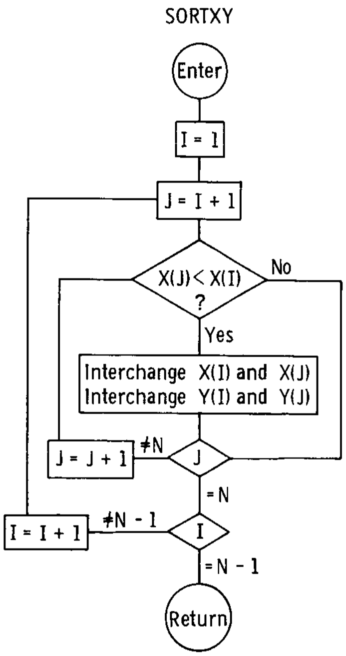


Enter
Integrate entire interval
Set N = 1, FRAC = 2 * T
1
FRAC = $\frac{1}{2}$ FRAC
2
Test = FRAC * ANS
K = N
I = 1
NTEST
≤NE(I)
Evaluate integral from V(I) to V(N)
>NE(I)
7
<200
N
≥ 200
KER = KER + 1
I = I + 1
≠ K
I
= K
>K
N
= K
Accumulate test answer
No
Is integral accurate?
Yes
Accumulate final answer
Return

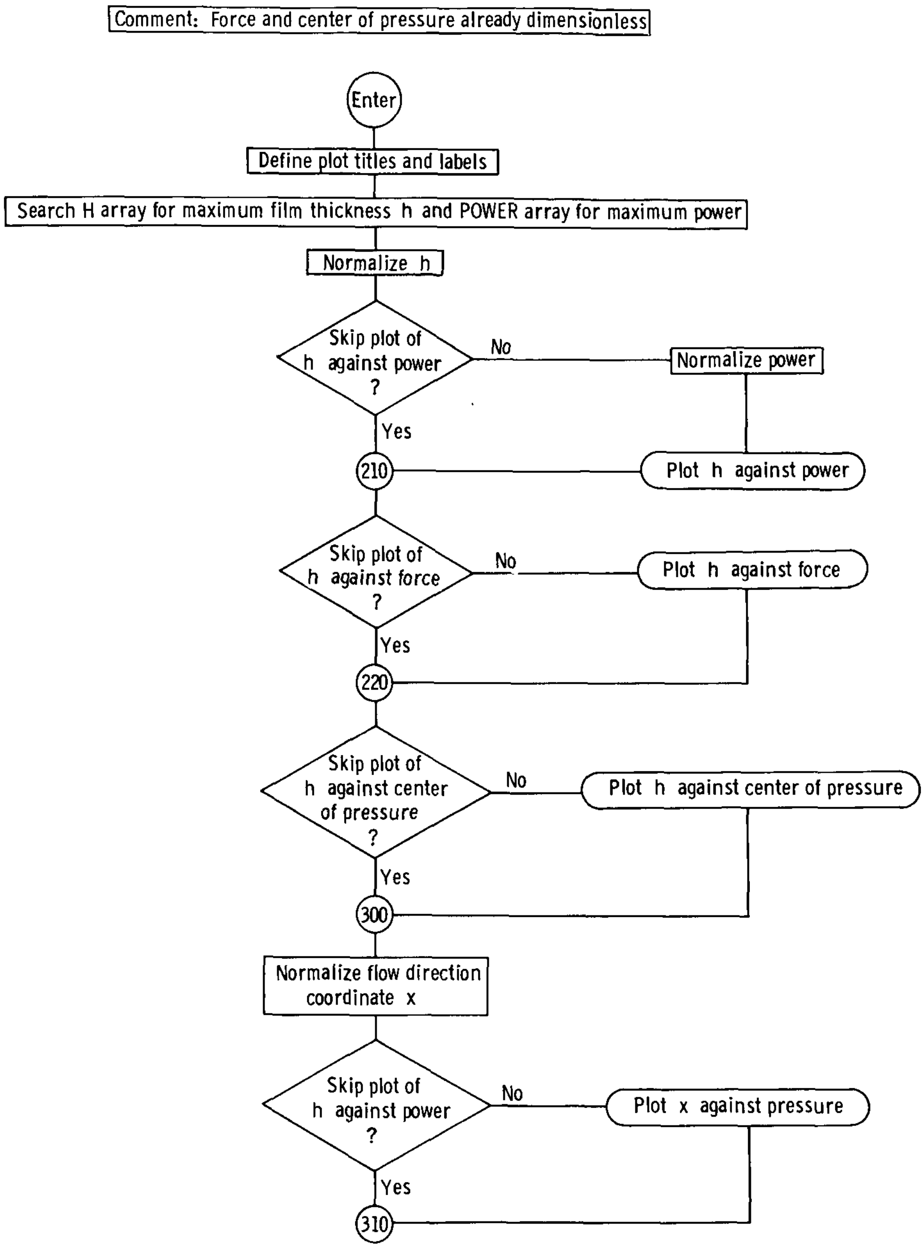

STFNSS
Enter
IND = 1
IND
= 1
Search XX array for laminar, nonchoked flow
≠ 1
IND
= 2
Search XX array for laminar, choked flow
≠ 2
IND
= 3
Search XX array for turbulent, nonchoked flow
≠ 3
Error condition: set derivatives to zero
≠ 4
IND
= 4
Search XX array for turbulent, choked flow
Return
Arrange selected values of XX in ascending order
Form sums and products for Lagrange numerical differentiation
Form derivative
IND = IND + 1
≠ 4
IND
= 4
Rearrange derivatives in original order of XX
Return

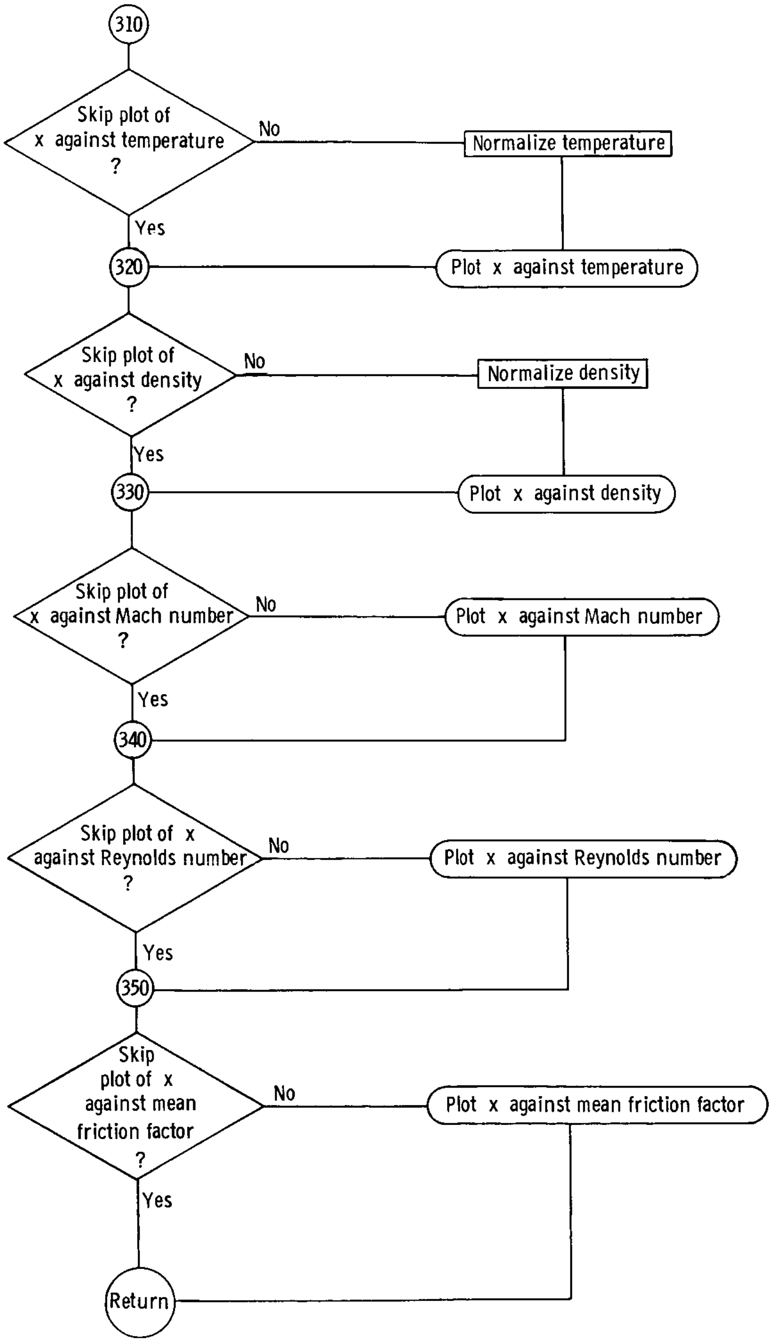

FFUNC
Enter
FFUNC = Pressure at X - P3
Return


XCFUNC
Enter
XCFUNC = (Pressure at X - P3) x X
Return


SORTXY
Enter
I = 1
J = I + 1
X(J) < X(I) ?
No
Yes
Interchange X(I) and X(J)
Interchange Y(I) and Y(J)
J = J + 1
≠N
J
=N
I = I + 1
≠N - 1
I
=N - 1
Return

GRAFIC


Comment: Force and center of pressure already dimensionless
Enter
Define plot titles and labels
Search H array for maximum film thickness h and POWER array for maximum power
Normalize h
Skip plot of h against power ?
No
Normalize power
Yes
210
Plot h against power
Skip plot of h against force ?
No
Plot h against force
Yes
220
Skip plot of h against center of pressure ?
No
Plot h against center of pressure
Yes
300
Normalize flow direction coordinate x
Skip plot of h against power ?
No
Plot x against pressure
Yes
310


310
Skip plot of x against temperature ?
No
Normalize temperature
Yes
320
Plot x against temperature
Skip plot of x against density ?
No
Normalize density
Yes
330
Plot x against density
Skip plot of x against Mach number ?
No
Plot x against Mach number
Yes
340
Skip plot of x against Reynolds number ?
No
Plot x against Reynolds number
Yes
350
Skip plot of x against mean friction factor ?
No
Plot x against mean friction factor
Yes
Return

```
C
C     QUASI-CNE DIMENSIONAL COMPRESSIBLE FLOW WITH FRICTICN AND AREA
C     CHANGE.  AREA CHANGE MAY BE DUE TO RADIAL EXPANSION AND/OR
C     RELATIVE TILTING OF THE SEALING SURFACES.
C
C     INPUT VARIABLES
C     ***************
C
C       TITLE - ALPHANUMERIC IDENTIFICATION OF THE DATA
C
C         NSI - NUMERICAL SIGNAL WHICH INDICATES WHICH SYSTEM OF UNITS IS
C               USED FOR INPUT, OUTPUT, AND INTERNAL CALCULATICNS
C                     (NSI = 1 MEANS SI UNITS - NSI = 2 MEANS US UNITS)
C      RINNER - INNER RADIUS OF CIRCULAR SEAL
C      ROUTER - OUTER RADIUS OF CIRCULAR SEAL
C      RDIFIN - DISTANCE ACROSS SEAL
C       WIDTH - FLOW WIDTH FOR SEALS WITH NO RADIAL EXPANSION
C       MOLWT - MOLECULAR WEIGHT
C          CP - SPECIFIC HEAT OF GAS
C        MUIN - RESERVOIR VISCOSITY FOR GAS OTHER THAN AIR
C       GAMMA - RATIO OF SPECIFIC HEATS
C       SPEED - ROTATIONAL VELOCITY
C        CAPV - SURFACE SPEED
C        XLAM - EXPONENT IN FORMULA FOR VARIATION OF FRICTION FACTOR
C                  WITH REYNOLDS NUMBER FOR LAMINAR FLCW
C       XTURB - EXPONENT IN FORMULA FOR VARIATION OF FRICTION FACTCR
C                  WITH REYNOLDS NUMBER FOR TURBULENT FLOW
C      CONLAM - CONSTANT IN FORMULA FOR VARIATION OF FRICTION FACTOR
C                  WITH REYNOLDS NUMBER FOR LAMINAR FLOW
C      CONTRB - CONSTANT IN FORMULA FOR VARIATICN OF FRICTION FACTCR
C                  WITH REYNOLDS NUMBER FOR TURBULENT FLOW
C       RELAM - UPPER LIMIT OF REYNOLDS NUMBER FCR LAMINAR FLCW
C      RETURB - LOWER LIMIT OF REYNOLDS NUMBER FOR TURBULENT FLOW
C      PWRSKP - LOGICAL VARIABLE - IF TRUE, SKIP CALCULATICNS
C                  INVOLVING POWER
C      PRSSKP - LOGICAL VARIABLE - IF TRUE, SKIP PRINTCUT CF
C                  DISTRIBUTIONS OF PRESSURE, TEMPERATURE, DENSITY,
C                  MACH NUMBER, VELOCITY, AND FRICTION PARAMETER
C                  ACROSS THE FACE OF THE SEAL
C      NRMSKP - LOGICAL VARIABLE - IF TRUE, SKIP NORMALIZATION OF
C                  FORCE AND CENTER OF PRESSURE
C      PLTSKP - LOGICAL ARRAY - IF ANY ELEMENT IS TRUE, SKIP THE
C                  PLOT OF THE CORRESPONDING VARIABLE
C                  PLTSKP(1) - POWER VS CHARACTERISTIC FILM THICKNESS
C                  PLTSKP(2) - CENTER OF PRESSURE VS CHARACTERISTIC
C                                FILM THICKNESS
C                  PLTSKP(3) - FORCE VS CHARACTERISTIC FILM THICKNESS
C                  PLTSKP(4) - PRESSURE VS X
C                  PLTSKP(5) - TEMPERATURE VS X
C                  PLTSKP(6) - DENSITY VS X
C                  PLTSKP(7) - MACH NUMBER VS X
```

```
C               PLTSKP(8) - REYNOLDS NUMBER VS X
C               PLTSKP(9) - MEAN FRICTION FACTOR VS X
C
C       HMEAN - MEAN FILM THICKNESS
C       ALPHA - TILT ANGLE
C          NJ - NUMBER OF FILM THICKNESS
C       JDONE - NUMBER OF CASES COMPLETED IN PREVIOUS RUNNING
C               OF THE PROGRAM
C
C        P1IN - PRESSURE AT INNER RADIUS OF CIRCULAR SEAL OR PRESSURE AT
C               ENTRANCE OF SEAL WITH NO RADIAL EXPANSION
C        P2IN - PRESSURE AT OUTER RADIUS OF CIRCULAR SEAL OR PRESSURE AT
C               EXIT OF SEAL WITH NO RADIAL EXPANSION
C        PRIN - PO/P3
C        TOIN - SEALED GAS TEMPERATURE
C        LOSS - ENTRANCE VELOCITY LOSS COEFFICIENT
C      INCODE - INPUT CODE
C               INCODE=1, PROGRAM TRANSFERS TO READ NEW TITLE CARD
C               INCODE=2, PROGRAM TRANSFERS TO READ NEW SEAL DATA
C               INCODE=3, PROGRAM TRANSFERS TO READ NEW FILM THICKNESS
C                         DATA
C               INCODE=4, PROGRAM TRANSFERS TO READ NEW RESERVOIR
C                         DATA
C
C      OUTPUT VARIABLES
C      ****************
C
C           X - DISTANCE ACROSS SEAL FACE
C           H - FILM THICKNESS THAT CORRESPONDS TO X
C
C       PARAMETERS THAT VARY ONLY WITH FILM THICKNESS
C       *********************************************
C
C        MDOT - MASS FLOW RATE
C           Q - VOLUME FLOW RATE
C          KN - KNUDSEN NUMBER
C       LAMDA - MEAN FREE PATH OF GAS MOLECULES
C         RER - ROTATIONAL FLOW REYNOLDS NUMBER
C       POWER - POWER DISSIPATED DUE TO VISCOUS SHEARING
C        DELT - APPARENT TEMPERATURE RISE DUE TO VISCOUS SHEARING
C      HSHEAR - SHEAR HEAT
C      TORQUE - TORQUE
C       FORCE - SEALING DAM FORCE
C        FBAR - NORMALIZED SEALING DAM FORCE
C          XC - CENTER OF PRESSURE
C       XCBAR - NORMALIZED CENTER OF PRESSURE
C       STIFF - AXIAL FILM STIFFNESS
C          H1 - FILM THICKNESS AT INNER RADIUS OF SEAL
C          H2 - FILM THICKNESS AT OUTER RADIUS OF SEAL
C
C       PARAMETERS THAT VARY WITH FLOW LENGTH AND FILM THICKNESS
C       ********************************************************
C
C           P - PRESSURE
C        MACH - MACH NUMBER
C           U - RADIAL VELOCITY
```

```
C           T - TEMPERATURE
C         RHO - DENSITY
C         REP - PRESSURE FLOW REYNOLDS NUMBER
C       FRICT - FRICTION FACTOR
C
C      PROGRAM VARIABLES - SOME OF THESE ARE OUTPUT, ALSO
C      ***********************************************
C
C          RO - RADIUS OF SEAL AT INLET (RO = R1 FOR INTERNALLY
C               PRESSURIZED CIRCULAR SEALS, RO = R2 FOR EXTERNALLY
C               PRESSURIZED CIRCULAR SEALS, AND RO = 0 FOR SEALS WITH NO
C               RADIAL EXPANSION)
C        RGAS - GAS CONSTANT
C       FAREA - SURFACE AREA
C          MU - RESERVOIR VISCOSITY
C          TO - SEALED GAS TEMPERATURE
C        PTOL - TOLERANCE FOR CUT-OFF ON PRESSURE ITERATION
C        HMIN - MINIMUM FILM THICKNESS
C        CNVT - ARRAY OF CONSTANTS NEEDED IN THE CALCULATIONS
C                (CNVT(I,1) ARE CONSTANTS IN SI UNITS)
C                (CNVT(I,2) ARE CONSTANTS IN US UNITS)
C
C       PARAMETERS CALCULATED AT POINT OF CHOKING
C       ****************************************
C
C       XSTAR - DISTANCE FROM ENTRANCE TO POINT OF CHOKING
C       PSTAR - PRESSURE
C       ASTAR - CROSS-SECTIONAL AREA
C       TSTAR - TEMPERATURE
C
      REAL MACH,MOLWT,LOSS,KN,LAMDA,MUIN,MU,MDOT
      DOUBLE PRECISION XX,FM,HH
      LOGICAL PWRSKP,PRSSKP,NRMSKP,PLTSKP
      EXTERNAL FFUNC,XCFUNC
      DIMENSION CALC(8,4),MDOT(20),Q(20),KN(20),LAMDA(20),RER(20),
     1      XC(20),DELT(20),HSHEAR(20),TORQUE(20),HMIN(20)
      COMMON/ARRAYS/X(11),P(11,20),MACH(11,20),U(11,20),T(11,20),
     1      RHO(11,20),REP(11,20),FRICT(11,20),H(11,20),XCBAR(20),
     2      POWER(20),FORCE(20),STIFF(20),FBAR(20),H1(20),H2(20),
     1      ALPHA(20),HMEAN(20),XSTAR(20),PSTAR(20),ASTAR(20)
      COMMON/CONSTS/GAMMA,RDIF,RO,SIGN,XLAM,XTURB,CONLAM,CONTRB,RELAM,
     1      RETURB,TO,PO,P3,PTOL,RGAS,LOSS,MU,PI,RUNIV(2),CNVT(11,2),NSI
      COMMON/TRAYS/N,XX(201),FM(201),HH(201),J,TSTAR
      COMMON/CTITLE/TITLE(12)
      COMMON/PRNT/C1(4),C2(4),C3(4),C4(4),C5(4),C6(4),C7(4),C8(4),BLANK
      COMMON/LOGICL/PWRSKP,NRMSKP,PRSSKP,PLTSKP(9)
      NAMELIST/SEAL/RINNER,ROUTER,RDIFIN,WIDTH,MOLWT,CP,MUIN,GAMMA,CAPV,
     1      SPEED,XLAM,XTURB,CONLAM,CONTRB,RELAM,RETURB,PWRSKP,PRSSKP,
     2      NRMSKP,PLTSKP,NSI
      NAMELIST/HDATA/ HMEAN,ALPHA,NJ,JDONE
      NAMELIST/RESDAT/P1IN,P2IN,PRIN,TCIN,LOSS,INCODE
C
C     READ TITLE CARD AND SEAL DATA
C
  100 READ(5,1) TITLE
  110 READ(5,SEAL)
```

```
C
C     CHECK CONSISTENCY OF FLOW LENGTH PARAMETERS
C
      IF (RINNER.EQ.0.0)   GO TO 111
      IF (ROUTER.EQ.0.0)   GO TO 112
      R1 = RINNER
      R2 = ROUTER
      RDIF = R2-R1
      GO TO 116
C
  111 IF (ROUTER.EQ.0.0)   GO TO 113
      IF (RDIFIN.EQ.0.0)   GO TO 114
      RDIF = RDIFIN
      R2 = ROUTER
      R1 = R2-RDIF
      GO TO 116
C
  112 IF (RDIFIN.EQ.0.0)   GO TO 114
      RDIF = RDIFIN
      R1 = RINNER
      R2 = R1+RDIF
      GO TO 116
C
  113 IF (RDIFIN.EQ.0.0)   GO TO 114
      RDIF = RDIFIN
      R1 = 0.0
      R2 = 0.0
      IF (WIDTH.NE.0.0)   GO TO 116
C
C     ERROR IN FLOW LENGTH DATA
C
  114 WRITE (6,10) TITLE,RINNER,ROUTER,RDIFIN,WIDTH
  115 READ (5,RESDAT)
      GO TO (100,110,115,115),INCODE
C
C     FLOW LENGTH DATA CONSISTANT
C           CHECK CONSISTENCY OF PLOT CONTROL PARAMETERS
C
  116 IF (NRMSKP)   PLTSKP(3)=.TRUE.
      IF (.NOT.PRSSKP)   GO TO 118
      DO 117 I=4,10
  117 PLTSKP(I) = .TRUE.
  118 DO 119 I=1,11
  119 X(I) = FLOAT(I-1)*RDIF/10.0
C
C     READ FILM THICKNESS DATA
C
  120 READ(5,HDATA)
C
C     READ RESERVOIR DATA AND CHECK CONSISTENCY OF PRESSURE DATA
C
  130 READ(5,RESDAT)
      IF (P1IN.EQ.0.0)   GO TO 134
      IF (P2IN.EQ.0.0)   GO TO 132
  131 P1 = P1IN
      P2 = P2IN
```

```
      PR = P1/P2
      GO TO 140
C
  132 IF (PRIN.EQ.0.0)   GO TO 133
      PR = PRIN
      P1 = P1IN
      P2 = P1/PR
      GO TO 140
C
  133 P1 = P1IN
      P2 = P2IN
      PR = 0.
      GO TO 140
C
  134 IF (P2IN.NE.0.0)   GO TO 131
C
C     ERROR IN PRESSURE DATA
C
  135 WRITE(6,12)  TITLE
      GO TO (100,110,120,130),INCODE
C
C     PRESSURE DATA CONSISTANT
C
  140 PO = AMAX1(P1,P2)
      P3 = AMIN1(P1,P2)
C
C     WRITE INPUT DATA
C
      WRITE (6,20) TITLE
      IF (NSI.EQ.1)   WRITE (6,22) RINNER,P1IN,MOLWT,ROUTER,P2IN,CP,
     1       CONLAM,RDIFIN,PRIN,GAMMA,XLAM,WIDTH,TOIN,MUIN,RELAM,LOSS,
     2       SPEED,CONTRB,CAPV,XTURB,RETURB
      IF (NSI.EQ.2)   WRITE (6,24) RINNER,P1IN,MOLWT,ROUTER,P2IN,CP,
     1       CONLAM,RDIFIN,PRIN,GAMMA,XLAM,WIDTH,TOIN,MUIN,RELAM,LOSS,
     2       SPEED,CONTRB,CAPV,XTURB,RETURB
C
C     CALCULATE PROGRAM CONSTANTS
C
      RGAS = RUNIV(NSI)/MOLWT
      SIGN = 1.0
      IF (WIDTH.NE.0.0)   GO TO 141
      WIDTH = PI*(R1+R2)
      FAREA = PI*(R2**2-R1**2)
      IF (P2.GT.P1)   SIGN = -1.0
      RO = R1
      IF (P2.GT.P1)   RO=R2
      GO TO 142
  141 RO = 0.0
      FAREA = WIDTH*RDIF
      CAPV = 0.0
      SPEED = 0.0
  142 TO = TOIN
      IF (NSI.EQ.2)   TO=TOIN+460.
      MU = MUIN
      IF (GAMMA.EQ.1.4)   MU=CNVT(1,NSI)*TO**1.5/(TO+CNVT(2,NSI))
      N = ALOG10(P3)
```

```
      PTOL = 5.*10.**(N-4)
      IF (SPEED.EQ.0.0)   GO TO 143
      CAPV = PI*SPEED*(R1+R2)/CNVT(3,NSI)
      GO TO 145
  143 IF (CAPV.EQ.0.0)   GO TO 144
      SPEED = CNVT(3,NSI)*CAPV/PI/(R1+R2)
      GO TO 145
  144 PWRSKP = .TRUE.
      CP = 0.0
  145 IF (PWRSKP)   PLTSKP(1)=.TRUE.
C
C     CALCULATE ENTRANCE, EXIT, AND MINIMUM FILM THICKNESSES - ALSO
C     CALCULATE RADIAL DISTRIBUTION OF FILM THICKNESS
C
      DO 147 J=1,NJ
      H1(J) = HMEAN(J)-.50*RDIF*SIN(ALPHA(J))
      H2(J) = 2.0*HMEAN(J)-H1(J)
      HMIN(J) = AMIN1(H1(J),H2(J))
      DO 146 I=1,11
  146 H(I,J) = H1(J)+(RO-R1+X(I)*SIGN)*SIN(ALPHA(J))
  147 CONTINUE
C
C     SET UP ARRAY OF LABELS
C
      DO 150 I=1,8
      DO 150 J=1,4
  150 CALC(I,J) = BLANK
      DO 160 I=1,8
      GO TO (151,152,153,154,155,156,157,158),I
  151 IF (PWRSKP)   GO TO 160
      DO 1151 J=1,4
 1151 CALC(I,J) = C1(J)
      GO TO 160
  152 IF (NRMSKP)   GO TO 160
      DO 1152 J=1,4
 1152 CALC(I,J) = C2(J)
      GO TO 160
  153 IF (PRSSKP)   GO TO 160
      DO 1153 J=1,4
 1153 CALC(I,J) = C3(J)
      GO TO 160
  154 IF (PLTSKP(1))   GO TO 1154
      CALC(I,1) = C4(1)
      CALC(I,2) = C4(2)
 1154 IF (PLTSKP(2))   GO TO 160
      CALC(I,3) = C4(3)
      CALC(I,4) = C4(4)
      GO TO 160
  155 IF (PLTSKP(3))   GO TO 1155
      CALC(I,1) = C5(1)
      CALC(I,2) = C5(2)
 1155 IF (PLTSKP(4))   GO TO 160
      CALC(I,3) = C5(3)
      CALC(I,4) = C5(4)
      GO TO 160
  156 IF (PLTSKP(5))   GO TO 1156
```

```
      CALC(I,1) = C6(1)
      CALC(I,2) = C6(2)
 1156 IF (PLTSKP(6))   GO TO 160
      CALC(I,3) = C6(3)
      CALC(I,4) = C6(4)
      GO TO 160
  157 IF (PLTSKP(7))   GO TO 1157
      CALC(I,1) = C7(1)
      CALC(I,2) = C7(2)
 1157 IF (PLTSKP(8))   GO TO 160
      CALC(I,3) = C7(3)
      CALC(I,4) = C7(4)
      GO TO 160
  158 IF (PLTSKP(9))   GO TO 160
      CALC(I,1) = C8(1)
      CALC(I,2) = C8(2)
  160 CONTINUE
C
C     WRITE CHECKED INPUT DATA
C
      IF (NSI.EQ.1)   WRITE (6,21) R1,PO,MOLWT,(CALC(1,I),I=1,4),R2,P3,
     1       CP,(CALC(2,I),I=1,4),RDIF,PR,GAMMA,(CALC(3,I),I=1,4),WIDTH,
     2       TO,MU,(CALC(4,I),I=1,4),RGAS,SPEED,(CALC(5,I),I=1,4),LOSS,
     3       CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4),(CALC(8,I),I=1,4)
      IF (NSI.EQ.2)   WRITE (6,23) R1,PO,MOLWT,(CALC(1,I),I=1,4),R2,P3,
     1       CP,(CALC(2,I),I=1,4),RDIF,PR,GAMMA,(CALC(3,I),I=1,4),WIDTH,
     2       TO,MU,(CALC(4,I),I=1,4),RGAS,SPEED,(CALC(5,I),I=1,4),LOSS,
     3       CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4),(CALC(8,I),I=1,4)
      WRITE (6,19)
C
C     BEGIN MAIN CALCULATION
C
  200 DO 270  J=1,NJ
C
C     CHECK FOR RESTARTING WHEN SOME CASES ARE FINISHED BY PREVIOUS
C     RUNNING OF THE PROGRAM.  IF JDONE IS GREATER THAN ZERO, READ X AND
C     MACH NUMBER DISTRIBUTIONS CALCULATED BY PREVIOUS RUNNING OF THE
C     PROGRAM.  CALCULATE H DISTRIBUTION AND A*.  DIMENSIONALIZE X, X*,
C     P*, AND T*.
C
      IF (J.GT.JDONE)   GO TO 210
      READ (5,2) JJ,N,PSTAR(JJ),XSTAR(JJ),TSTAR
      IF (J.EQ.JJ)   GO TO 201
      WRITE (6,15)
      STOP
C
  201 READ (5,3) (XX(I),I=1,N)
      READ (5,3) (FM(I),I=1,N)
      DO 202 I=1,N
      XX(I) = XX(I)*RDIF
      HH(I) = H1(J)+(RO-R1+XX(I)*SIGN)*SIN(ALPHA(J))
  202 CONTINUE
      PSTAR(J) = PSTAR(J)*PC
      XSTAR(J) = XSTAR(J)*RDIF
      TSTAR = TSTAR*TO
      ASTAR(J) = HH(N)
```

```
      IF (RO.NE.0.0)    ASTAR(J)=2.0*PI*(RO+XX(N)*SIGN)*HH(N)
      GO TO 240
C
C     CALL SUBROUTINES TO DETERMINE SOLUTION OF MACH NUMBER EQUATION AND
C     DISTRIBUTIONS OF PARAMETERS THAT VARY WITH X
C
  210 CALL NCFLOW
  240 CALL DISTS
C
C     CALCULATE PARAMETERS THAT VARY ONLY WITH FILM THICKNESS
C
  245 MDOT(J) = WIDTH*H(6,J)*RHO(6,J)*U(6,J)*CNVT(4,NSI)
      Q(J) = CNVT(5,NSI)*MDOT(J)
      KN(J) = 2.96*MACH(6,J)/REP(6,J)
      LAMDA(J) = KN(J)*HMEAN(J)
      FMU = MU
      IF (GAMMA.EQ.1.4) FMU=CNVT(1,NSI)*T(6,J)**1.5/(T(6,J)+CNVT(2,NSI))
      RER(J) = RHO(6,J)*CAPV*HMEAN(J)/FMU/CNVT(6,NSI)
      IF(PWRSKP)  GO TO 260
C
C     CALCULATE POWER, SHEAR HEAT,TORQUE, AND TEMPERATURE RISE DUE
C     TO POWER DISSIPATION
C
  250 POWER(J)= 0.
      IF (REP(6,J).LE.RELAM)    POWER(J)=FMU*FAREA*CAPV**2/HMEAN(J)/
     1                          CNVT(7,NSI)
      HSHEAR(J) = CNVT(8,NSI)*POWER(J)
      DELT(J) = HSHEAR(J)/ABS(MDOT(J))/CP
      TORQUE(J) = POWER(J)*CNVT(9,NSI)/SPEED
C
C     CALCULATE FORCE AND CENTER OF PRESSURE
C
  260 K=0
      KK=0
      FORCE(J) = SIMPS1(0.,RDIF,FFUNC,K)*WIDTH
      XC(J) = SIMPS1(0.,RDIF,XCFUNC,KK)*WIDTH/FORCE(J)
  265 IF (K.NE.0)   WRITE (6,13)
      IF(KK.NE.0)  WRITE(6,14)
      IF (NRMSKP)   GO TO 270
      FBAR(J) = FORCE(J)/RDIF/(PO-P3)/WIDTH
      XCBAR(J) = XC(J)/RDIF
  270 CONTINUE
  275 CALL STFNSS
C
C     WRITE OUTPUT DATA AND PLOT THEM (SUBROUTINE GRAFIC)
C
      IF (NSI.EQ.1)   WRITE (6,25)
      IF (NSI.EQ.2)   WRITE (6,26)
      DO 710 J=1,NJ
      WRITE (6,43) HMEAN(J),HMIN(J),ALPHA(J),MDOT(J),Q(J),RER(J),
     1       STIFF(J),FORCE(J),XC(J)
      IF (ABS(MACH(11,J)-1.0).LT.1.E-5)   WRITE (6,45)
      IF (REP(6,J).GT.RELAM.AND.REP(6,J).LT.RETURB)   WRITE (6,46)
      IF (REP(6,J).GE.RETURB)   WRITE (6,47)
  710 CONTINUE
C
```

```
      WRITE (6,27)
      IF (.NOT.NRMSKP)   WRITE (6,28)
      IF (NSI.EQ.1)   WRITE (6,29)
      IF (NSI.EQ.2)   WRITE (6,30)
      IF (.NOT.NRMSKP)   WRITE (6,31)
      DO 720 J=1,NJ
      WRITE (6,48) HMEAN(J),HMIN(J),ALPHA(J),KN(J),LAMDA(J),
     1      XSTAR(J),PSTAR(J)
      IF (.NOT.NRMSKP)   WRITE (6,44) FBAR(J),XCBAR(J)
      IF (ABS(MACH(11,J)-1.0).LT.1.E-5)   WRITE (6,45)
      IF (REP(6,J).GT.RELAM.AND.REP(6,J).LT.RETURB)   WRITE (6,46)
      IF (REP(6,J).GE.RETURB)   WRITE (6,47)
  720 CONTINUE
C
      IF (PWRSKP)   GO TO 740
      WRITE (6,32)
      IF (NSI.EQ.1)   WRITE (6,33)
      IF (NSI.EQ.2)   WRITE (6,34)
      DO 730 J=1,NJ
      WRITE (6,43) HMEAN(J),HMIN(J),ALPHA(J),POWER(J),HSHEAR(J),DELT(J),
     1      TORQUE(J)
      IF (ABS(MACH(11,J)-1.0).LT.1.E-5)   WRITE (6,45)
      IF (REP(6,J).GT.RELAM.AND.REP(6,J).LT.RETURB)   WRITE (6,46)
      IF (REP(6,J).GE.RETURB)   WRITE (6,47)
  730 CONTINUE
C
  740 IF (PRSSKP)   GO TO 800
      DO 750 J=1,NJ
      DO 745 I=1,11
      IF (NSI.EQ.2)   T(I,J) = T(I,J)-460.
  745 CONTINUE
      IF (MOD(J,3).EQ.1)   WRITE (6,35)
      A1 = WIDTH*H1(J)
      A2 = WIDTH*H2(J)
      IF (RO.NE.0.0)   A1=2.0*PI*R1*H1(J)
      IF (RO.NE.0.0)   A2=2.0*PI*R2*H2(J)
      DADR = ABS(A1-A2)/RDIF
      DELA = ABS(A1-A2)/AMIN1(A1,A2)
      IF (NSI.EQ.1)   WRITE (6,36) HMEAN(J),H1(J),DADR,ALPHA(J),
     1      H2(J),DELA
      IF (NSI.EQ.2)   WRITE (6,37) HMEAN(J),H1(J),DADR,ALPHA(J),
     1      H2(J),DELA
      IF (ABS(MACH(11,J)-1.0).GT.1.E-5)   WRITE (6,38)
      IF (ABS(P(11,J)-P3).GT.PTOL)   WRITE (6,39)
      WRITE (6,40)
      IF (NSI.EQ.1)   WRITE (6,41)
      IF (NSI.EQ.2)   WRITE (6,42)
      WRITE (6,43) (X(I),H(I,J),MACH(I,J),U(I,J),RHO(I,J),P(I,J),
     1      T(I,J),REP(I,J),FRICT(I,J),I=1,11)
  750 CONTINUE
C
  800 CALL GRAFIC
      GO TO (100,110,120,130), INCODE
C
C     END OF PROGRAM
C
```

```
    1 FORMAT (12A6)
    2 FORMAT (2X,I3,3X,I3,5X,E14.7,5X,E14.7,5X,E14.7)
    3 FORMAT (5E14.7)
   10 FORMAT (1H1,22HAREA EXPANSION PROGRAM,5X,12A6,/,1H0,
     1       35HFLOW LENGTH PARAMETERS INCONSISTANT,5X,4HR1 =,G10.3,5X,
     2       4HR2 =,G10.3,5X,7HR2-R1 =,G10.3,5X,7HWIDTH =,G10.3)
   12 FORMAT (1H1,22HAREA EXPANSION PROGRAM,5X,12A6,/,1H0,
     1       26HINSUFFICIENT PRESSURE DATA,5X,11HPO = P3 = 0)
   13 FORMAT (1H0,53HINACCURATE NUMERICAL INTEGRATION IN FORCE CALCULATI
     1ON)
   14 FORMAT (1H0,66HINACCURATE NUMERICAL INTEGRATION IN CENTER OF PRESS
     1URE CALCULATION)
   15 FORMAT (1H0,26HDISTRIBUTIONS OUT OF ORDER)
   19 FORMAT (1H0,44X,30H******************************,/,1H ,44X,1H*,
     1       28X,1H*,/,1H ,44X,30H*   / - CHOKED FLOW            *,/,1H ,
     2       44X,30H*   + - TRANSITION REGION    *,/,1H ,44X,
     3       30H*   T - TURBULENT FLOW         *,/,1H ,44X,1H*,28X,1H*,/,
     4       1H ,44X,30H******************************)
   20 FORMAT (1H1,71HPROGRAM FOR QUASI-ONE DIMENSIONAL FLOW WITH FRICTIO
     1N AND AREA EXPANSION,/,1H0,20X,12A6,/)
   22 FORMAT (1H0,12HINPUT DATA -,/,1H0,10X,9HR1,METERS,22X,7HP1,NSMA,
     1       18X,16HMOLECULAR WEIGHT,17X,9HF=K/RE**N,/,1H ,E18.3,E30.3,
     2       F29.3,22X,9H*********,/,1H0,10X,9HR2,METERS,22X,7HP2,NSMA,
     3       17X,18HCP,JOULES/KG-DEG K,16X,10HK(LAMINAR),/,1H ,E18.3,
     4       E30.3,E28.3,F30.3,/,1H0,6X,18HFLOW LENGTH,METERS,18X,
     5       5HP1/P2,24X,5HGAMMA,23X,10HN(LAMINAR),/,1H ,E18.3,E29.3,
     6       F29.3,F30.2,/,1H0,7X,17HFLOW WIDTH,METERS,16X,8HTC,DEG K,
     7       17X,18HVISCOSITY,N-SEC/M2,9X,24HUPPER LIMIT RE (LAMINAR),/,
     8       1H ,E18.3,F29.1,G32.4,F28.1,/,1H0,39X,10HLOSS COEF.,21X,
     9       9HSPEED,RPS,19X,12HK(TURBULENT),/,1H ,F47.2,E32.4,G30.4,/,
     X       1H0,70X,7HV,M/SEC,21X,12HN(TURBULENT),/,1H ,F77.2,G32.4,/,
     1       1H0,91X,26HLOWER LIMIT RE (TURBULENT),/,1H ,F107.1)
   21 FORMAT (1H0,13HOUTPUT DATA -,/,1H0,10X,9HR1,METERS,22X,7HPC/NSMA,
     1       18X,16HMOLECULAR WEIGHT,17X,9HCALCULATE,/,1H ,E18.3,E30.3,
     2       F29.3,22X,9H*********,/,1H0,10X,9HR2,METERS,22X,7HP3/NSMA,
     3       17X,18HCP,JOULES/KG-DEG K,9X,4A6,/,1H ,E18.3,E30.3,E28.3,/,
     4       1H ,92X,4A6,/,1H ,6X,18HFLOW LENGTH,METERS,18X,5HPO/P3,24X,
     5       5HGAMMA,/,1H ,E18.3,2F29.3,16X,4A6,/,1H0,4X,
     6       22HMEAN FLOW WIDTH,METERS,14X,8HTO,DEG K,17X,
     7       18HVISCOSITY,N-SEC/M2,19X,4HPLOT,/,1H ,E18.3,F29.3,G32.4,
     8       14X,22H**********************,/,1H0,30X,
     9       28HGAS CONSTANT,JOULES/KG-DEG K,12X,9HSPEED,RPS,14X,4A6,/,
     X       1H ,E48.3,G32.4,/,1H ,93X,4A6,/,1H ,39X,10HLOSS COEF.,
     1       21X,7HV,M/SEC,/,1H ,F47.2,E31.3,15X,4A6,/,1H0,93X,4A6,/,
     2       1H0,93X,4A6,/)
   23 FORMAT (1H0,13HOUTPUT DATA -,/,1H0,10X,9HR1,INCHES,22X,7HPC,PSIA,
     1       18X,16HMOLECULAR WEIGHT,17X,9HCALCULATE,/,1H ,F18.4,F30.3,
     2       F29.3,22X,9H*********,/,1H0,10X,9HR2,INCHES,22X,7HP3,PSIA,
     3       18X,16HCP,BTU/LBM-DEG R,10X,4A6,/,1H ,F18.4,F30.3,F28.3,/,
     4       1H ,92X,4A6,/,1H ,6X,18HFLOW LENGTH,INCHES,18X,5HPO/P3,24X,
     5       5HGAMMA,/,1H ,F18.4,2F29.3,16X,4A6,/,1H0,4X,
     6       22HMEAN FLOW WIDTH,INCHES,14X,8HTO,DEG R,16X,
     7       20HVISCOSITY,LB-SEC/IN2,18X,4HPLOT,/,1H ,F18.4,F29.3,G32.3,
     8       14X,22H**********************,/,1H0,32X,
     9       24HGAS CONSTANT,LB-FT/LBM-R,14X,9HSPEED,RPM,14X,4A6,/,1H ,
     X       F47.5,G32.4,/,1H ,93X,4A6,/,1H ,39X,10HLOSS COEF.,
```

```
     1        21X,8HV,FT/SEC,/,1H ,F47.2,F30.2,16X,4A6,/,1H0,93X,4A6,/,
     2        1H0,93X,4A6,/)
  24 FORMAT (1H0,12HINPUT DATA -,/,1H0,10X,9HR1,INCHES,22X,7HP1,PSIA,
     1        18X,16HMOLECULAR WEIGHT,17X,9HF=K/RE**N,/,1H ,F18.4,F30.3,
     2        F29.3,22X,9H*********,/,1H0,10X,9HR2,INCHES,22X,7HP2,PSIA,
     3        18X,16HCP,BTU/LBM-DEG R,17X,10HK(LAMINAR),/,1H ,F18.4,F30.3,
     4        F28.3,F30.3,/,1H0,6X,18HFLOW LENGTH,INCHES,18X,5HP1/P2,24X,
     5        5HGAMMA,23X,10HN(LAMINAR),/,1H ,F18.4,F29.3,F29.3,F30.2/,
     6        1H0,7X,17HFLOW WIDTH,INCHES,16X,8HT0,DEG F,17X,
     7        20HVISCOSITY,LB-SEC/IN2,8X,24HUPPER LIMIT RE (LAMINAR),/,
     8        1H ,F18.4,F29.1,G32.4,F28.1,/,1H0,39X,10HLOSS COEF.,21X,
     9        9HSPEED,RPM,19X,12HK(TURBULENT),/,1H ,F47.2,E32.4,G30.4,/,
     X        1H0,70X,8HV,FT/SEC,20X,12HN(TURBULENT),/,1H ,F77.2,G32.4/,
     1        1H0,91X,26HLOWER LIMIT RE (TURBULENT),/,1H ,F107.1)
  25 FORMAT (1H1,5X,7HH(CHAR),7X,6HH(MIN),7X,5HALPHA,7X,6HM(DOT),9X,
     1        1HQ,11X,5HRE(R),6X,9HSTIFFNESS,6X,5HFORCE,10X,2HXC,/,1H ,5X,
     2        6HMETERS,8X,6HMETERS,6X,7HRADIANS,6X,6HKG/SEC,8X,4HSCMS,23X,
     3        3HN/M,11X,1HN,10X,6HMETERS)
  26 FORMAT (1H1,5X,7HH(MEAN),7X,6HH(MIN),7X,5HALPHA,7X,6HM(DOT),9X,
     1        1HQ,11X,5HRE(R),6X,9HSTIFFNESS,6X,5HFORCE,10X,2HXC,/,1H ,6X,
     2        6HINCHES,7X,6HINCHES,7X,7HRADIANS,5X,6HLB/MIN,8X,4HSCFM,22X,
     3        5HLB/IN,10X,2HLB,9X,6HINCHES)
  27 FORMAT (1H0,5X,7HH(MEAN),7X,6HH(MIN),7X,5HALPHA,7X,7HKNUDSEN,6X,
     1        6HLAMBDA,9X,4HX(*),9X,4HP(*))
  28 FORMAT (1H+,97X,5HFORCE,10X,2HXC)
  29 FORMAT (1H ,5X,6HMETERS,8X,6HMETERS,6X,7HRADIANS,6X,6HNUMBER,7X,
     1        6HMETERS,8X,6HMETERS,8X,4HN/M2)
  30 FORMAT (1H ,5X,6HINCHES,8X,6HINCHES,6X,7HRADIANS,6X,6HNUMBER,7X,
     1        6HINCHES,8X,6HINCHES,8X,4HPSIA)
  31 FORMAT (1H+,97X,5H(BAR),9X,5H(BAR))
  32 FORMAT (1H0,5X,7HH(MEAN),7X,6HH(MIN),7X,5HALPHA,8X,5HPOWER,6X,
     1        8HH(SHEAR),5X,8HDELTA(T),7X,6HTORQUE)
  33 FORMAT (1H ,5X,6HMETERS,8X,6HMETERS,6X,7HRADIANS,7X,5HWATTS.7X,
     1        5HWATTS,8X,5HDEG K,10X,3HN-M)
  34 FORMAT (1H ,5X,6HINCHES,7X,6HINCHES,7X,7HRADIANS,9X,2HHP,8X,
     1        7HBTU/MIN,7X,5HDEG F,9X,5HFT-LB)
  35 FORMAT (1H1)
  36 FORMAT (1H0,9HH(MEAN) =,G11.3,7H METERS,5X,4HH1 =,G11.3,7H METERS,
     1        5X,11HDA/DR     =,G11.3,5X,7HALPHA =,G11.3,8H RADIANS,/,1H ,
     2        32X,4HH2 =,G11.3,7H METERS,5X,11HDA/A(MIN) =,G11.3)
  37 FORMAT (1H0,9HH(MEAN) =,G11.3,7H INCHES,5X,4HH1 =,G11.3,7H INCHES,
     1        5X,11HDA/DR     =,G11.3,5X,7HALPHA =,G11.3,8H RADIANS,/,1H ,
     2        32X,4HH2 =,G11.3,7H INCHES,5X,11HDA/A(MIN) =,G11.3)
  38 FORMAT (1H+,92X,15H(SUBSONIC FLOW))
  39 FORMAT (1H+,93X,13H(CHOKED FLOW))
  40 FORMAT (1H0,8X,1HX,11X,1HH,11X,4HMACH,5X,8HVELOCITY,8X,7HDENSITY,
     1        3X,8HPRESSURE,4X,11HTEMPERATURE,7X,5HRE(P),6X,8HFRICTION)
  41 FORMAT (1H ,6X,6HMETERS,6X,6HMETERS,7X,6HNUMBER,6X,5HM/SEC,10X,
     1        5HKG/M3,6X,4HN/M2,9X,5HDEG K,22X,6HFACTOR)
  42 FORMAT (1H ,5X,6HINCHES,7X,6HINCHES,7X,6HNUMBER,5X,6HFT/SEC,7X,
     1        11HLB-SEC2/FT4,3X,4HPSIA,9X,5HDEG F,22X,6HFACTOR)
  43 FORMAT (1H ,9G13.3)
  44 FORMAT (1H+,91X,2G13.3)
  45 FORMAT (1H+,1H/)
  46 FORMAT (1H+,2H +)
  47 FORMAT (1H+,2H T)
  48 FORMAT (1H ,7G13.3)
C
      END
```

```
C
C     DETERMINE THE MACH NUMBER DISTRIBUTION SUCH THAT M=1.0 AT X=X*.
C     FOR CHOKED FLOW, X*=RDIF - FOR SUBSONIC FLOW, P2=P3.
C
C     PROGRAM VARIABLES
C     *****************
C
C      ENTRANCE CONDITIONS
C      *******************
C
C          H1 - FILM THICKNESS
C          A1 - CROSS-SECTIONAL AREA
C       FM(1) - INITIAL GUESS OF MACH NUMBER
C         TT1 - TEMPERATURE
C          P1 - PRESSURE
C
C      EXIT CONDITIONS
C      ***************
C
C          H2 - FILM THICKNESS
C          A2 - CROSS-SECTIONAL AREA
C          P2 - PRESSURE
C         FM2 - MACH NUMBER
C
C      CONDITIONS AT CHOKING
C      *********************
C
C      XSTAR - FLOW LENGTH
C      HSTER - FILM THICKNESS
C      ASTER - CROSS-SECTIONAL AREA
C      PSTER - PRESSURE
C      TSTAR - TEMPERATURE
C
C     PROGRAM VARIABLES
C     *****************
C
C        DELX - STEP SIZE
C           N - NUMBER OF POINTS IN SOLUTION OF MACH NUMBER EQUATICN
C
C     ARITHMETIC FUNCTION FLGRNG DOES A 3 POINT LAGRANGE INTERPOLATION
C
      SUBROUTINE NCFLOW
      DOUBLE PRECISION X,FM,H,XO,X1,X2,YO,Y1,Y2,XX(2),PP(2),FM2,P2,
     1       ASTER,PSTER,P1,A1,A2
      REAL LOSS,MU
      COMMON/ARRAYS/E1(231),FMM(11,20),E2(1420),H1(20),H2(20),ALPHA(20),
     1       HMEAN(20),XSTAR(20),PSTAR(20),ASTAR(20)
      COMMON/TRAYS/N,X(201),FM(201),H(201),J,TSTAR
      COMMON/CONSTS/GAMMA,RDIF,RO,SIGN,REF(6),TO,PO,P3,PTCL,RGAS,LOSS,
     1       MU,PI,RUNIV(2),CNVT(11,2),NSI
      DIMENSION SX(201),SY(201)
      FLGRNG(X,XO,X1,X2,YO,Y1,Y2) = YO*(X-X1)*(X-X2)/(XO-X1)/(XO-X2)+
     1       Y1*(X-XO)*(X-X2)/(X1-XO)/(X1-X2)+Y2*(X-XO)*(X-X1)/(X2-XO)/
     2       (X2-X1)
C
C     SET BOUNDARY CONDITIONS - DEFINE CONSTANTS NEEDED IN SOLUTICN OF
C     MACH NUMBER EQUATION
C
```

```
      POLD = 0.0
      EX = .50
      NN = ALOG10(RDIF)
      XTOL  = RDIF*10.0**(NN-5)
      FM(1)  =  .25D0
      IF (J.NE.1)    FM(1)=FMM(1,J-1)*H1(J)/H1(J-1)
      CON =  SIN(ALPHA(J))
      X(1) = 0.
      H(1) = H1(J)
      IF (SIGN.LT.0.0)    H(1)=H2(J)
      IF (RO.EQ.0.0)    GO TO 90
      A1 = 2.0*PI*RO*H(1)
      IF (SIGN.GT.0.0)    A2=2.0*PI*(RO+RDIF)*H2(J)
      IF (SIGN.LT.0.0)    A2=2.0*PI*(RO-RDIF)*H1(J)
      GO TO 95
   90 A1 = H(1)
      A2 = H(1)+RDIF*CON
   95 XX(1)  = 0.0
      XX(2)  = 0.0
      PP(1)  = 0.0
      PP(2)  = 0.0
C
C     GUESS A STARTING VALUE FOR THE ENTRANCE MACH NUMBER - CALL
C     SUBROUTINE RK1 TO FIND THE SOLUTION OF THE MACH NUMBER EQUATION
C
  100 CALL RK1(CON)
      FMOLD = FM(1)
      XSTAR(J) = X(N)
      IF (XSTAR(J).LT.RDIF)    GO TO 145
C
C     CALCULATE P2
C
  120 TT1 = TO/(1.0+.50*(GAMMA-1.0)*(FM(1)/LOSS)**2)
      TSTAR  = TT1*(1.+.5*(GAMMA-1.)*FM(1)**2)/.5/(GAMMA+1.)
      HSTER  = H(N)
      ASTER  = HSTER
      IF (RO.NE.0.0)    ASTER=2.0*PI*(RO+XSTAR(J)*SIGN)*HSTER
      P1 = PO/(1.+.5*(GAMMA-1.)*(FM(1)/LOSS)**2)**(GAMMA/(GAMMA-1.))
      PSTER  = P1*A1*FM(1)/ASTER*SQRT((1.0+.50*(GAMMA-1.0)*FM(1)**2)/
     1        .5/(GAMMA+1.))
C
  130 FM2 = 1.D0
      II = 1
      IF (ABS(RDIF-XSTAR(J)).LE.XTOL)    GO TO 143
  135 DO 140 I=1,N
      II = I
      IF (RDIF-X(I))    141,142,140
  140 CONTINUE
  141 IF (II.LE.2)    II=2
      IF (II.GE.N)    II=N-1
      FM2 = FLGRNG(RDIF,X(II-1),X(II),X(II+1),FM(II-1),FM(II),FM(II+1))
      GO TO 143
  142 FM2 = FM(II)
  143 P2 = ASTER*PSTER/A2/FM2*SQRT(.50*(GAMMA+1.0)/(1.0+.50*(GAMMA-1.0)
     1        *FM2**2))
C
C     FOR CHOKED FLOW, OMIT ITERATION FOR P2=P3
C
      IF (ABS(XSTAR(J)-RDIF).LE.XTOL.AND.P2.GE.P3)    GO TO 160
      IF (ABS(P2-P3).LT.PTOL)    GO TO 160
```

```
C
C     FOR SUBSONIC FLOW, COMPARE P2 AND P3.  IF THEY ARE NOT EQUAL, SAVE
C     THE VALUES OF P2 AND M1.  WHEN 2 SUCH POINTS HAVE BEEN SAVED, DO A
C     LINEAR INTERPOLATION TO DETERMINE THE M1 THAT CORRESPONDS TO P2=P3
C
      IF (PSTER.LE.P3)   GO TO 146
      IF (PSTER.LT..5D0*P2)   EX=EX/2.0
      IF (ABS(POLD-P2).LT.10.0*PTOL)   EX=EX/2.0
      IF (EX.LT..1)   EX=EX*2.0
  144 POLD = P2
  145 FM(1) = FM(1)*(XSTAR(J)/RDIF)**EX
      GO TO 153
  146 IF (P2.GT.P3)   GO TO 150
      XX(1) = FM(1)
      PP(1) = P2
      IF (XX(2).NE.0.0)   GO TO 152
      IF (SIGN.GT.0.0.OR.ABS(XSTAR(J)-RDIF).LT.XTOL)   GO TO 151
      FM(1) = FM(1)*(RDIF/XSTAR(J))**.25
      GO TO 153
  150 IF (P2.GT.PP(2))   EX=EX/2.0
      XX(2) = FM(1)
      PP(2) = P2
      IF (XX(1).NE.0.0)   GO TO 152
  151 FM(1) = FM(1)*(P2/P3)**EX
      GO TO 153
  152 FM(1) = (P3-PP(2))*(XX(1)-XX(2))/(PP(1)-PP(2))+XX(2)
  153 IF (FM(1).LT.1.D0)   GO TO 100
      FM(1) = (2.D0*FMOLD+1.D0)/3.D0
      GO TO 100
C
C     SOLUTION COMPLETE (SATISFACTORY X* FOUND AND P2=P3 FOR SUBSONIC
C     FLOW) - PUNCH X AND M ON CARDS FOR RESTARTING
C
  160 ASTAR(J) = ASTER
      PSTAR(J) = PSTER
      IND = 0
      DO 170 I=1,N
      IF (I.EQ.1)   GO TO 165
      IF (I.EQ.N)   GO TO 166
      IF (X(I)-SX(IND).LT.1.E-8)   GO TO 170
      IF (FM(I)-SY(IND).LT.1.E-8)   GO TO 170
  165 IND = IND+1
  166 SX(IND) = X(I)
      SY(IND) = FM(I)
  170 CONTINUE
      DO 175 I=1,IND
      SX(I) = SX(I)/RDIF
  175 CONTINUE
      PPUNCH = PSTAR(J)/PC
      XPUNCH = XSTAR(J)/RDIF
      TPUNCH = TSTAR/TO
      WRITE (6,10) J,IND,PPUNCH,XPUNCH,TPUNCH
      K = 0
      NNN = (IND/5)*5
      NN = NNN+1
      DO 180 I=1,NNN,5
      II = I+4
      WRITE (6,11) (SX(J),J=I,II),K
      K = K+1
```

```
  180 CONTINUE
      II = IND-NNN
      IF (II.EQ.1)   WRITE (6,12) (SX(J),J=NN,IND),K
      IF (II.EQ.2)   WRITE (6,13) (SX(J),J=NN,IND),K
      IF (II.EQ.3)   WRITE (6,14) (SX(J),J=NN,IND),K
      IF (II.EQ.4)   WRITE (6,15) (SX(J),J=NN,IND),K
      K = K+1
      DO 185 I=1,NNN,5
      II = I+4
      WRITE (6,11) (SY(J),J=I,II),K
      K = K+1
  185 CONTINUE
      II = IND-NNN
      IF (II.EQ.1)   WRITE (6,12) (SY(J),J=NN,IND),K
      IF (II.EQ.2)   WRITE (6,13) (SY(J),J=NN,IND),K
      IF (II.EQ.3)   WRITE (6,14) (SY(J),J=NN,IND),K
      IF (II.EQ.4)   WRITE (6,15) (SY(J),J=NN,IND),K
      RETURN
C
   10 FORMAT (2H* ,2HJ=,I3,3H N=,I3,5H P* =,E14.7,5H X* =,E14.7,5H T* =,
     1       E14.7)
   11 FORMAT (2H* ,5E14.7,I10)
   12 FORMAT (2H* ,E14.7,I66)
   13 FORMAT (2H* ,2E14.7,I52)
   14 FORMAT (2H* ,3E14.7,I38)
   15 FORMAT (2H* ,4E14.7,I24)
C
      END
```

```
C
C     DISTRIBUTIONS OF PRESSURE, TEMPERATURE, DENSITY, MACH NUMBER,
C     VELOCITY, REYNOLDS NUMBER, AND MEAN FRICTION FACTOR
C
C     PROGRAM VARIABLES
C     *****************
C
C            N - NUMBER OF POINTS IN SOLUTION OF MACH NUMBER EQUATION
C           XX - ARRAY OF INDEPENDENT VARIABLE (DISTANCE) IN SOLUTION OF
C                MACH NUMBER EQUATION
C           FM - MACH NUMBER ARRAY FROM SOLUTION OF MACH NUMBER EQUATION
C
C            X - ARRAY OF EQUALLY SPACED DISTANCES
C         MACH - MACH NUMBER AT X
C            T - TEMPERATURE
C            U - RADIAL VELOCITY
C          RHO - DENSITY
C            P - PRESSURE
C          REP - REYNOLDS NUMBER
C        FRICT - MEAN FRICTION FACTOR
C
C     ARITHMETIC FUNCTION FLGRNG DOES A 3 POINT LAGRANGE INTERPOLATION
C
      SUBROUTINE DISTS
      REAL MACH,LOSS,ML,MLX
```

```
      DOUBLE PRECISION FRFUNC,XX,FM,HH,X0,X1,X2,Y0,Y1,Y2
      COMMON/ARRAYS/X(11),P(11,20),MACH(11,20),U(11,20),T(11,20),
     1          RHO(11,20),REP(11,20),FRICT(11,20),H(11,20),XCBAR(20),
     2          POWER(20),FORCE(20),STIFF(20),FBAR(20),EXTRA(80),XSTAR(20),
     3          PSTAR(20),ASTAR(20)
      COMMON/TRAYS/N,XX(201),FM(201),HH(201),J,TSTAR
      COMMON/CONSTS/GAMMA,RDIF,RO,SIGN,EX(8),P3,PTOL,RGAS,LOSS,MU,PI,
     1          RUNIV(2),CNVT(11,2),NSI
      FLGRNG(X,X0,X1,X2,Y0,Y1,Y2) = Y0*(X-X1)*(X-X2)/(X0-X1)/(X0-X2)+
     1          Y1*(X-X0)*(X-X2)/(X1-X0)/(X1-X2)+Y2*(X-X0)*(X-X1)/(X2-X0)/
     2          (X2-X1)
C
      AN = 1.0
      KK = 1
  100 DO 160 I=1,11
      DO 120 K=KK,N
      KK = K
      IF (X(I)-XX(K))    121,122,120
  120 CONTINUE
  121 IF (KK.LT.2)    KK=2
      IF (KK.GE.N)    KK=N-1
      MACH(I,J) = FLGRNG(X(I),XX(KK-1),XX(KK),XX(KK+1),FM(KK-1),
     1               FM(KK),FM(KK+1))
      GO TO 130
  122 MACH(I,J) = FM(KK)
C
  130 T(I,J) = .50*(GAMMA+1.0)*TSTAR/(1.0+.50*(GAMMA-1.0)*MACH(I,J)**2)
      U(I,J) = MACH(I,J)*SQRT(CNVT(11,NSI)*GAMMA*RGAS*T(I,J))
      IF (RO.NE.0.0)    AN=2.0*PI*(RO+X(I)*SIGN)
      P(I,J) = PSTAR(J)*ASTAR(J)/AN/H(I,J)*SQRT(.50*(GAMMA+1.0)/
     1          (1.0+.50*(GAMMA-1.0)*MACH(I,J)**2))/MACH(I,J)
      IF (KK.GT.250)    GO TO 135
      IF (I.LT.11)    GO TO 135
      IF (ABS(P(I,J)-P3).LT.PTOL)    GO TO 135
      KK = 300
      MACH(I,J) = 1.0
      GO TO 130
  135 RHO(I,J) = P(I,J)*CNVT(10,NSI)/RGAS/T(I,J)
      MUX = MU
      IF (GAMMA.EQ.1.4) MUX=CNVT(1,NSI)*T(I,J)**1.5/(T(I,J)+CNVT(2,NSI))
      REP(I,J) = RHO(I,J)*U(I,J)*2.0*H(I,J)/MUX/CNVT(6,NSI)
      FRICT(I,J) = FRFUNC(REP(I,J))
  160 CONTINUE
C
      RETURN
      END
```

```
C
C     PRESSURE CALCULATION FOR NUMERICAL INTEGRATIONS
C
C     PROGRAM VARIABLES
C     *****************
C
C          X - DISTANCE ACROSS FACE OF SEAL
C         XX - STORED X DISTRIBUTION FROM 0 TO X*
C         FM - MACH NUMBER DISTRIBUTION WITH XX
C         HH - FILM THICKNESS DISTRIBUTION WITH XX
C
C        FMM - MACH NUMBER AT X
C          H - FILM THICKNESS AT X
C         AN - AREA AT X
C      PRESS - PRESSURE AT X
C
C     ARITHMETIC FUNCTION FLGRNG DOES A 3 POINT LAGRANGE INTERPOLATION
C
      FUNCTION PRESS(X)
      DOUBLE PRECISION XX,FM,HH,X0,X1,X2,Y0,Y1,Y2
      REAL LOSS
      COMMON/ARRAYS/EXTRA(1971),PSTAR(20),ASTAR(20)
      COMMON/TRAYS/N,XX(201),FM(201),HH(201),J,TSTAR
      COMMON/CONSTS/GAMMA,RDIF,RO,SIGN,D(6),TC,PC,P3,FT,RGAS,LOSS,MU,PI,
     1      RUNIV(2),CNVT(11,2),NSI
      FLGRNG(X,X0,X1,X2,Y0,Y1,Y2) = Y0*(X-X1)*(X-X2)/(X0-X1)/(X0-X2)+
     1      Y1*(X-X0)*(X-X2)/(X1-X0)/(X1-X2)+Y2*(X-X0)*(X-X1)/(X2-X0)/
     2      (X2-X1)
C
      AN = 1.0
      DO 120 I=1,N
      KK = I
      IF (X-XX(I))   122,121,120
  120 CONTINUE
      GO TO 122
  121 FMM = FM(KK)
      H = HH(KK)
      GO TO 135
  122 IF (KK.LE.2)   KK=2
      IF (KK.GE.N)   KK=N-1
C
  130 FMM = FLGRNG(X,XX(KK-1),XX(KK),XX(KK+1),FM(KK-1),FM(KK),FM(KK+1))
      H = FLGRNG(X,XX(KK-1),XX(KK),XX(KK+1),HH(KK-1),HH(KK),HH(KK+1))
C
  135 IF (RO.NE.0.0)   AN=2.0*PI*(RO+X*SIGN)
      PRESS = PSTAR(J)*ASTAR(J)/AN/H*SQRT(.50*(GAMMA+1.0)/
     1      (1.0+.50*(GAMMA-1.0)*FMM**2))/FMM
C
      RETURN
      END
```

```
C
C     DOUBLE PRECISION RUNGE-KUTTA SOLUTION OF THE MACH NUMBER EQUATION
C     FOR FLOW WITH AREA CHANGE AND FRICTION
C
C     BOUNDARY CONDITION IS - Y=1.0 AT X=X*.  DECREASE STEP SIZE UNTIL A
C     SATISFACTORY X IS FOUND.
C
C     WORKING VARIABLES ARE IN DOUBLE PRECISION
C
C     PROGRAM VARIABLES
C     *****************
C
C           X - DISTANCE FROM INLET
C           H - FILM THICKNESS
C           Y - SOLUTION OF MACH NUMBER EQUATION
C           R - RADIUS THAT CORRESPONDS TO X
C           T - LOCAL TEMPERATURE
C          T1 - ENTRANCE TEMPERATURE
C          MU - VISCOSITY
C          RE - REYNOLDS UNMBER
C           F - FRICTION FACTOR
C
C         CON - SIN(TILT ANGLE)
C           G - RATIO OF SPECIFIC HEATS
C       GAMMA - RATIO OF SPECIFIC HEATS
C          R1 - RADIUS AT ENTRANCE
C
C          Y0 - SQUARE OF ENTRANCE MACH NUMBER  - INITIAL ESTIMATE
C               SUPPLIED BY CALLING PROGRAM
C     RECNST - RHO*U*D
C     FACTOR - MULTIPLICATIVE FACTOR FOR CHANGING Y0 TO ACCELERATE THE
C               SOLUTION
C        DELX - LENGTH OF X INTERVAL (STEP SIZE)
C          HI - FILM THICKNESS AT MIDPOINT OF X INTERVAL
C        DELY - LENGTH OF Y INTERVAL
C          HR - RATIO OF FILM THICKNESS TO RADIUS FOR SEALS WITH RADIAL
C               EXPANSION
C
C     ******
C      FK1 *
C      FK2 * -  INTERMEDIATE VALUES OF THE DERIVATIVE DY/DX IN THE
C      FK3 *    RUNGE-KUTTA FORMULA
C      FK4 *
C     ******
C
C     ARITHMETIC FUNCTION DYDX DEFINES THE DERIVATIVE OF THE SQUARE OF
C     THE MACH NUMBER WITH RESPECT TO X
C     ARITHMETIC FUNCTION HFUNC DEFINES THE FILM THICKNESS AS A FUNCTION
C     OF X
C
      SUBROUTINE RK1(SCON)
      DOUBLE PRECISION DYDX,CON,F,G,R,Y0,DELX,R1,FK1,FK2,FK3,FK4,HI,
     1      DELY,FRFUNC,HFUNC,SIGN,HR,XTOL,X,Y,H
      REAL LOSS,MU,MUIN
      COMMON/TRAYS/N,X(201),Y(201),H(201),J,TSTAR
      COMMON/CONSTS/GAMMA,RDIF,SR1,SSIGN,EX(6),T0,P0,P3,PT,RGAS,LOSS,
     1      MUIN,PI,RUNIV(2),CNVT(11,2),NSI
      DYDX(Y,H,CON,F,G,HR) = 2.D0*Y*(1.D0+.5D0*(G-1.D0)*Y)*(F*G*Y-CON-
     1      HR)/H/(1.D0-Y)
      HFUNC(X,H,CON) = H+X*CON
```

```
C
C     INITIAL STEPS - TRANSFER PERMANENTLY STORED SINGLE PRECISION
C     CONSTANTS TO DOUBLE PRECISION VARIABLES
C
      G = GAMMA
      R1= SR1
      CON= SCON
      SIGN = SSIGN
      FACTOR = 10.0
      X(1) = 0.D0
      YO = Y(1)**2
      HR = 0.D0
      IF (R1.EQ.0.D0)   SR1=1.0
C
  100 Y(1) = YO
      NST = 11
      N1 = 2
      N2 = 11
      DELX = RDIF/FACTOR
      NN = ALOG10(RDIF)
      XTOL = RDIF*10.D0**(NN-4)
      NOTE = 0
C
      RECNST = 2.0*CNVT(10,NSI)*PO*SR1*H(1)*SQRT(Y(1)*GAMMA*CNVT(11,NSI)
     1        /RGAS/TO)/CNVT(6,NSI)/(1.0+.50*(GAMMA-1.0)*Y(1)/LOSS**2)**
     2        ((GAMMA+1.0)/2.0/(GAMMA-1.0))
      T1 = TO/(1.0+.50*(GAMMA-1.0)*Y(1)/LOSS**2)
C
C     RUNGE-KUTTA SOLUTION
C
  200 DO 300 I=N1,N2
      II = I
      X(I) = X(I-1)+DELX
      R = R1+X(I-1)*SIGN
      IF (R1.NE.0.D0)   HR=H(I-1)/R
      T = T1*(1.0+.50*(GAMMA-1.0)*Y(1))/(1.0+.50*(GAMMA-1.0)*Y(I-1))
      MU = MUIN
      IF (GAMMA.EQ.1.4)   MU=CNVT(1,NSI)*T**1.5/(T+CNVT(2,NSI))
      RE = RECNST/MU
      IF (R1.NE.0.D0)   RE=RE/R
      F = FRFUNC(RE)
      FK1 = DELX*DYDX(Y(I-1),H(I-1),CON,F,G,HR)
      R = (X(I-1)+.5D0*DELX)*SIGN+R1
      HI = HFUNC(X(I-1)+.5D0*DELX,H(1),CON)
      IF (R1.NE.0.D0)   HR=HI/R
      T = T1*(1.0+.50*(GAMMA-1.0)*Y(1))/(1.0+.50*(GAMMA-1.0)*
     1        (Y(I-1)+.5D0*FK1))
      MU = MUIN
      IF (GAMMA.EQ.1.4)   MU=CNVT(1,NSI)*T**1.5/(T+CNVT(2,NSI))
      RE = RECNST/MU
      IF (R1.NE.0.D0)   RE=RE/R
      F = FRFUNC(RE)
      FK2 = DELX*DYDX(Y(I-1)+.5D0*FK1,HI,CON,F,G,HR)
      T = T1*(1.0+.50*(GAMMA-1.0)*Y(1))/(1.0+.50*(GAMMA-1.0)*
     1        (Y(I-1)+.5D0*FK2))
      MU = MUIN
      IF (GAMMA.EQ.1.4)   MU=CNVT(1,NSI)*T**1.5/(T+CNVT(2,NSI))
      RE = RECNST/MU
      IF (R1.NE.0.D0)   RE=RE/R
```

```
      F = FRFUNC(RE)
      FK3 = DELX*DYDX(Y(I-1)+.5D0*FK2,HI,CON,F,G,HR)
      R = X(I)*SIGN+R1
      H(I) = HFUNC(X(I),H(1),CON)
      IF (R1.NE.0.D0)   HR=H(I)/R
      T = T1*(1.0+.50*(GAMMA-1.0)*Y(1))/(1.0+.50*(GAMMA-1.0)*
     1       (Y(I-1)+FK3))
      MU = MUIN
      IF (GAMMA.EQ.1.4)   MU=CNVT(1,NSI)*T**1.5/(T+CNVT(2,NSI))
      RE = RECNST/MU
      IF (R1.NE.0.D0)   RE=RE/R
      F = FRFUNC(RE)
      FK4 = DELX*DYDX(Y(I-1)+FK3,H(I),CON,F,G,HR)
      DELY= (FK1+2.D0*(FK2+FK3)+FK4)/6.D0
      Y(I) = Y(I-1)+DELY
  280 IF (DABS(1.D0-Y(I)).LE.1.D-8)   GO TO 600
C
C     FLOW MUST REMAIN SUBSONIC UNTIL EXIT - IF Y(I) EXCEEDS 1.0 AT ANY
C     POINT, LOWER DELX
C
      IF ((Y(I-1)+.5D0*FK1.GT.1.D0.OR.Y(I-1)+.5D0*FK2.GT.1.D0).OR.
     1 (Y(I-1)+FK3.GT.1.D0.OR.Y(I).GT.1.D0))   GO TO 320
      IF (DELY.LE.0.D0)   GO TO 410
      IF (DELY.GT..1D0)   GO TO 320
      IF (Y(I).LT.0.D0)   GO TO 320
      IF (DABS(X(I)-RDIF).GT.XTOL)   GO TO 290
      II = I-1
      IF (NOTE.EQ.0)   GO TO 315
  290 IF (I.GE.201)   GO TO 400
  300 CONTINUE
C
  310 N1 = N2+1
      GO TO 330
  315 NOTE = 1
  320 IF (II.GE.11)   N1=II
      DELX = DELX/10.D0
  330 N2 = N1+9
      GO TO 200
C
C     IF INITIAL GUESS OF Y0 WAS TOO LOW, RAISE IT
C
  400 IF (1.D0-Y(II).LE..5D0)   GO TO 420
  410 Y0 = Y0*1.05
      GO TO 100
C
C     IF NUMBER OF STEPS EXCEEDS THE SIZE OF THE ARRAY, ELIMINATE POINTS
C     WHERE THE VALUE OF THE FUNCTION IS NOT CHANGING RAPIDLY
C
  420 DDELX = RDIF/50.0
      IND = NST
      N = 201
      IF (N2.LT.201)   N=N2
      DO 440 I=NST,N
      IF (DABS(X(I)-RDIF).LE.XTOL)   GO TO 430
      IF (I.EQ.1.OR.I.EQ.N)   GO TO 430
      IF (X(I).GT.X(IND-1)+DDELX)   GO TO 430
      IF (Y(I).LE.Y(IND-1)+.2D-1)   GO TO 440
  430 X(IND) = X(I)
      H(IND) = H(I)
```

```
      Y(INC) = Y(I)
      INC = INC+1
  440 CONTINUE
      NST = INC-1
      N1 = INC
      N2 = N1+9
      IF (NST.LE.90)   GO TO 200
      FACTOR = FACTOR/2.0
      GO TO 100
C
C     STAISFACTORY X* FOUND - SOLUTION COMPLETE
C
  600 N = II
      DO 650 I=1,N
  650 Y(I) = DSQRT(Y(I))
      IF (R1.EQ.0.D0)   SR1=0.0
C
      RETURN
      END
```

```
C
C     NUMERICAL INTEGRATION BY SIMPSONS RULE
C
C            INTEGRAL OF Y DX FROM XMIN TO XMAX = (H/3)*(Y0+4Y1+Y2)
C                 WHERE Y0 = Y EVALUATED AT XMIN
C                       Y1 = Y EVALUATED ATA (XMIN+XMAX)/2
C                       Y2 = Y EVALUATED AT XMAX
C                        H = (XMAX-XMIN)/2   (STEP SIZE)
C
C     CALL VECTOR VARIABLES
C     *********************
C
C          J - INDEX OF FILM THICKNESS
C       XMAX - LOWER LIMIT OF INTEGRATION
C       XMAX - UPPER LIMIT OF INTEGRATION
C      FUNC2 - FUNCTION SUBPROGRAM TO EVALUATE Y
C        KER - NUMERICAL CONSTANT TO INDICATE IF INTEGRATION IS ACCURATE
C
C     PROGRAM VARIABLES
C     *****************
C
C          V - INDEPENDENT VARIABLE IN INTEGRATION
C          H - STEP SIZE
C          A - Y0
C          B - Y1
C          C - Y2
C          P - 3*(VALUE OF INTEGRAND)
C        ***
C         E* - DIFFERENCE BETWEEN ANSWERS USING DIFFERENT STEP SIZES
C        NE*
C        ***
C        ANS - ACCUMULSTED ANSWER FOR MANY SUBINTERVALS
C          N - SUBINTERVAL COUNTER (N GE 200 MEANS INTEGRAL IS
C                 INACCURATE)
C          T - ERROR TOLERANCE
```

```
C        FRAC - FRACTION OF ERROR TOLERANCE APPLICABLE TO N(TH)
C                   SUBDIVISION
C      ******
C       TEST* - TEST VALUE FOR ERROR IN INTEGRAL
C      NTEST*
C      ******
C            Q - TEST VALUE OF FINAL ANSWER
C
      FUNCTION SIMPS1(XMIN,XMAX,FUNC1,KER)
      DIMENSION V(200),H(200),A(200),B(200),C(200),P(200),E(200),NE(200)
C     DIMENSION V(200),H(200),A(200),B(200),C(200),P(200),E(200),NE(200)
      EQUIVALENCE (E,NE),(TEST,NTEST)
C
C     DEFINE STARTING VALUES
C
      T=3.0E-5
      V(1)=XMIN
      H(1)=0.5*(XMAX-XMIN)
      A(1)=FUNC1(XMIN)
      B(1)=FUNC1(XMIN+H(1))
      C(1)=FUNC1(XMAX)
      P(1)=H(1)*(A(1)+4.0*B(1)+C(1))
      E(1)=P(1)
      ANS=P(1)
      N=1
      FRAC=2.0*T
    1 FRAC=0.5*FRAC
C
C     BEGIN INTEGRATION USING MORE SUBINTERVALS WHERE VALUE OF INTEGRAND
C     IS CHANGING RAPIDLY
C
    2 TEST=ABS(FRAC*ANS)
      K=N
      DO 7 I=1,K
      IF (NTEST.GT.IABS(NE(I)))  GO TO 7
    5 N = N+1
      V(N)=V(I)+H(I)
      H(N)=0.5*H(I)
      A(N)=B(I)
      B(N)=FUNC1(V(N)+H(N))
      C(N)=C(I)
      P(N)=H(N)*(A(N)+4.0*B(N)+C(N))
      Q=P(I)
      H(I)=H(N)
      B(I)=FUNC1(V(I)+H(I))
      C(I)=A(N)
      P(I)=H(I)*(A(I)+4.0*B(I)+C(I))
      Q=P(I)+P(N)-Q
      ANS=ANS+Q
      E(I)=Q
      E(N)=Q
      IF (N.GE.200)   GO TO 13
    7 CONTINUE
      IF (N.GT.K)   GO TO 2
      Q = 0.0
      DO 11 I=1,N
   11 Q=Q+E(I)
   12 IF (ABS(Q)-T*ABS(ANS)) 14,14,1
   13 KER=KER+1
```

```
C
C     ACCUMULATE FINAL ANSWER
C
   14 ANS=0.0
      DO 16 I=1,N
   16 ANS=ANS+P(I)
      SIMPS1=(ANS+Q/30.0)/3.0
C
   17 RETURN
      END
```

```
C     PROGRAM VARIABLES
C     *****************
C
C          XX - CHARACTERISTIC FILM THICKNESS
C          YY - SEALING DAM FORCE
C         DDY - AXIAL FILM STIFFNESS
C         MAX - NUMBER OF FILM THICKNESSES
C        MACH - MACH NUMBER
C         REP - PRESSURE FLOW REYNOLDS NUMBER
C
C     ******
C         X *
C         Y *
C        DY *
C         A *** WORKING VARIABLES IN NUMERICAL DIFFERENTIATION
C        S1 *
C        S2 *
C        P2 *
C        KY *
C     ******
C
C     LAGRANGE NUMERICAL DIFFERENTIATION OVER MAXIMUM OF 5 POINTS
C     TO DETERMINE AXIAL FILM STIFFNESS
C
      SUBROUTINE STFNSS
      REAL MACH
      DIMENSION X(20), Y(20), DY(20),A(5,5)
      COMMON/CONSTS/D1(8),RELAM,RETURB,D2(10),CNVT(23)
      COMMON/ARRAYS/D3(231),MACH(11,20),D4(660),REP(11,20),D5(480),
     1       YY(20),DDY(20),D6(80),XX(20),D7(60)
      COMMON/TRAYS/D8(1207),MAX,TSTAR
C
C     ELIMINATE INVALID POINTS AND ARRANGE VALID POINTS IN ASCENDING
C     ORDER.  IF THERE ARE LESS THAN 2 VALID POINTS, NO DIFFERENTIATION
C     IS POSSIBLE.
C
      DO 90 M=1,MAX
   90 DDY(M) = 0.
C
      DO 400 IND=1,4
      MM = 0
  100 DO 110 M=1,MAX
      GO TO (1,2,3,4),IND
    1 IF (MACH(11,M).GE.1.0.AND.REP(6,M).LE.RELAM)    GO TO 105
```

```
      GO TO 110
    2 IF (MACH(11,M).GE.1.0.AND.REP(6,M).GE.RETURB)   GO TO 105
      GO TO 110
    3 IF (MACH(11,M).LT.1.0.AND.REP(6,M).LE.RELAM)   GO TO 105
      GO TO 110
    4 IF (MACH(11,M).LT.1.0.AND.REP(6,M).GE.RETURB)   GO TO 105
      GO TO 110
  105 MM = MM+1
      X(MM) = XX(M)
      Y(MM) = YY(M)
  110 CONTINUE
      IF (MM.LT.2)   GO TO 400
  130 CALL SORTXY(X,Y,MM)
C
C     SET UP MATRIX OF X DIFFERENCES FOR EACH POINT X(K)
C
  200 N = MINO(MM,5)
      DO 250 K=1,MM
      IST = MAX0(K-2,1)
      IST = MINO(MM-N+1,IST)
      IN = IST+N-1
      DO 211 II=IST,IN
      I = II-IST+1
      DO 210 JJ=IST,IN
      J = JJ-IST+1
      A(I,J)  = X(II)-X(JJ)
  210 CONTINUE
  211 CONTINUE
C
C     FORM SUMS AND PRODUCTS FOR DERIVATIVE FORMULA
C
  220 S1 = 0.
      S2 = 0.
      P2 = 1.
      DO 231 II=IST,IN
      IF (II.EQ.K)   GO TO 231
      I = II-IST+1
      P1 = X(II)-X(K)
      S2 = S2-1./P1
      P2 = P2*P1
      DO 230 JJ=1,N
      IF (I.NE.JJ)   P1=P1*A(I,JJ)
  230 CONTINUE
      S1 = S1+Y(II)/P1
  231 CONTINUE
      IF ((N/2)*2.NE.N)   S2=-S2
C
C     DERIVATIVE
C
      KY = S2*Y(K)+P2*S1
      DY(K) = KY
  250 CONTINUE
C
C     PUT CALCULATED DERIVATIVES IN ORDER TO CORRESPOND TO INPUT XX
C     ARRAY
C
  300 DO 320 M=1,MAX
      DO 310 II=1,MM
      IF (XX(M).NE.X(II)) GO TO 310
```

```
      IF ((N/2)*2.NE.N)   GO TO 311
      DDY(M) = -DY(II)
      GO TO 320
  311 DDY(M) = DY(II)
      GO TO 320
  310 CONTINUE
  320 CONTINUE
  400 CONTINUE
C
      RETURN
      END
```

```
C
C     FUNCTION FOR FINDING LOCAL FRICTION FACTOR AS A FUNCTION OF
C     REYNOLDS NUMBER
C
      DOUBLE PRECISION FUNCTION FRFUNC(RE)
      COMMON/CONSTS/EX1(4),XLAM,XTURB,CONLAM,CONTRB,RELAM,RETURB,EX2(33)
      DOUBLE PRECISION X1,X2,X3,Y2
C
C     LAMINAR FLOW
C
      IF (RE.GT.RELAM)   GO TO 100
      FRFUNC = CONLAM/RE**XLAM
      RETURN
C
C     TRANSITION FLOW
C
  100 IF (RE.GE.RETURB)   GO TO 110
      X1 = ALOG(RELAM)
      X2 = ALOG(RETURB)
      X3 = ALOG(RE)
      Y2 = ALOG(CONTRB)-XTURB*X2-2.0D0*(ALOG(CONTRB/CONLAM)+XLAM*X1-
     1 XTURB*X2)*((X3*(X3*(X3-1.5D0*(X1+X2))+3.0D0*X1*X2)-.5D0*X2**2
     2    *(3.0D0*X1-X2)))/(X2-X1)**3
      FRFUNC = DEXP(Y2)
      RETURN
C
C     TURBULENT FLOW
C
  110 FRFUNC = CONTRB/RE**XTURB
      RETURN
C
      END
```

```
C
C     INTEGRAND OF FORCE INTEGRAL
C
      FUNCTION FFUNC(X)
      COMMON/CONSTS/DD(12),P3,DDD(30)
      FFUNC = PRESS(X)-P3
      RETURN
      END
```

```
C
C     INTEGRAND OF CENTER OF PRESSURE INTEGRAL
C
      FUNCTION XCFUNC(X)
      COMMON/CONSTS/DD(12),P3,DDD(30)
      XCFUNC = (PRESS(X)-P3)*X
      RETURN
      END
```

```
C
C     ARRANGE POINTS (X,Y) IN ORDER OF ASCENDING X
C
      SUBROUTINE SORTXY(X,Y,N)
      DIMENSION X(100), Y(100)
      NN= N-1
C
      DO 110  I=1,NN
      II = I
      DO 100  J=2,N
      IF(X(J) .GE. X(I)) GO TO 100
      T= X(J)
      X(J)= X(I)
      X(I)= T
      T= Y(J)
      Y(J)= Y(I)
      Y(I)= T
  100 CONTINUE
  110 CONTINUE
C
      RETURN
      END
```

```
C
C     DUMMY PLOTTING ROUTINE - EACH USER MUST WRITE HIS OWN SUBROUTINE
C     TO FIT THE PLOTTING EQUIPMENT AVAILABLE TO HIM
C
      SUBROUTINE GRAFIC
      LOGICAL PWRSKP,PRSSKP,NRMSKP,PLTSKP
      REAL MACH,LOSS,MU
      COMMON/ARRAYS/X(11),P(11,20),MACH(11,20),U(11,20),T(11,20),
     1      RHO(11,20),REP(11,20),FRICT(11,20),H(11,20),XCBAR(20),
     2      POWER(20),FORCE(20),STIFF(20),FBAR(20),E1(60),HMEAN(20),
     2      E2(60)
      COMMON/CONSTS/GAMMA,RDIF,R1,RECON(6),TC,PC,P3,PT,RGAS,LOSS,MU,PI,
     1      RUNIV(2),CNVT(11,2),NSI
      COMMON/CTITLE/TITLE(12)
      COMMON/LOGICL/PWRSKP,NRMSKP,PRSSKP,PLTSKP(9)
C
      WRITE (6,10)
   10 FORMAT (1H1,47HPLOTS CANNOT BE MADE BY THE SUBROUTINE SUPPLIED)
      RETURN
      END
```

```
C
C     BLOCK DATA SUBROUTINE FOR CONSTANTS
C
      BLOCK DATA
      COMMON/CONSTS/D(17),PI,RUNIV(2),CNVT(11,2),NSI
      COMMON/PRNT/C1(4),C2(4),C3(4),C4(4),C5(4),C6(4),C7(4),C8(4),BLANK
      DATA PI,(RUNIV(I),I=1,2)/ 3.1415927, 8.31436E3, 1545.4 /
      DATA (CNVT(I,1),I=1,11)/ .14591E-5, 110.3, 2*1., .5051554E2,
     1      6*1. /
      DATA (CNVT(I,2),I=1,11)/ 1.57639E-10, 198.6, 720.0, 13.405833,
     1      13.083, 1728., 45.833333, 42.42, 33000.0, 4.4756636, 32.174/
      DATA (C1(I),I=1,4)/6H      ,6H   POW,6HER    ,6H      /
      DATA (C2(I),I=1,4)/6HDIMENS,6HIONLES,6HS QUAN,6HTITIES/
      DATA (C3(I),I=1,4)/6H PRESS,6HURE DI,6HSTRIBU,6HTIONS /
      DATA (C4(I),I=1,4)/6HPOWER ,6H      ,6H   XC(,6HBAR)  /
      DATA (C5(I),I=1,4)/6HFORCE ,6H      ,6H  PRES,6HSURE  /
      DATA (C6(I),I=1,4)/6HTEMPER,6HATURE ,6H   DEN,6HSITY  /
      DATA (C7(I),I=1,4)/6HMACH N,6HUMBER ,6H RE NU,6HMBER  /
      DATA (C8(I),I=1,4)/6HFRICT ,6HFACTOR,6H      ,6H      /
      DATA BLANK/6H      /
C
      END
```

APPENDIX D

SAMPLE OUTPUT

PROGRAM FOR QUASI-ONE DIMENSIONAL FLOW WITH FRICTION AND AREA EXPANSION

SAMPLE PROBLEM - AREA EXPANSION PROGRAM - SI UNITS

INPUT DATA -

R1,METERS 0.825E-01	P1,NSMA 0.448E+06	MOLECULAR WEIGHT 28.966	F=K/RE**N *********
R2,METERS 0.842E-01	P2,NSMA 0.103E+06	CP,JOULES/KG-DEG K 0.100E+04	K(LAMINAR) 24.000
FLOW LENGTH,METERS 0.	P1/P2 0.	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,METERS 0.	T0,DEG K 311.1	VISCOSITY,N-SEC/M2 0	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 1.00	SPEED,RPS 0.	K(TURBULENT) 0.7900E-01
		V,M/SEC 60.96	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,METERS 0.825E-01	P0/NSMA 0.448E+06	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,METERS 0.842E-01	P3/NSMA 0.103E+06	CP,JOULES/KG-DEG K 0.100E+04	POWER
			DIMENSIONLESS QUANTITIES
FLOW LENGTH,METERS 0.127E-02	P0/P3 4.333	GAMMA 1.400	PRESSURE DISTRIBUTIONS
MEAN FLOW WIDTH,METERS 0.525E+00	T0,DEG K 311.111	VISCOSITY,N-SEC/M2 0.1900E-04	PLOT *********************
	GAS CONSTANT,JOULES/KG-DEG K 0.287E+03	SPEED,RPS 116.10	POWER XC(BAR)
			FORCE PRESSURE
	LOSS COEF. 1.00	V,M/SEC 0.610E+02	TEMPERATURE DENSITY
			MACH NUMBER RE NUMBER
			FRICT FACTOR

```
******************************
*                            *
*   / - CHOKED FLOW          *
*   + - TRANSITION REGION    *
*   T - TURBULENT FLOW       *
*                            *
******************************
```

	H(BAR) METERS	H(MIN) METERS	ALPHA RADIANS	M(OUT) KG/SEC	Q SCMS	RE(H)	STIFFNESS N/M	FORCE N	XC METERS
	0.762E-05	0.659E-05	-0.100E-02	0.790E-03	0.379E-01	94.68	0.741E+06	148.3	0.494E-03
	0.102E-04	0.953E-05	-0.100E-02	0.170E-02	0.857E-01	126.5	0.287E+06	147.0	0.499E-03
/	0.127E-04	0.121E-04	-0.100E-02	0.285E-02	0.145	159.8	-0.167E+06	145.8	0.509E-03
/	0.152E-04	0.146E-04	-0.100E-02	0.418E-02	0.211	193.9	0.206E+06	145.6	0.520E-03
/	0.178E-04	0.171E-04	-0.100E-02	0.560E-02	0.283	228.1	0.456E+06	145.7	0.530E-03
/	0.203E-04	0.197E-04	-0.100E-02	0.706E-02	0.357	262.3	0.609E+06	144.3	0.539E-03
/	0.229E-04	0.222E-04	-0.100E-02	0.855E-02	0.432	296.2	0.691E+06	142.7	0.546E-03
/	0.254E-04	0.248E-04	-0.100E-02	0.100E-01	0.507	329.8	0.727E+06	140.9	0.552E-03
/+	0.279E-04	0.273E-04	-0.100E-02	0.114E-01	0.576	363.5	0	139.9	0.556E-03
/+	0.305E-04	0.298E-04	-0.100E-02	0.126E-01	0.637	390.3	0	139.1	0.558E-03
/+	0.330E-04	0.324E-04	-0.100E-02	0.138E-01	0.699	428.9	0	135.2	0.559E-03
/T	0.356E-04	0.349E-04	-0.100E-02	0.151E-01	0.765	461.5	0.381E+06	137.2	0.561E-03
/T	0.381E-04	0.375E-04	-0.100E-02	0.165E-01	0.831	494.2	0.364E+06	136.2	0.563E-03
/T	0.406E-04	0.400E-04	-0.100E-02	0.178E-01	0.898	526.9	0.347E+06	135.3	0.564E-03

	H(MEAN) METERS	H(MIN) METERS	ALPHA RADIANS	KNUDSEN NUMBER	LAMBDA METERS	X(*) METERS	P(*) N/M2	FORCE (BAR)	XC (BAR)
	0.762E-05	0.659E-05	-0.100E-02	0.270E-02	0.206E-07	0.129E-02	0.494E+05	0.645	0.339
	0.102E-04	0.953E-05	-0.100E-02	0.205E-02	0.206E-07	0.128E-02	0.777E+05	0.639	0.393
/	0.127E-04	0.121E-04	-0.100E-02	0.162E-02	0.205E-07	0.127E-02	0.103E+06	0.639	0.401
/	0.152E-04	0.146E-04	-0.100E-02	0.134E-02	0.204E-07	0.127E-02	0.125E+06	0.638	0.410
/	0.178E-04	0.171E-04	-0.100E-02	0.114E-02	0.203E-07	0.127E-02	0.142E+06	0.634	0.418
/	0.203E-04	0.197E-04	-0.100E-02	0.996E-03	0.202E-07	0.127E-02	0.156E+06	0.628	0.424
/	0.229E-04	0.222E-04	-0.100E-02	0.886E-03	0.203E-07	0.127E-02	0.168E+06	0.621	0.430
/	0.254E-04	0.248E-04	-0.100E-02	0.799E-03	0.203E-07	0.127E-02	0.177E+06	0.613	0.434
/+	0.279E-04	0.273E-04	-0.100E-02	0.726E-03	0.203E-07	0.127E-02	0.182E+06	0.609	0.438
/+	0.305E-04	0.298E-04	-0.100E-02	0.667E-03	0.203E-07	0.127E-02	0.184E+06	0.605	0.439
/+	0.330E-04	0.324E-04	-0.100E-02	0.617E-03	0.204E-07	0.127E-02	0.186E+06	0.601	0.440
/T	0.356E-04	0.349E-04	-0.100E-02	0.574E-03	0.204E-07	0.127E-02	0.189E+06	0.597	0.442
/T	0.381E-04	0.375E-04	-0.100E-02	0.537E-03	0.204E-07	0.127E-02	0.191E+06	0.593	0.443
/T	0.406E-04	0.400E-04	-0.100E-02	0.504E-03	0.203E-07	0.127E-02	0.194E+06	0.589	0.444

	H(MEAN) INCHES	H(MIN) INCHES	ALPHA RADIANS	POWER HP	H(SHEAR) BTU/MIN	DELTA(T) DEG F	TORQUE FT-LB
	0.300E-03	0.275E-03	-0.100E-02	0.825E-02	0.350	13.96	0.391E-01
	0.400E-03	0.375E-03	-0.100E-02	0.616E-02	0.261	4.851	0.292E-01
/	0.500E-03	0.475E-03	-0.100E-02	0.489E-02	0.208	2.284	0.232E-01
/	0.600E-03	0.575E-03	-0.100E-02	0.405E-02	0.172	1.293	0.192E-01
/	0.700E-03	0.675E-03	-0.100E-02	0.344E-02	0.146	0.822	0.163E-01
/	0.800E-03	0.775E-03	-0.100E-02	0.299E-02	0.127	0.567	0.142E-01
/	0.900E-03	0.875E-03	-0.100E-02	0.264E-02	0.112	0.413	0.125E-01
/	0.100E-02	0.975E-03	-0.100E-02	0.237E-02	0.100	0.315	0.112E-01
/+	0.110E-02	0.107E-02	-0.100E-02	0	0	0	0
/+	0.120E-02	0.117E-02	-0.100E-02	0	0	0	0
/+	0.130E-02	0.128E-02	-0.100E-02	0	0	0	0
/T	0.140E-02	0.137E-02	-0.100E-02	0	0	0	0
/T	0.150E-02	0.147E-02	-0.100E-02	0	0	0	0
/T	0.160E-02	0.158E-02	-0.100E-02	0	0	0	0

H(MEAN) = 0.300E-03 INCHES   H1 = 0.325E-03 INCHES   DA/DR = 0.188E-01   ALPHA = -0.100E-02 RADIANS
H2 = 0.275E-03 INCHES   DA/A(MIN) = 0.164   (SUBSONIC FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.325E-03	0.104	120.7	0.968E-02	64.51	98.79	159.9	0.150
0.500E-02	0.320E-03	0.110	127.1	0.933E-02	62.10	98.66	159.7	0.150
0.100E-01	0.315E-03	0.116	134.6	0.893E-02	59.47	98.49	159.5	0.150
0.150E-01	0.310E-03	0.124	143.5	0.850E-02	56.58	98.29	159.3	0.151
0.200E-01	0.305E-03	0.133	154.3	0.802E-02	53.38	98.02	159.1	0.151
0.250E-01	0.300E-03	0.145	167.8	0.749E-02	49.79	97.66	159.0	0.151
0.300E-01	0.295E-03	0.160	185.4	0.688E-02	45.70	97.14	158.8	0.151
0.350E-01	0.290E-03	0.182	210.0	0.617E-02	40.93	96.33	158.8	0.151
0.400E-01	0.285E-03	0.214	247.6	0.532E-02	35.17	94.90	158.8	0.151
0.450E-01	0.280E-03	0.276	317.9	0.421E-02	27.68	91.59	159.3	0.151
0.500E-01	0.275E-03	0.509	575.5	0.236E-02	15.00	72.43	163.5	0.147

H(MEAN) = 0.400E-03 INCHES   H1 = 0.425E-03 INCHES   DA/DR = 0.182E-01   ALPHA = -0.100E-02 RADIANS
H2 = 0.375E-03 INCHES   DA/A(MIN) = 0.116   (SUBSONIC FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.425E-03	0.173	200.1	0.959E-02	63.66	96.67	344.5	0.697E-01
0.500E-02	0.420E-03	0.182	210.0	0.924E-02	61.26	96.33	344.1	0.697E-01
0.100E-01	0.415E-03	0.192	221.4	0.885E-02	58.66	95.92	343.8	0.698E-01
0.150E-01	0.410E-03	0.203	234.9	0.843E-02	55.84	95.41	343.5	0.699E-01
0.200E-01	0.405E-03	0.217	251.1	0.797E-02	52.74	94.75	343.3	0.699E-01
0.250E-01	0.400E-03	0.235	271.1	0.747E-02	49.29	93.88	343.2	0.699E-01
0.300E-01	0.395E-03	0.256	297.0	0.689E-02	45.40	92.66	343.2	0.699E-01
0.350E-01	0.390E-03	0.289	332.2	0.623E-02	40.90	90.81	343.6	0.699E-01
0.400E-01	0.385E-03	0.336	385.0	0.544E-02	35.50	87.67	344.6	0.697E-01
0.450E-01	0.380E-03	0.421	479.8	0.441E-02	28.46	80.84	347.4	0.691E-01
0.500E-01	0.375E-03	0.776	850.9	0.252E-02	15.00	39.75	368.8	0.651E-01

H(MEAN) = 0.500E-03 INCHES   H1 = 0.525E-03 INCHES   DA/DR = 0.175E-01   ALPHA = -0.100E-02 RADIANS
H2 = 0.475E-03 INCHES   DA/A(MIN) = 0.886E-01

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.525E-03	0.240	277.2	0.946E-02	62.44	93.60	583.9	0.411E-01
0.500E-02	0.520E-03	0.251	289.7	0.913E-02	60.17	93.02	583.4	0.411E-01
0.100E-01	0.515E-03	0.264	304.0	0.877E-02	57.73	92.31	583.1	0.412E-01
0.150E-01	0.510E-03	0.279	320.7	0.838E-02	55.09	91.44	582.9	0.412E-01
0.200E-01	0.505E-03	0.296	340.6	0.796E-02	52.21	90.35	582.9	0.412E-01
0.250E-01	0.500E-03	0.318	364.8	0.749E-02	49.02	88.92	583.2	0.412E-01
0.300E-01	0.495E-03	0.345	395.5	0.697E-02	45.45	86.98	583.9	0.411E-01
0.350E-01	0.490E-03	0.382	436.3	0.637E-02	41.34	84.16	585.3	0.410E-01
0.400E-01	0.485E-03	0.435	495.4	0.566E-02	36.42	79.57	588.3	0.408E-01
0.450E-01	0.480E-03	0.526	596.5	0.474E-02	29.99	70.39	595.2	0.403E-01
0.500E-01	0.475E-03	1.000	0.106E+04	0.270E-02	15.00	6.667	657.1	0.365E-01

H(MEAN) = 0.600E-03 INCHES   H1 = 0.625E-03 INCHES   DA/DR = 0.169E-01   ALPHA = -0.100E-02 RADIANS
H2 = 0.575E-03 INCHES   DA/A(MIN) = 0.706E-01   (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.625E-03	0.301	345.9	0.931E-02	61.04	90.04	857.5	0.280E-01
0.500E-02	0.620E-03	0.313	360.0	0.900E-02	58.95	89.22	857.2	0.280E-01
0.100E-01	0.615E-03	0.328	376.0	0.868E-02	56.70	88.23	857.1	0.280E-01
0.150E-01	0.610E-03	0.344	394.5	0.832E-02	54.28	87.05	857.2	0.280E-01
0.200E-01	0.605E-03	0.364	416.5	0.794E-02	51.65	85.57	857.6	0.280E-01
0.250E-01	0.600E-03	0.387	442.6	0.752E-02	48.75	83.70	858.6	0.280E-01
0.300E-01	0.595E-03	0.417	475.1	0.705E-02	45.51	81.21	860.3	0.279E-01
0.350E-01	0.590E-03	0.455	517.5	0.652E-02	41.60	77.71	863.3	0.278E-01
0.400E-01	0.585E-03	0.510	577.0	0.569E-02	37.37	72.29	868.8	0.276E-01
0.450E-01	0.580E-03	0.602	674.1	0.508E-02	31.61	62.19	880.4	0.273E-01
0.500E-01	0.575E-03	1.000	0.106E+04	0.326E-02	18.11	6.667	960.4	0.250E-01

H(MEAN) = 0.178E-04 METERS   H1 = 0.184E-04 METERS   DA/DR = 0.413E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.171E-04 METERS   DA/A(MIN) = 0.579E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.184E-04	0.354	123.7	4.717	0.411E+06	303.5	0.115E+04	0.208E-01
0.127E-03	0.183E-04	0.368	128.3	4.573	0.398E+06	302.9	0.115E+04	0.208E-01
0.254E-03	0.182E-04	0.383	133.4	4.420	0.383E+06	302.3	0.115E+04	0.208E-01
0.381E-03	0.180E-04	0.400	139.4	4.255	0.368E+06	301.4	0.115E+04	0.208E-01
0.508E-03	0.179E-04	0.421	146.3	4.077	0.352E+06	300.5	0.115E+04	0.208E-01
0.635E-03	0.178E-04	0.445	154.5	3.882	0.333E+06	299.2	0.116E+04	0.208E-01
0.762E-03	0.177E-04	0.476	164.5	3.665	0.313E+06	297.6	0.116E+04	0.207E-01
0.889E-03	0.175E-04	0.515	177.4	3.419	0.290E+06	295.5	0.116E+04	0.206E-01
0.102E-02	0.174E-04	0.569	195.0	3.129	0.262E+06	292.2	0.117E+04	0.205E-01
0.114E-02	0.173E-04	0.656	222.7	2.755	0.227E+06	286.4	0.119E+04	0.202E-01
0.127E-02	0.171E-04	1.000	322.8	1.912	0.142E+06	259.3	0.128E+04	0.187E-01

H(MEAN) = 0.203E-04 METERS   H1 = 0.210E-04 METERS   DA/DR = 0.397E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.197E-04 METERS   DA/A(MIN) = 0.485E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.210E-04	0.401	139.4	4.637	0.401E+06	301.4	0.146E+04	0.164E-01
0.127E-03	0.208E-04	0.415	144.2	4.506	0.389E+06	300.8	0.146E+04	0.164E-01
0.254E-03	0.207E-04	0.430	149.5	4.366	0.376E+06	300.0	0.146E+04	0.164E-01
0.381E-03	0.206E-04	0.448	155.5	4.217	0.362E+06	299.1	0.146E+04	0.164E-01
0.508E-03	0.204E-04	0.469	162.4	4.055	0.347E+06	298.0	0.147E+04	0.164E-01
0.635E-03	0.203E-04	0.494	170.6	3.878	0.330E+06	296.6	0.147E+04	0.163E-01
0.762E-03	0.202E-04	0.524	180.5	3.683	0.312E+06	294.9	0.147E+04	0.163E-01
0.889E-03	0.201E-04	0.563	193.0	3.461	0.291E+06	292.6	0.148E+04	0.162E-01
0.102E-02	0.199E-04	0.615	209.8	3.200	0.266E+06	289.2	0.149E+04	0.161E-01
0.114E-02	0.198E-04	0.698	235.6	2.864	0.233E+06	283.5	0.151E+04	0.159E-01
0.127E-02	0.197E-04	1.000	322.8	2.100	0.156E+06	259.3	0.162E+04	0.148E-01

H(MEAN) = 0.229E-04 METERS   H1 = 0.235E-04 METERS   DA/DR = 0.381E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.222E-04 METERS   DA/A(MIN) = 0.412E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.235E-04	0.441	153.1	4.561	0.392E+06	299.5	0.178E+04	0.135E-01
0.127E-03	0.234E-04	0.455	157.8	4.441	0.381E+06	298.7	0.178E+04	0.135E-01
0.254E-03	0.232E-04	0.471	163.1	4.313	0.369E+06	297.9	0.178E+04	0.135E-01
0.381E-03	0.231E-04	0.490	169.1	4.177	0.356E+06	296.9	0.178E+04	0.135E-01
0.508E-03	0.230E-04	0.511	176.0	4.029	0.342E+06	295.7	0.178E+04	0.135E-01
0.635E-03	0.229E-04	0.535	184.1	3.869	0.327E+06	294.3	0.179E+04	0.134E-01
0.762E-03	0.227E-04	0.565	193.7	3.691	0.310E+06	292.4	0.179E+04	0.134E-01
0.889E-03	0.226E-04	0.603	205.7	3.490	0.291E+06	290.1	0.180E+04	0.133E-01
0.102E-02	0.225E-04	0.653	221.6	3.253	0.268E+06	286.7	0.182E+04	0.132E-01
0.114E-02	0.224E-04	0.731	245.5	2.948	0.238E+06	281.1	0.184E+04	0.130E-01
0.127E-02	0.222E-04	1.000	322.8	2.252	0.168E+06	259.3	0.196E+04	0.122E-01

H(MEAN) = 0.254E-04 METERS   H1 = 0.260E-04 METERS   DA/DR = 0.365E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.248E-04 METERS   DA/A(MIN) = 0.354E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.260E-04	0.477	164.9	4.491	0.384E+06	297.6	0.210E+04	0.114E-01
0.127E-03	0.259E-04	0.491	169.6	4.380	0.373E+06	296.8	0.210E+04	0.114E-01
0.254E-03	0.258E-04	0.507	174.9	4.263	0.362E+06	295.9	0.210E+04	0.114E-01
0.381E-03	0.257E-04	0.525	180.8	4.137	0.350E+06	294.8	0.210E+04	0.114E-01
0.508E-03	0.255E-04	0.546	187.5	4.002	0.337E+06	293.6	0.211E+04	0.114E-01
0.635E-03	0.254E-04	0.570	195.4	3.855	0.323E+06	292.1	0.211E+04	0.114E-01
0.762E-03	0.253E-04	0.599	204.7	3.693	0.308E+06	290.3	0.212E+04	0.113E-01
0.889E-03	0.251E-04	0.636	216.1	3.509	0.290E+06	287.9	0.213E+04	0.113E-01
0.102E-02	0.250E-04	0.684	231.2	3.292	0.269E+06	284.5	0.215E+04	0.112E-01
0.114E-02	0.249E-04	0.757	253.4	3.014	0.242E+06	279.1	0.218E+04	0.110E-01
0.127E-02	0.248E-04	1.000	322.8	2.375	0.177E+06	259.3	0.230E+04	0.104E-01

H(MEAN) = 0.279E-04 METERS   H1 = 0.286E-04 METERS   DA/DR = 0.350E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.273E-04 METERS   DA/A(MIN) = 0.307E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.286E-04	0.500	172.4	4.443	0.378E+06	296.3	0.239E+04	0.104E-01
0.127E-03	0.284E-04	0.514	177.1	4.340	0.368E+06	295.5	0.239E+04	0.104E-01
0.254E-03	0.283E-04	0.529	182.2	4.230	0.358E+06	294.6	0.240E+04	0.104E-01
0.381E-03	0.282E-04	0.547	187.9	4.113	0.347E+06	293.5	0.240E+04	0.105E-01
0.508E-03	0.281E-04	0.567	194.4	3.987	0.335E+06	292.3	0.240E+04	0.105E-01
0.635E-03	0.279E-04	0.591	202.0	3.850	0.321E+06	290.8	0.241E+04	0.105E-01
0.762E-03	0.278E-04	0.619	210.9	3.699	0.307E+06	289.0	0.242E+04	0.105E-01
0.889E-03	0.277E-04	0.654	221.8	3.527	0.290E+06	286.6	0.243E+04	0.105E-01
0.102E-02	0.276E-04	0.700	236.1	3.324	0.270E+06	283.4	0.245E+04	0.105E-01
0.114E-02	0.274E-04	0.769	257.1	3.062	0.245E+06	278.2	0.248E+04	0.105E-01
0.127E-02	0.273E-04	1.000	322.8	2.446	0.182E+06	259.3	0.262E+04	0.105E-01

H(MEAN) = 0.305E-04 METERS   H1 = 0.311E-04 METERS   DA/DR = 0.334E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.298E-04 METERS   DA/A(MIN) = 0.268E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.311E-04	0.511	176.1	4.419	0.375E+06	295.7	0.265E+04	0.106E-01
0.127E-03	0.310E-04	0.525	180.7	4.318	0.365E+06	294.9	0.265E+04	0.106E-01
0.254E-03	0.309E-04	0.540	185.8	4.211	0.355E+06	293.9	0.265E+04	0.106E-01
0.381E-03	0.307E-04	0.558	191.4	4.097	0.344E+06	292.9	0.266E+04	0.106E-01
0.508E-03	0.306E-04	0.578	197.8	3.974	0.333E+06	291.6	0.266E+04	0.106E-01
0.635E-03	0.305E-04	0.601	205.3	3.841	0.320E+06	290.1	0.267E+04	0.106E-01
0.762E-03	0.304E-04	0.629	214.0	3.693	0.306E+06	288.3	0.268E+04	0.106E-01
0.889E-03	0.302E-04	0.663	224.8	3.526	0.289E+06	286.0	0.269E+04	0.106E-01
0.102E-02	0.301E-04	0.708	238.7	3.329	0.270E+06	282.7	0.271E+04	0.106E-01
0.114E-02	0.300E-04	0.776	259.2	3.074	0.245E+06	277.7	0.275E+04	0.106E-01
0.127E-02	0.298E-04	1.000	322.8	2.476	0.184E+06	259.3	0.289E+04	0.107E-01

H(MEAN) = 0.330E-04 METERS   H1 = 0.337E-04 METERS   DA/DR = 0.318E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.324E-04 METERS   DA/A(MIN) = 0.235E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.337E-04	0.522	179.6	4.396	0.372E+06	295.1	0.291E+04	0.107E-01
0.127E-03	0.335E-04	0.535	184.1	4.297	0.363E+06	294.2	0.291E+04	0.107E-01
0.254E-03	0.334E-04	0.551	189.1	4.193	0.353E+06	293.3	0.292E+04	0.107E-01
0.381E-03	0.333E-04	0.568	194.8	4.081	0.342E+06	292.2	0.292E+04	0.107E-01
0.508E-03	0.331E-04	0.588	201.1	3.961	0.331E+06	291.0	0.293E+04	0.107E-01
0.635E-03	0.330E-04	0.611	208.5	3.831	0.318E+06	289.5	0.293E+04	0.107E-01
0.762E-03	0.329E-04	0.639	217.1	3.687	0.304E+06	287.7	0.294E+04	0.107E-01
0.889E-03	0.328E-04	0.672	227.7	3.524	0.289E+06	285.3	0.296E+04	0.107E-01
0.102E-02	0.326E-04	0.717	241.4	3.331	0.270E+06	282.1	0.298E+04	0.107E-01
0.114E-02	0.325E-04	0.784	261.5	3.083	0.245E+06	277.1	0.302E+04	0.107E-01
0.127E-02	0.324E-04	1.000	322.8	2.503	0.186E+06	259.3	0.318E+04	0.105E-01

H(MEAN) = 0.356E-04 METERS   H1 = 0.362E-04 METERS   DA/DR = 0.302E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.349E-04 METERS   DA/A(MIN) = 0.207E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.362E-04	0.534	183.8	4.368	0.369E+06	294.3	0.319E+04	0.105E-01
0.127E-03	0.361E-04	0.548	188.3	4.272	0.360E+06	293.5	0.319E+04	0.105E-01
0.254E-03	0.359E-04	0.564	193.3	4.170	0.350E+06	292.5	0.320E+04	0.105E-01
0.381E-03	0.358E-04	0.581	198.8	4.062	0.340E+06	291.4	0.320E+04	0.105E-01
0.508E-03	0.357E-04	0.601	205.1	3.945	0.329E+06	290.2	0.321E+04	0.105E-01
0.635E-03	0.356E-04	0.623	212.3	3.819	0.316E+06	288.7	0.321E+04	0.105E-01
0.762E-03	0.354E-04	0.650	220.8	3.680	0.303E+06	286.8	0.323E+04	0.105E-01
0.889E-03	0.353E-04	0.684	231.2	3.522	0.288E+06	284.5	0.324E+04	0.105E-01
0.102E-02	0.352E-04	0.727	244.5	3.336	0.269E+06	281.3	0.327E+04	0.105E-01
0.114E-02	0.351E-04	0.792	264.0	3.097	0.246E+06	276.4	0.331E+04	0.104E-01
0.127E-02	0.349E-04	1.000	322.8	2.538	0.189E+06	259.3	0.347E+04	0.103E-01

H(MEAN) = 0.381E-04 METERS   H1 = 0.387E-04 METERS   DA/DR = 0.286E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.375E-04 METERS   DA/A(MIN) = 0.183E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.387E-04	0.547	187.8	4.340	0.366E+06	293.6	0.348E+04	0.103E-01
0.127E-03	0.386E-04	0.561	192.3	4.247	0.357E+06	292.7	0.348E+04	0.103E-01
0.254E-03	0.385E-04	0.576	197.2	4.149	0.347E+06	291.8	0.348E+04	0.103E-01
0.381E-03	0.384E-04	0.593	202.7	4.044	0.337E+06	290.7	0.349E+04	0.103E-01
0.508E-03	0.382E-04	0.612	208.8	3.931	0.327E+06	289.4	0.349E+04	0.103E-01
0.635E-03	0.381E-04	0.635	215.9	3.809	0.315E+06	287.9	0.350E+04	0.103E-01
0.762E-03	0.380E-04	0.661	224.2	3.674	0.302E+06	286.1	0.351E+04	0.103E-01
0.889E-03	0.378E-04	0.694	234.4	3.522	0.287E+06	283.8	0.353E+04	0.102E-01
0.102E-02	0.377E-04	0.737	247.4	3.343	0.269E+06	280.6	0.356E+04	0.102E-01
0.114E-02	0.376E-04	0.800	266.3	3.112	0.246E+06	275.8	0.360E+04	0.102E-01
0.127E-02	0.375E-04	1.000	322.8	2.572	0.191E+06	259.3	0.377E+04	0.101E-01

H(MEAN) = 0.406E-04 METERS   H1 = 0.413E-04 METERS   DA/DR = 0.270E-03   ALPHA = -0.100E-02 RADIANS
H2 = 0.400E-04 METERS   DA/A(MIN) = 0.162E-01   (CHOKED FLOW)

X METERS	H METERS	MACH NUMBER	VELOCITY M/SEC	DENSITY KG/M3	PRESSURE N/M2	TEMPERATURE DEG K	RE(P)	FRICTION FACTOR
0	0.413E-04	0.558	191.6	4.314	0.363E+06	292.8	0.376E+04	0.101E-01
0.127E-03	0.411E-04	0.572	196.0	4.224	0.354E+06	292.0	0.376E+04	0.101E-01
0.254E-03	0.410E-04	0.587	200.8	4.128	0.345E+06	291.0	0.377E+04	0.101E-01
0.381E-03	0.409E-04	0.604	206.2	4.027	0.335E+06	289.9	0.377E+04	0.101E-01
0.508E-03	0.408E-04	0.623	212.3	3.916	0.325E+06	288.7	0.378E+04	0.101E-01
0.635E-03	0.406E-04	0.645	219.2	3.799	0.313E+06	287.2	0.379E+04	0.101E-01
0.762E-03	0.405E-04	0.672	227.4	3.669	0.301E+06	285.4	0.380E+04	0.101E-01
0.889E-03	0.404E-04	0.704	237.3	3.522	0.286E+06	283.1	0.382E+04	0.100E-01
0.102E-02	0.403E-04	0.745	250.0	3.348	0.269E+06	280.0	0.385E+04	0.100E-01
0.114E-02	0.401E-04	0.807	268.4	3.124	0.247E+06	275.3	0.389E+04	0.100E-01
0.127E-02	0.400E-04	1.000	322.8	2.602	0.194E+06	259.3	0.408E+04	0.989E-02

PROGRAM FOR QUASI-ONE DIMENSIONAL FLOW WITH FRICTION AND AREA EXPANSION

SAMPLE PROBLEM - AREA EXPANSION PROGRAM - U. S. UNITS

INPUT DATA -

R1,INCHES 3.2650	P1,PSIA 65.000	MOLECULAR WEIGHT 28.966	F=K/RE**N *********
R2,INCHES 3.3150	P2,PSIA 15.000	CP,BTU/LBM-DEG R 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 0.	P1/P2 0.	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.	T0,DEG F 100.0	VISCOSITY,LB-SEC/IN2 0	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 1.00	SPEED,RPM 0.	K(TURBULENT) 0.7900E-01
		V,FT/SEC 200.00	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA

R1,INCHES 3.2650	P0,PSIA 65.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 3.3150	P3,PSIA 15.000	CP,BTU/LBM-DEG R 0.240	POWER
			DIMENSIONLESS QUANTITIES
FLOW LENGTH,INCHES 0.0500	P0/P3 4.333	GAMMA 1.400	PRESSURE DISTRIBUTIONS
MEAN FLOW WIDTH,INCHES 20.6717	T0,DEG R 560.000	VISCOSITY,LB-SEC/IN2 0.275E-08	PLOT **********************
	GAS CONSTANT,LB-FT/LBM-R 53.35221	SPEED,RPM 6966.1	
	LOSS COEF. 1.00	V,FT/SEC 200.00	

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*                            *
*   / - CHOKED FLOW          *
*   + - TRANSITION REGION    *
*   T - TURBULENT FLOW       *
*                            *
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	H(MEAN) INCHES	H(MIN) INCHES	ALPHA RADIANS	M(DOT) LB/MIN	Q SCFM	RE(R)	STIFFNESS LB/IN	FORCE LB	XC INCHES
	0.300E-03	0.275E-03	-0.100E-02	0.104	1.367	94.74	0.423E+04	33.34	0.194E-01
	0.400E-03	0.375E-03	-0.100E-02	0.224	2.935	126.6	0.164E+04	33.05	0.196E-01
/	0.500E-03	0.475E-03	-0.100E-02	0.379	4.955	159.9	-955.0	33.01	0.200E-01
/	0.600E-03	0.575E-03	-0.100E-02	0.555	7.241	194.0	0.118E+04	32.95	0.205E-01
/	0.700E-03	0.675E-03	-0.100E-02	0.740	9.687	228.3	0.260E+04	32.75	0.209E-01
/	0.800E-03	0.775E-03	-0.100E-02	0.934	12.22	262.4	0.348E+04	32.45	0.212E-01
/	0.900E-03	0.875E-03	-0.100E-02	1.131	14.79	296.3	0.395E+04	32.07	0.215E-01
/	0.100E-02	0.975E-03	-0.100E-02	1.329	17.38	330.0	0.415E+04	31.66	0.217E-01
/+	0.110E-02	0.107E-02	-0.100E-02	1.509	19.74	363.8	0	31.45	0.219E-01
/+	0.120E-02	0.117E-02	-0.100E-02	1.669	21.83	396.6	0	31.26	0.220E-01
/+	0.130E-02	0.128E-02	-0.100E-02	1.831	23.96	429.2	0	31.07	0.220E-01
/T	0.140E-02	0.137E-02	-0.100E-02	2.003	26.20	461.8	0.217E+04	30.84	0.221E-01
/T	0.150E-02	0.147E-02	-0.100E-02	2.176	28.47	494.6	0.208E+04	30.63	0.222E-01
/T	0.160E-02	0.156E-02	-0.100E-02	2.351	30.76	527.2	0.198E+04	30.42	0.222E-01

	H(MEAN) INCHES	H(MIN) INCHES	ALPHA RADIANS	KNUDSEN NUMBER	LAMBDA INCHES	X(*) INCHES	P(*) PSIA	FORCE (BAR)	XC (BAR)
	0.300E-03	0.275E-03	-0.100E-02	0.270E-02	0.810E-06	0.509E-01	7.169	0.645	0.389
	0.400E-03	0.375E-03	-0.100E-02	0.203E-02	0.811E-06	0.503E-01	11.26	0.639	0.393
/	0.500E-03	0.475E-03	-0.100E-02	0.161E-02	0.806E-06	0.500E-01	15.00	0.639	0.401
/	0.600E-03	0.575E-03	-0.100E-02	0.133E-02	0.801E-06	0.500E-01	18.11	0.638	0.410
/	0.700E-03	0.675E-03	-0.100E-02	0.114E-02	0.798E-06	0.500E-01	20.64	0.634	0.418
/	0.800E-03	0.775E-03	-0.100E-02	0.996E-03	0.797E-06	0.500E-01	22.67	0.628	0.424
/	0.900E-03	0.875E-03	-0.100E-02	0.885E-03	0.797E-06	0.500E-01	24.31	0.621	0.430
/	0.100E-02	0.975E-03	-0.100E-02	0.798E-03	0.798E-06	0.500E-01	25.64	0.613	0.434
/+	0.110E-02	0.107E-02	-0.100E-02	0.726E-03	0.798E-06	0.500E-01	26.41	0.609	0.438
/+	0.120E-02	0.117E-02	-0.100E-02	0.666E-03	0.800E-06	0.500E-01	26.72	0.605	0.439
/+	0.130E-02	0.128E-02	-0.100E-02	0.616E-03	0.801E-06	0.500E-01	27.02	0.601	0.440
/T	0.140E-02	0.137E-02	-0.100E-02	0.574E-03	0.803E-06	0.500E-01	27.40	0.597	0.442
/T	0.150E-02	0.147E-02	-0.100E-02	0.536E-03	0.804E-06	0.500E-01	27.76	0.593	0.443
/T	0.160E-02	0.156E-02	-0.100E-02	0.504E-03	0.806E-06	0.500E-01	28.08	0.589	0.444

	H(MEAN) INCHES	H(MIN) INCHES	ALPHA RADIANS	POWER HP	H(SHEAR) BTU/MIN	DELTA(T) DEG F	TORQUE FT-LB
	0.300E-03	0.275E-03	-0.100E-02	0.625E-02	0.355	15.96	0.391E-01
	0.400E-03	0.375E-03	-0.100E-02	0.516E-02	0.261	4.551	0.292E-01
/	0.500E-03	0.475E-03	-0.100E-02	0.469E-02	0.206	2.284	0.232E-01
/	0.600E-03	0.575E-03	-0.100E-02	0.405E-02	0.172	1.293	0.192E-01
/	0.700E-03	0.675E-03	-0.100E-02	0.344E-02	0.146	0.822	0.163E-01
/	0.800E-03	0.775E-03	-0.100E-02	0.297E-02	0.127	0.567	0.142E-01
/	0.900E-03	0.875E-03	-0.100E-02	0.264E-02	0.112	0.413	0.125E-01
/	0.100E-02	0.975E-03	-0.100E-02	0.237E-02	0.100	0.315	0.112E-01
/*	0.110E-02	0.107E-02	-0.100E-02	0	0	0	0
/*	0.120E-02	0.117E-02	-0.100E-02	0	0	0	0
/*	0.130E-02	0.128E-02	-0.100E-02	0	0	0	0
/T	0.140E-02	0.137E-02	-0.100E-02	0	0	0	0
/T	0.150E-02	0.147E-02	-0.100E-02	0	0	0	0
/T	0.160E-02	0.158E-02	-0.100E-02	0	0	0	0

H(MEAN) = 0.300E-03 INCHES H1 = 0.325E-03 INCHES H2 = 0.275E-03 INCHES DA/DR = 0.188E-01 DA/A(MIN) = 0.164 ALPHA = -0.100E-02 RADIANS (SUBSONIC FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.325E-03	0.104	120.7	0.968E-02	64.51	98.79	159.9	0.150
0.500E-02	0.320E-03	0.110	127.1	0.953E-02	62.13	98.66	159.7	0.150
0.100E-01	0.315E-03	0.116	134.6	0.893E-02	59.47	98.49	159.5	0.150
0.150E-01	0.310E-03	0.124	143.5	0.850E-02	56.56	98.29	159.3	0.151
0.200E-01	0.305E-03	0.133	154.3	0.802E-02	53.38	98.02	159.1	0.151
0.250E-01	0.300E-03	0.145	167.8	0.749E-02	49.79	97.66	159.0	0.151
0.300E-01	0.295E-03	0.160	185.4	0.688E-02	45.70	97.14	158.8	0.151
0.350E-01	0.290E-03	0.182	210.0	0.617E-02	40.93	96.33	158.8	0.151
0.400E-01	0.285E-03	0.214	247.6	0.532E-02	35.17	94.90	158.8	0.151
0.450E-01	0.280E-03	0.276	317.9	0.421E-02	27.68	91.59	159.3	0.151
0.500E-01	0.275E-03	0.505	575.5	0.236E-02	15.00	72.43	163.5	0.147

H(MEAN) = 0.400E-03 INCHES H1 = 0.425E-03 INCHES H2 = 0.375E-03 INCHES DA/DR = 0.182E-01 DA/A(MIN) = 0.116 ALPHA = -0.100E-02 RADIANS (SUBSONIC FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.425E-03	0.173	200.1	0.959E-02	63.66	96.67	344.5	0.697E-01
0.500E-02	0.420E-03	0.182	210.3	0.924E-02	61.26	96.33	344.1	0.697E-01
0.100E-01	0.415E-03	0.192	221.4	0.885E-02	58.66	95.92	343.8	0.698E-01
0.150E-01	0.410E-03	0.203	234.9	0.843E-02	55.84	95.41	343.5	0.699E-01
0.200E-01	0.405E-03	0.217	251.1	0.797E-02	52.74	94.75	343.3	0.699E-01
0.250E-01	0.400E-03	0.235	271.1	0.747E-02	49.29	93.88	343.2	0.699E-01
0.300E-01	0.395E-03	0.258	297.0	0.689E-02	45.40	92.66	343.2	0.699E-01
0.350E-01	0.390E-03	0.289	332.2	0.623E-02	40.90	90.81	343.6	0.699E-01
0.400E-01	0.385E-03	0.336	385.0	0.544E-02	35.50	87.67	344.6	0.697E-01
0.450E-01	0.380E-03	0.421	479.8	0.441E-02	28.46	80.84	347.4	0.691E-01
0.500E-01	0.375E-03	0.776	850.9	0.252E-02	15.00	39.75	368.8	0.651E-01

H(MEAN) = 0.500E-03 INCHES H1 = 0.525E-03 INCHES H2 = 0.475E-03 INCHES DA/DR = 0.175E-01 DA/A(MIN) = 0.886E-01 ALPHA = -0.100E-02 RADIANS

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.525E-03	0.240	277.2	0.946E-02	62.44	93.60	583.9	0.411E-01
0.500E-02	0.520E-03	0.251	289.7	0.913E-02	60.17	93.02	583.4	0.411E-01
0.100E-01	0.515E-03	0.264	304.0	0.877E-02	57.75	92.31	583.1	0.412E-01
0.150E-01	0.510E-03	0.279	320.7	0.838E-02	55.09	91.44	582.9	0.412E-01
0.200E-01	0.505E-03	0.296	340.6	0.796E-02	52.21	90.35	582.9	0.412E-01
0.250E-01	0.500E-03	0.318	364.8	0.749E-02	49.02	88.92	583.2	0.412E-01
0.300E-01	0.495E-03	0.345	395.5	0.697E-02	45.45	86.98	583.9	0.411E-01
0.350E-01	0.490E-03	0.382	436.3	0.637E-02	41.34	84.16	585.3	0.410E-01
0.400E-01	0.485E-03	0.435	495.4	0.566E-02	36.42	79.57	588.3	0.408E-01
0.450E-01	0.480E-03	0.526	598.0	0.474E-02	29.99	70.39	595.2	0.403E-01
0.500E-01	0.475E-03	1.000	0.100E+04	0.270E-02	15.00	6.667	657.1	0.365E-01

H(MEAN) = 0.600E-03 INCHES H1 = 0.625E-03 INCHES H2 = 0.575E-03 INCHES DA/DR = 0.169E-01 DA/A(MIN) = 0.706E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.625E-03	0.301	345.9	0.931E-02	61.04	90.04	657.5	[illegible]
0.500E-02	0.620E-03	0.310	363.0	0.903E-02	58.95	89.22	657.2	[illegible]
0.100E-01	0.615E-03	0.328	376.0	0.868E-02	56.70	88.23	657.1	[illegible]
0.150E-01	0.610E-03	0.344	394.5	0.832E-02	54.26	87.05	657.2	[illegible]
0.200E-01	0.605E-03	0.364	416.5	0.794E-02	51.65	85.57	657.6	[illegible]
0.250E-01	0.600E-03	0.387	442.6	0.752E-02	48.75	83.70	658.6	[illegible]
0.300E-01	0.595E-03	0.417	475.1	0.703E-02	45.51	81.21	[illegible]	[illegible]
0.350E-01	0.590E-03	0.455	517.3	0.652E-02	41.63	77.71	[illegible]	[illegible]
0.400E-01	0.585E-03	0.510	577.6	0.569E-02	37.37	72.24	[illegible]	[illegible]
0.450E-01	0.580E-03	0.602	674.1	0.508E-02	31.61	62.19	[illegible]	[illegible]
0.500E-01	0.575E-03	1.000	0.100E+04	0.320E-02	18.11	[illegible]	[illegible]	[illegible]

H(MEAN) = 0.700E-03 INCHES H1 = 0.725E-03 INCHES H2 = 0.675E-03 INCHES DA/DR = 0.163E-01 DA/A(MIN) = 0.579E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.725E-03	0.354	405.8	0.915E-02	59.60	86.30	0.115E+04	0.208E-01
0.500E-02	0.720E-03	0.368	420.8	0.887E-02	57.67	85.26	0.115E+04	0.208E-01
0.100E-01	0.715E-03	0.383	437.8	0.858E-02	55.61	84.05	0.115E+04	0.208E-01
0.150E-01	0.710E-03	0.400	457.2	0.826E-02	53.40	82.60	0.115E+04	0.208E-01
0.200E-01	0.705E-03	0.421	479.9	0.791E-02	50.99	80.83	0.116E+04	0.208E-01
0.250E-01	0.700E-03	0.445	506.8	0.753E-02	48.36	78.62	0.116E+04	0.207E-01
0.300E-01	0.695E-03	0.476	539.8	0.711E-02	45.42	75.75	0.116E+04	0.207E-01
0.350E-01	0.690E-03	0.515	581.9	0.663E-02	42.06	71.82	0.116E+04	0.206E-01
0.400E-01	0.685E-03	0.565	639.6	0.607E-02	38.06	65.95	0.117E+04	0.205E-01
0.450E-01	0.680E-03	0.656	730.5	0.535E-02	32.86	55.59	0.119E+04	0.202E-01
0.500E-01	0.675E-03	1.000	0.106E+04	0.371E-02	20.64	6.667	0.128E+04	0.187E-01

H(MEAN) = 0.800E-03 INCHES H1 = 0.825E-03 INCHES H2 = 0.775E-03 INCHES DA/DR = 0.156E-01 DA/A(MIN) = 0.485E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.825E-03	0.401	457.5	0.900E-02	58.19	82.58	0.146E+04	0.164E-01
0.500E-02	0.820E-03	0.415	473.0	0.874E-02	56.42	81.38	0.146E+04	0.164E-01
0.100E-01	0.815E-03	0.430	490.3	0.847E-02	54.53	79.99	0.146E+04	0.164E-01
0.150E-01	0.810E-03	0.448	510.1	0.818E-02	52.50	78.34	0.146E+04	0.164E-01
0.200E-01	0.805E-03	0.469	532.9	0.787E-02	50.30	76.36	0.147E+04	0.164E-01
0.250E-01	0.800E-03	0.494	559.8	0.752E-02	47.89	73.92	0.147E+04	0.163E-01
0.300E-01	0.795E-03	0.524	592.3	0.715E-02	45.21	70.80	0.147E+04	0.163E-01
0.350E-01	0.790E-03	0.563	633.3	0.672E-02	42.16	66.62	0.148E+04	0.162E-01
0.400E-01	0.785E-03	0.615	688.4	0.621E-02	38.52	60.56	0.149E+04	0.161E-01
0.450E-01	0.780E-03	0.698	772.9	0.556E-02	33.80	50.29	0.151E+04	0.159E-01
0.500E-01	0.775E-03	1.000	0.106E+04	0.408E-02	22.67	6.667	0.162E+04	0.148E-01

H(MEAN) = 0.900E-03 INCHES H1 = 0.925E-03 INCHES H2 = 0.875E-03 INCHES DA/DR = 0.150E-01 DA/A(MIN) = 0.412E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.925E-03	0.441	502.2	0.885E-02	56.87	79.01	0.178E+04	0.135E-01
0.500E-02	0.920E-03	0.455	517.8	0.862E-02	55.23	77.69	0.178E+04	0.135E-01
0.100E-01	0.915E-03	0.471	535.2	0.837E-02	53.49	76.16	0.178E+04	0.135E-01
0.150E-01	0.910E-03	0.490	554.9	0.810E-02	51.62	74.37	0.178E+04	0.135E-01
0.200E-01	0.905E-03	0.511	577.5	0.782E-02	49.60	72.25	0.179E+04	0.134E-01
0.250E-01	0.900E-03	0.535	603.9	0.751E-02	47.39	69.65	0.179E+04	0.134E-01
0.300E-01	0.895E-03	0.565	635.5	0.716E-02	44.94	66.39	0.180E+04	0.134E-01
0.350E-01	0.890E-03	0.603	674.9	0.677E-02	42.14	62.09	0.180E+04	0.133E-01
0.400E-01	0.885E-03	0.653	727.1	0.631E-02	38.82	56.00	0.182E+04	0.132E-01
0.450E-01	0.880E-03	0.731	805.6	0.572E-02	34.50	46.00	0.184E+04	0.130E-01
0.500E-01	0.875E-03	1.000	0.106E+0	0.437E-02	24.31	6.667	0.196E+04	0.122E-01

H(MEAN) = 0.100E-02 INCHES H1 = 0.103E-02 INCHES H2 = 0.975E-03 INCHES DA/DR = 0.144E-01 DA/A(MIN) = 0.354E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.103E-02	0.477	541.0	0.871E-02	55.63	75.65	0.210E+04	0.114E-01
0.500E-02	0.102E-02	0.491	556.5	0.850E-02	54.12	74.23	0.210E+04	0.114E-01
0.100E-01	0.101E-02	0.507	573.7	0.827E-02	52.51	72.60	0.210E+04	0.114E-01
0.150E-01	0.101E-02	0.525	593.2	0.803E-02	50.78	70.72	0.211E+04	0.114E-01
0.200E-01	0.100E-02	0.546	615.3	0.777E-02	48.92	68.50	0.211E+04	0.114E-01
0.250E-01	0.100E-02	0.570	640.9	0.748E-02	46.89	65.81	0.211E+04	0.113E-01
0.300E-01	0.995E-03	0.595	671.5	0.716E-02	44.62	62.48	0.212E+04	0.113E-01
0.350E-01	0.990E-03	0.636	709.2	0.681E-02	42.05	58.15	0.213E+04	0.113E-01
0.400E-01	0.985E-03	0.684	758.5	0.639E-02	39.00	52.12	0.215E+04	0.112E-01
0.450E-01	0.980E-03	0.757	831.5	0.585E-02	35.03	42.46	0.218E+04	0.110E-01
0.500E-01	0.975E-03	1.000	0.106E+04	0.461E-02	25.64	6.667	0.231E+04	0.104E-01

H(MEAN) = 0.110E-02 INCHES H1 = 0.112E-02 INCHES H2 = 0.107E-02 INCHES DA/DR = 0.138E-01 DA/A(MIN) = 0.307E-01 ALPHA = -0.100E-02 RADIANS (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.112E-02	0.500	565.8	0.862E-02	54.81	73.36	0.239E+04	0.104E-01
0.500E-02	0.112E-02	0.514	580.9	0.842E-02	53.39	71.92	0.240E+04	0.104E-01
0.100E-01	0.111E-02	0.529	597.7	0.821E-02	51.88	70.27	0.240E+04	0.105E-01
0.150E-01	0.111E-02	0.547	616.5	0.798E-02	50.26	68.37	0.240E+04	0.105E-01
0.200E-01	0.110E-02	0.567	637.9	0.774E-02	48.52	66.14	0.240E+04	0.105E-01
0.250E-01	0.110E-02	0.591	662.6	0.747E-02	46.62	63.46	0.241E+04	0.105E-01
0.300E-01	0.109E-02	0.619	691.8	0.718E-02	44.50	60.17	0.242E+04	0.105E-01
0.350E-01	0.109E-02	0.654	727.7	0.684E-02	42.09	55.93	0.243E+04	0.105E-01
0.400E-01	0.108E-02	0.700	774.5	0.645E-02	39.22	50.07	0.245E+04	0.105E-01
0.450E-01	0.108E-02	0.765	843.5	0.594E-02	35.46	40.79	0.248E+04	0.105E-01
0.500E-01	0.107E-02	1.000	0.106E+04	0.475E-02	26.41	6.667	0.262E+04	0.105E-01

H(MEAN) = 0.120E-02 INCHES H1 = 0.122E-02 INCHES DA/DR = 0.131E-01 ALPHA = -0.100E-02 RADIANS
H2 = 0.117E-02 INCHES DA/A(MIN) = 0.266E-01 (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.122E-02	0.511	577.8	0.857E-02	54.40	72.22	0.265E+04	0.106E-01
0.500E-02	0.122E-02	0.525	592.8	0.838E-02	53.01	70.75	0.265E+04	0.106E-01
0.100E-01	0.121E-02	0.540	609.4	0.817E-02	51.53	69.09	0.266E+04	0.106E-01
0.150E-01	0.121E-02	0.558	628.0	0.795E-02	49.95	67.18	0.266E+04	0.106E-01
0.200E-01	0.120E-02	0.578	649.1	0.771E-02	48.25	64.93	0.266E+04	0.106E-01
0.250E-01	0.120E-02	0.601	673.4	0.745E-02	46.39	62.26	0.267E+04	0.106E-01
0.300E-01	0.119E-02	0.629	702.2	0.717E-02	44.33	58.96	0.268E+04	0.106E-01
0.350E-01	0.119E-02	0.663	737.5	0.684E-02	41.98	54.74	0.269E+04	0.106E-01
0.400E-01	0.118E-02	0.708	783.3	0.646E-02	39.18	48.94	0.271E+04	0.106E-01
0.450E-01	0.118E-02	0.776	850.6	0.596E-02	35.53	39.79	0.275E+04	0.106E-01
0.500E-01	0.117E-02	1.000	0.106E+04	0.480E-02	26.72	6.667	0.290E+04	0.107E-01

H(MEAN) = 0.130E-02 INCHES H1 = 0.133E-02 INCHES DA/DR = 0.125E-01 ALPHA = -0.100E-02 RADIANS
H2 = 0.128E-02 INCHES DA/A(MIN) = 0.235E-01 (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.133E-02	0.522	589.2	0.853E-02	54.00	71.11	0.291E+04	0.107E-01
0.500E-02	0.132E-02	0.535	604.1	0.834E-02	52.64	69.63	0.292E+04	0.107E-01
0.100E-01	0.131E-02	0.551	620.6	0.813E-02	51.19	67.95	0.292E+04	0.107E-01
0.150E-01	0.131E-02	0.568	639.0	0.792E-02	49.65	66.02	0.292E+04	0.107E-01
0.200E-01	0.130E-02	0.588	659.9	0.769E-02	47.98	63.76	0.293E+04	0.107E-01
0.250E-01	0.130E-02	0.611	683.9	0.743E-02	46.17	61.07	0.294E+04	0.107E-01
0.300E-01	0.129E-02	0.639	712.3	0.715E-02	44.15	57.78	0.295E+04	0.107E-01
0.350E-01	0.129E-02	0.672	747.0	0.684E-02	41.85	53.56	0.296E+04	0.107E-01
0.400E-01	0.128E-02	0.717	792.0	0.646E-02	39.12	47.80	0.298E+04	0.107E-01
0.450E-01	0.128E-02	0.784	857.9	0.598E-02	35.56	38.75	0.302E+04	0.107E-01
0.500E-01	0.127E-02	1.000	0.106E+04	0.486E-02	27.02	6.667	0.318E+04	0.105E-01

H(MEAN) = 0.140E-02 INCHES H1 = 0.142E-02 INCHES DA/DR = 0.119E-01 ALPHA = -0.100E-02 RADIANS
H2 = 0.137E-02 INCHES DA/A(MIN) = 0.207E-01 (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.142E-02	0.534	602.9	0.847E-02	53.52	69.75	0.319E+04	0.105E-01
0.500E-02	0.142E-02	0.548	617.7	0.829E-02	52.19	68.24	0.320E+04	0.105E-01
0.100E-01	0.141E-02	0.564	634.1	0.809E-02	50.78	66.54	0.320E+04	0.105E-01
0.150E-01	0.141E-02	0.581	652.3	0.788E-02	49.28	64.59	0.320E+04	0.105E-01
0.200E-01	0.140E-02	0.601	672.9	0.766E-02	47.66	62.32	0.321E+04	0.105E-01
0.250E-01	0.140E-02	0.623	696.6	0.741E-02	45.90	59.62	0.322E+04	0.105E-01
0.300E-01	0.139E-02	0.650	724.4	0.714E-02	43.94	56.32	0.323E+04	0.105E-01
0.350E-01	0.139E-02	0.684	758.4	0.683E-02	41.72	52.13	0.324E+04	0.105E-01
0.400E-01	0.138E-02	0.727	802.3	0.647E-02	39.08	46.42	0.327E+04	0.104E-01
0.450E-01	0.138E-02	0.792	866.2	0.601E-02	35.64	37.56	0.331E+04	0.104E-01
0.500E-01	0.137E-02	1.000	0.106E+04	0.493E-02	27.40	6.667	0.347E+04	0.103E-01

H(MEAN) = 0.150E-02 INCHES H1 = 0.152E-02 INCHES DA/DR = 0.112E-01 ALPHA = -0.100E-02 RADIANS
H2 = 0.147E-02 INCHES DA/A(MIN) = 0.183E-01 (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.152E-02	0.547	616.2	0.842E-02	53.04	68.40	0.348E+04	0.103E-01
0.500E-02	0.152E-02	0.561	630.8	0.824E-02	51.76	66.88	0.348E+04	0.103E-01
0.100E-01	0.151E-02	0.576	646.9	0.805E-02	50.39	65.17	0.348E+04	0.103E-01
0.150E-01	0.151E-02	0.593	664.9	0.785E-02	48.93	63.21	0.349E+04	0.103E-01
0.200E-01	0.150E-02	0.612	685.2	0.763E-02	47.37	60.93	0.349E+04	0.103E-01
0.250E-01	0.150E-02	0.635	708.4	0.739E-02	45.66	58.23	0.350E+04	0.103E-01
0.300E-01	0.149E-02	0.661	735.7	0.713E-02	43.76	54.95	0.352E+04	0.103E-01
0.350E-01	0.149E-02	0.694	769.0	0.683E-02	41.61	50.79	0.353E+04	0.102E-01
0.400E-01	0.148E-02	0.737	811.7	0.649E-02	39.05	45.16	0.356E+04	0.102E-01
0.450E-01	0.148E-02	0.800	873.7	0.604E-02	35.73	36.48	0.360E+04	0.102E-01
0.500E-01	0.147E-02	1.000	0.106E+04	0.499E-02	27.76	6.667	0.378E+04	0.101E-01

H(MEAN) = 0.160E-02 INCHES H1 = 0.163E-02 INCHES DA/DR = 0.106E-01 ALPHA = -0.100E-02 RADIANS
H2 = 0.158E-02 INCHES DA/A(MIN) = 0.162E-01 (CHOKED FLOW)

X INCHES	H INCHES	MACH NUMBER	VELOCITY FT/SEC	DENSITY LB-SEC2/FT4	PRESSURE PSIA	TEMPERATURE DEG F	RE(P)	FRICTION FACTOR
0	0.163E-02	0.558	628.5	0.837E-02	52.60	67.12	0.376E+04	0.101E-01
0.500E-02	0.162E-02	0.572	643.0	0.820E-02	51.35	65.60	0.377E+04	0.101E-01
0.100E-01	0.161E-02	0.587	658.9	0.801E-02	50.02	63.87	0.377E+04	0.101E-01
0.150E-01	0.161E-02	0.604	676.5	0.781E-02	48.61	61.91	0.378E+04	0.101E-01
0.200E-01	0.160E-02	0.623	696.5	0.760E-02	47.08	59.63	0.378E+04	0.101E-01
0.250E-01	0.160E-02	0.645	719.3	0.737E-02	45.43	56.94	0.379E+04	0.101E-01
0.300E-01	0.159E-02	0.672	746.1	0.712E-02	43.59	53.67	0.381E+04	0.101E-01
0.350E-01	0.159E-02	0.704	778.6	0.683E-02	41.50	49.55	0.382E+04	0.100E-01
0.400E-01	0.158E-02	0.745	820.3	0.650E-02	39.03	44.00	0.385E+04	0.100E-01
0.450E-01	0.158E-02	0.807	880.4	0.606E-02	35.81	35.49	0.390E+04	0.100E-01
0.500E-01	0.157E-02	1.000	0.106E+04	0.505E-02	28.08	6.667	0.408E+04	0.988E-02

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TABLE I. - PARAMETERS CALCULATED BY AREAX

Parameter	Formula[a]	Units	
		SI	U.S.
Gas constant	$\mathcal{R} = \dfrac{\text{Universal gas constant}}{\text{Molecular weight}}$	J/kg-K	$\dfrac{\text{lbf-ft}}{\text{lbm-}^{\circ}\text{R}}$
Seal surface area	$A = \pi\left(R_2^2 - R_1^2\right)$	m^2	$in.^2$
Flow length	$\Delta R = R_2 - R_1$	m	in.
Flow width (mean)	$W = 2\pi\left(\dfrac{R_1 + R_2}{2}\right)$	m	in.
Mass flow rate	$\dot{M} = Wh\rho u$	kg/sec	lbm/min
Volume flow rate	$Q = c_1\dot{M}$	scms	scfm
Reynolds number due to rotational flow	[b]$Re(r) = \bar{\rho}Vh\sqrt{\bar{\mu}}$		
Knudsen number	$Kn = \dfrac{2.96\ M_{max}}{Re(p)}$		
Mean free path	$\lambda = Kn \times h$	m	in.
Viscosity of air (Sutherland's law)	$\mu_{air} = \dfrac{c_2T^{1.5}}{T + c_3}$	$N\text{-sec}/m^2$	$lbf\text{-sec}/in.^2$
Power	$\mu AV^2/h$	W	hp
Apparent temperature rise due to power dissipation	$\Delta T = \dfrac{c_4 \times \text{Power}}{Mc_p}$	K	$^{\circ}R$
Shear heat	$H = c_5 \times \text{Power}$	W	Btu/min
Torque	Power/Speed	N-m	ft-lb
Seal opening force	$F = W\int_0^{\Delta R}(P - P_3)dx$	N	lbf
Center of pressure	$x_c = \dfrac{W}{F}\int_0^{\Delta R}(P - P_3)x\,dx$	m	in.
Axial film stiffness	$S = -dF/dh$	N/m	lbf/in.

[a]Constants in equations are as follows (for Si and U.S. units, respectively): $c_1 = 5.051554\times10^{-3}$ (13.083); $c_2 = 1.4591\times10^{-6}$ (1.57639×10^{-10}); $c_3 = 110.33333$ (198.6); $c_4 = 1.0$ (42.42); and $c_5 = 1.0$ (42.42).

[b]Where $\bar{\rho}$ is density at midseal, $\bar{\mu}$ is viscosity at midseal, and V is mean rotational velocity.

TABLE II. - VARIABLES IN NAMELIST/SEAL/

Variable name	Description	Units	
		SI	U.S.
RINNER	Inner radius of seal	m	in.
ROUTER	Outer radius of seal	m	in.
RDIFIN	Flow length	m	in.
MOLWT	Molecular weight		
CP	Specific heat	J/kg-K	Btu/lbm-$^{\circ}$R
MUIN	Reservoir viscosity. The program will calculate MUIN for air but not for other gases.	N-sec/m^2	lbf-sec/in.^{2}
GAMMA	Ratio of specific heats		
SPEED	Rotational velocity	rps	rpm
CAPV	Seal-face speed	m/sec	ft/sec
XLAM	Exponent in friction factor - Reynolds number relation for laminar flow (eq. (22))	---------	-----------
XTURB	Exponent in friction factor - Reynolds number relation for turbulent flow	---------	-----------
CONLAM	Constant in friction factor - Reynolds number relation for laminar flow	---------	-----------
CONTRB	Constant in friction factor - Reynolds number relation for turbulent flow	---------	-----------
RELAM	Maximum Reynolds number for laminar flow	---------	-----------
RETURB	Minimum Reynolds number for turbulent flow	---------	-----------
PWRSKP	Logical variable. If it is set to .TRUE., calculations involving power are omitted.	---------	-----------
NRMSKP	Logical variable. If it is set to .TRUE., normalized values of F and x_c will be omitted.	---------	-----------
PRSSKP	Logical variable. If it is set to .TRUE., printout of distributions across face of seal of P, T, ρ, u, M, $\bar{f}$, and Re will be omitted.	---------	-----------
PLTSKP	Array of logical variables. If any element is set to .TRUE., the corresponding plot will be omitted: PLTSKP(1) applies to plot of power against h. PLTSKP(2) applies to plot of x_c against h. PLTSKP(3) applies to plot of F against h. PLTSKP(4) applies to plot of P against x. PLTSKP(5) applies to plot of T against x. PLTSKP(6) applies to plot of ρ against x. PLTSKP(7) applies to plot of M against x. PLTSKP(8) applies to plot of Reynolds number against x. PLTSKP(9) applies to plot of mean friction factor against x.	---------	-----------
NSI	Numerical indicator for units. NSI = 1 means SI units. NSI = 2 means U.S. units.		

TABLE III. - VARIABLES IN NAMELIST/HDATA/

Variable name	Description	Units	
		SI	U.S.
HMEAN	Mean film thickness	m	in.
ALPHA	Tilt angle	rad	rad
NJ	Number of film thicknesses	---	----
JDONE	Number of film thicknesses for which cards were punched in previous running of program	---	----

TABLE IV. - VARIABLES IN NAMELIST/RESDAT/

Variable name	Description	Units	
		SI	U.S.
P1IN	Gas pressure at inner radius	N/m^2	$lbf/in.^2$
P2IN	Gas pressure at outer radius	N/m^2	$lbf/in.^2$
PRIN	Ratio of sealed-gas pressure to ambient pressure, P_0/P_3	-----	-------
TOIN	Sealed-gas temperature (upstream reservoir temperature), T_0	K	^oF
LOSS	Entrance velocity loss coefficient	-----	-------
INCODE	Input code. For running many cases with one loading of the program, the input code tells the program what new data are expected for the next case: INCODE = 1 means a new title card is expected. INCODE = 2 means new SEAL data are expected. INCODE = 3 means new HDATA data are expected. INCODE = 4 means new RESDAT data are expected.	-----	-------

TABLE V. - INPUT DATA FOR SAMPLE PROBLEM

cc 2-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	49-54	55-60	61-66	67-72	73-80

```
     SAMPLE PROBLEM - AREA EXPANSION PROGRAM - SI UNITS
$SEAL RINNER=.082931, ROUTER=.084201, RDIFIN=0., MOLWT=28.966, CP=1004.16,
GAMMA=1.4, MUIN=0., SPEED=0., CAPV=60.96, XLAM=1., XTURB=.25, CONLAM=24.,
CONTRB=.079, RELAM=2300., RETURB=3000., PWRSKP=F, PRSSKP=F, NRMSKP=F,
PLTSKP=9*F, NSI=1, WIDTH=0. $
$HDATA HMEAN=.762E-5,1.016E-5,1.270E-5,1.524E-5,1.778E-5,2.032E-5,2.286E-5,
2.540E-5,2.794E-5,3.048E-5,3.302E-5,3.556E-5,3.810E-5,4.064E-5,6*0.,
ALPHA=20*-.001, NJ=14, JDONE=14 $
$RESDAT P1IN=448159.22, P2IN=103423.59, PRIN=0., TOIN=311.11111, LOSS=1.,
INCODE=1 $
```

```
  SAMPLE PROBLEM - AREA EXPANSION PROGRAM - U. S. UNITS
$SEAL RINNER=3.265, ROUTER=3.315, RDIFIN=0., WIDTH=0., MOLWT=28.966, CP=.24,
MUIN=0., GAMMA=1.4, CAPV=200., SPEED=0., XLAM=1., XTURB=.25, CONLAM=24.,
CONTRB=.079, RELAM=2300., RETURB=3000., PWRSKP=F, NRMSKP=F, PRSSKP=F,
PLTSKP=9*T, NSI=2 $
$HDATA HMEAN=.3E-3,.4E-3,.5E-3,.6E-3,.7E-3,.8E-3,.9E-3,1.0E-3,1.1E-3,1.2E-3,
1.3E-3,1.4E-3,1.5E-3,1.6E-3,6*0., ALPHA=20*-.001, NJ=14, JDONE=14 $
$RESDAT P1IN=65., P2IN=15., PRIN=0., TOIN=100., LOSS=1., INCODE=1 $
```

TABLE VI. - PARAMETERS IN COMMON BLOCK/ARRAYS/

Array	Symbol	Array dimension	Description
1	x	(11)	Distance across face of seal
2	P	(11, 20)	Pressure
3	M	(11, 20)	Mach number
4	u	(11, 20)	Leakage flow velocity (x-direction)
5	T	(11, 20)	Temperature
6	ρ	(11, 20)	Density
7	Re(p)	(11, 20)	Pressure-flow Reynolds number
8	$\overline{f}$	(11, 20)	Mean friction factor
9	h	(11, 20)	Film thickness
10	$\overline{x}_c$	(20)	Dimensionless center of pressure
11		(20)	Power
12	F	(20)	Force
13	S	(20)	Axial film stiffness
14	$\overline{F}$	(20)	Pressure profile factor
15	h_1	(20)	Film thickness at entrance
16	h_2	(20)	Film thickness at exit
17	α	(20)	Tilt angle
18	h_m	(20)	Mean film thickness
19	x^*	(20)	Choking flow length
20	P^*	(20)	Choking pressure
21	A^*	(20)	Area at point of choking

TABLE VII. - PARAMETERS IN COMMON BLOCK/CONSTS/

Word	Symbol	Description
1	γ	Ratio of specific heats
2	ΔR	Flow length
3	R_0 SIGN	Radius of seal at entrance If SIGN $>$ 0, flow is radially outward; if SIGN $<$ 0, flow is radially inward.
4	n_l	Exponent in friction factor - Reynolds number relation for laminar flow
5	n_t	Exponent in friction factor - Reynolds number relation for turbulent flow
6	k_l	Constant in friction factor - Reynolds number relation for laminar flow
7	k_t	Constant in friction factor - Reynolds number relation for turbulent flow
8	$(Re)_l$	Upper limit on Re for laminar flow
9	$(Re)_t$	Lower limit on Re for turbulent flow
10	T_0	Sealed-gas-reservoir temperature
11	P_0	Sealed-gas-reservoir pressure
12	P_3	Ambient pressure
13	P_{tol}	Pressure tolerance to stop iteration on exit pressure for subcritical flow
14	$\mathscr{R}$	Gas constant
15	C_L	Entrance velocity loss coefficient
16	μ_0	Sealed-gas-reservoir viscosity
17	π	3.1415927
18	$\mathscr{R}_u(2)$	Universal gas constant
19	CNVT(11, 2)	Constants needed for internal calculations
20	NSI	Numerical indicator for system of units being used: NSI = 1 means SI units; NSI = 2 means U.S. units.

TABLE VIII. - CONSTANTS FOR INTERNAL CALCULATIONS

Word in array CNVT	Variable to which constant applies	Word in array CNVT	Variable to which constant applies
1	Sutherland's law	7	Power
2	Sutherland's law	8	Shear heat
3	Speed	9	Torque
4	Mass flow rate	10	Density
5	Standard volume flow	11	Velocity
6	Reynolds number		

TABLE IX. - PARAMETERS IN COMMON BLOCK/TRAYS/

Array	Symbol	Array dimension	Description
1	N	(1)	Number of grid points
2	x	(101)	x-grid points
3	M	(101)	Mach number at each x
4	h	(101)	Film thickness at each x
5	NJ	(1)	Index of film thickness for which solution is being found
6	Γ^*	(1)	Temperature at choking

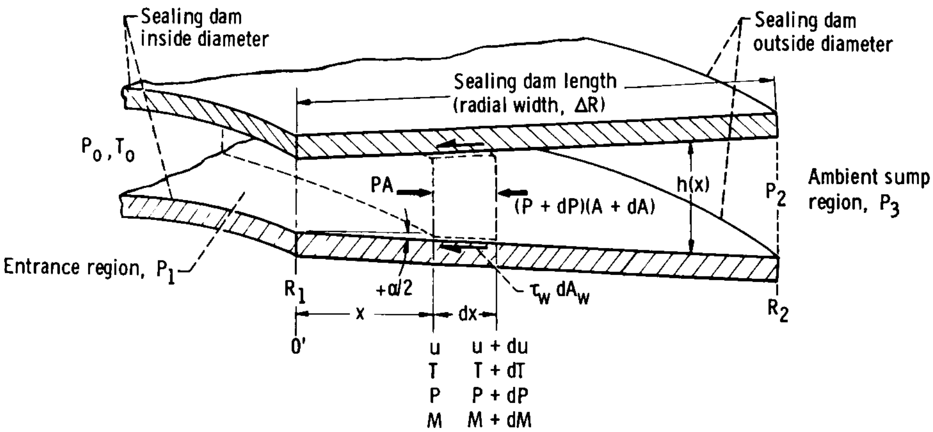

Figure 1. - Model and notation of sealing faces, including control volume for quasi-one-dimensional flow with area change.

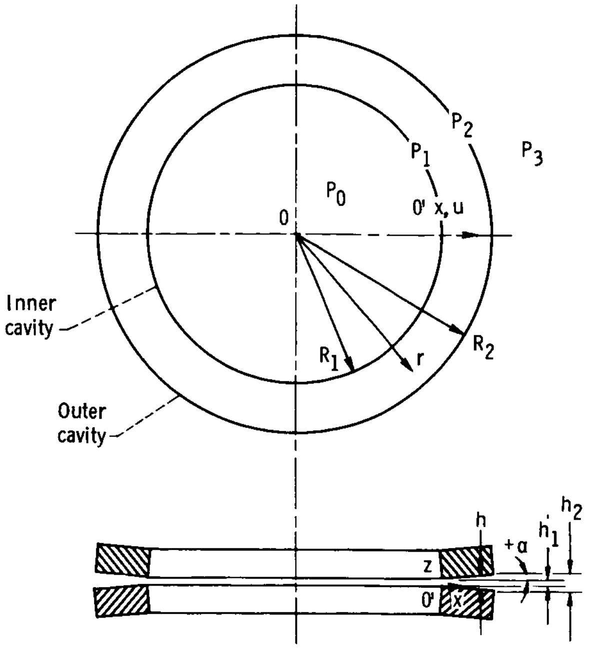

Figure 2. - Model of sealing dam with small tilt angle (not to scale). Sealed gas is in inner cavity region; upper ring removed for clarity in top view.

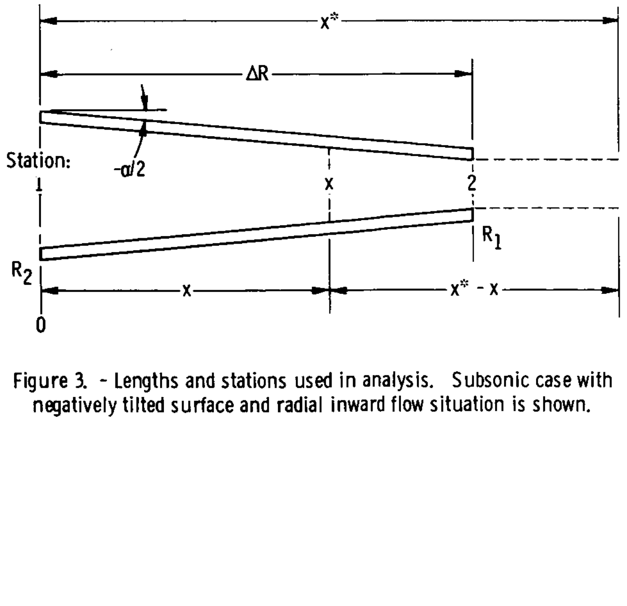

Figure 3. - Lengths and stations used in analysis. Subsonic case with negatively tilted surface and radial inward flow situation is shown.

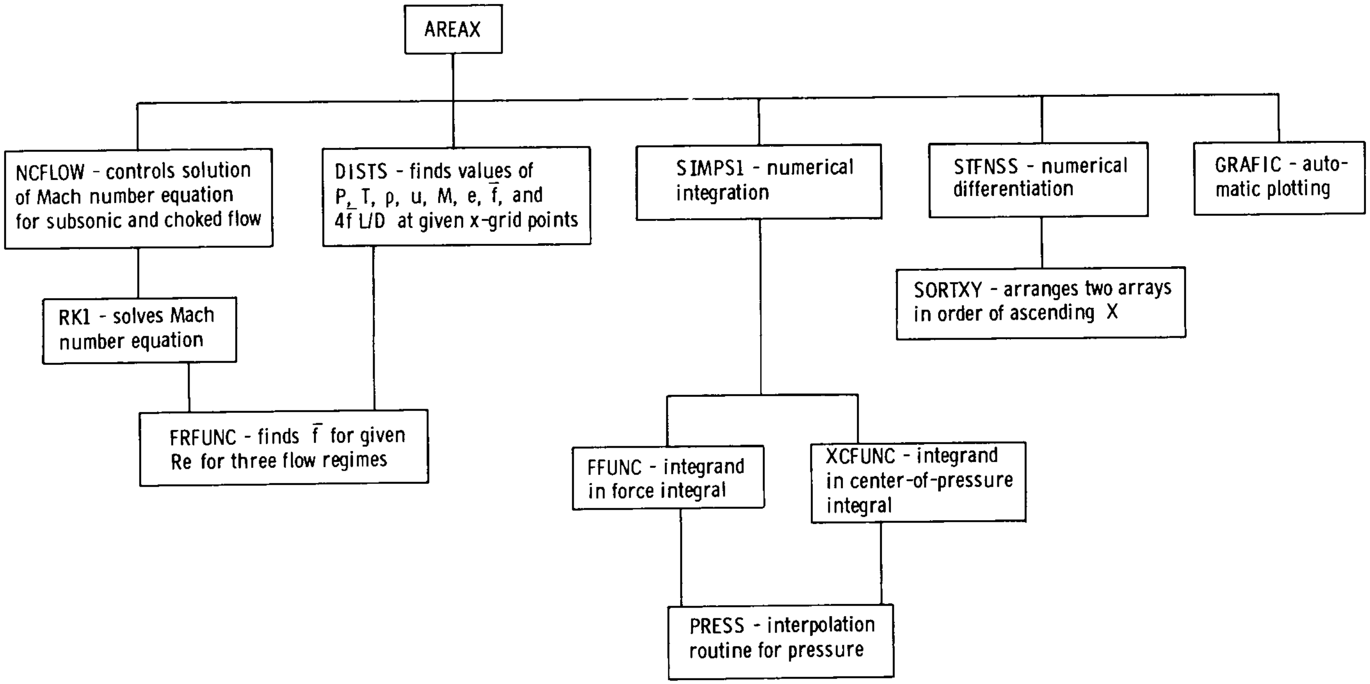

Figure 4. - Heirachy of subprogram calls.

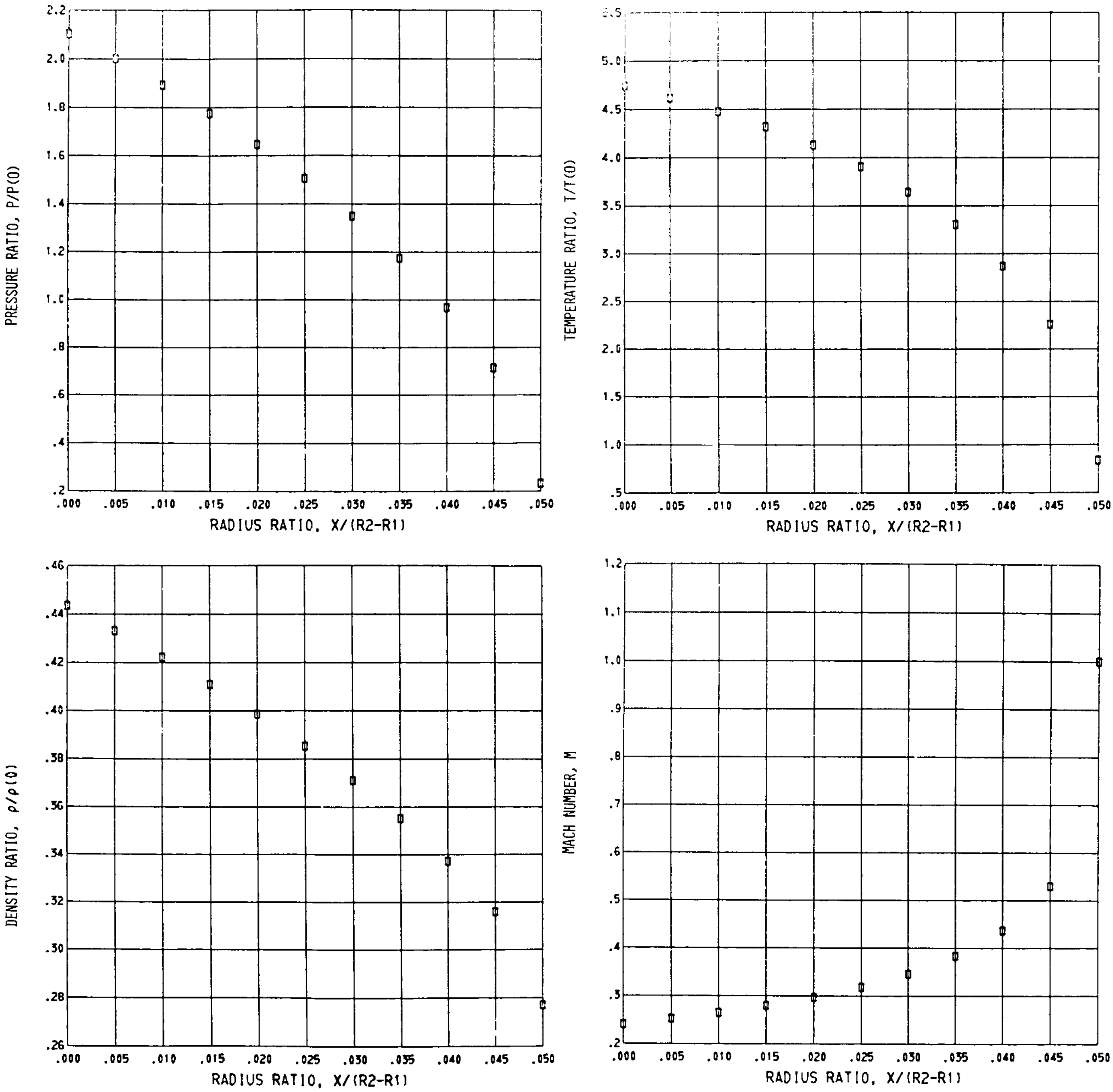

Figure 5. - Computer plots for sample problems, evaluated at film thickness of 12.7 micrometers (0.5 mil).

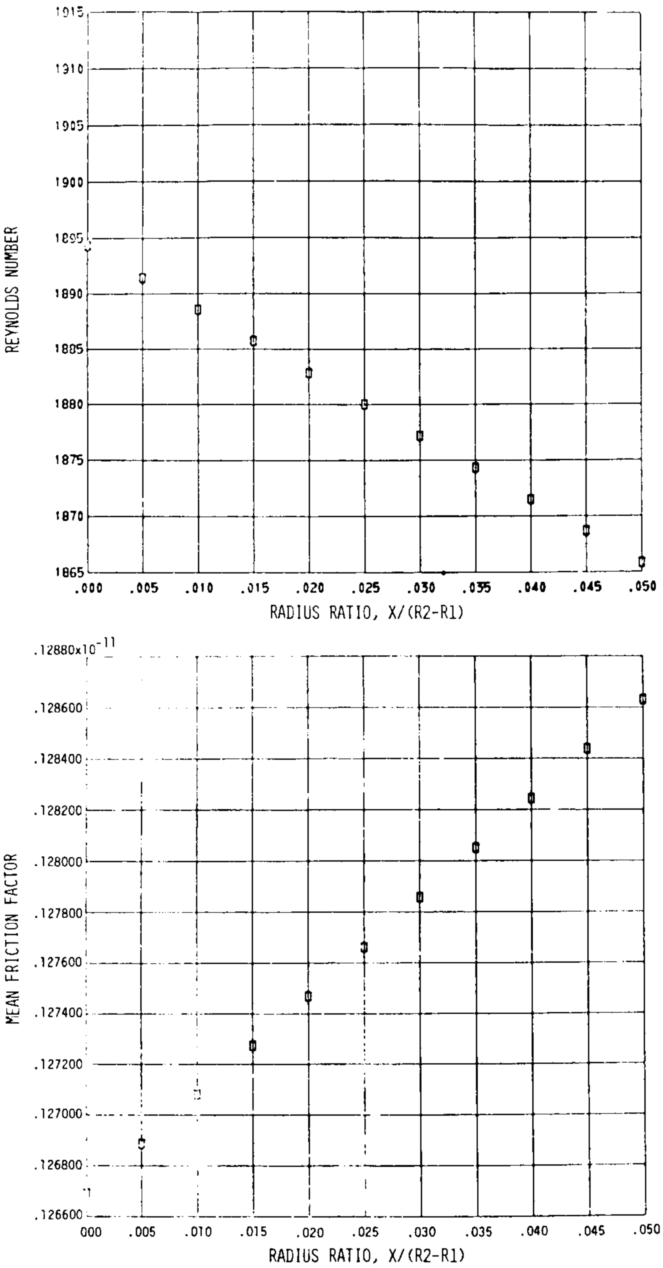

Figure 5. - Concluded.

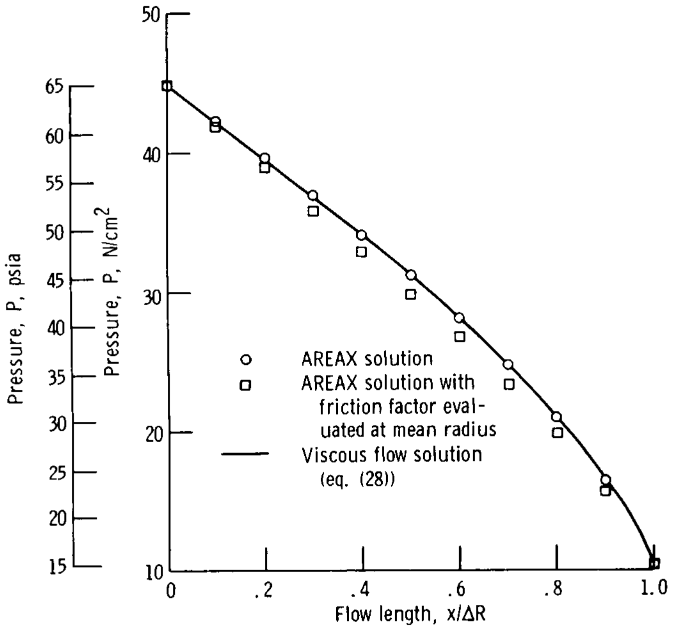

Figure 6. - Comparison of variable-area approximate analysis with exact compressible-viscous-flow solution for pure radial flow. Parallel film; film thickness, 12.7 micrometers (0.5 mil); sealed-gas-reservoir pressure, 45 N/cm^2 (65 psia); exit pressure, 10.3 N/cm^2 (15 psia); sealed-gas-reservoir temperature, 311 K (100^o F); inner radius, 5.880 centimeters (2.315 in.); outer radius, 8.410 centimeters (3.315 in.).

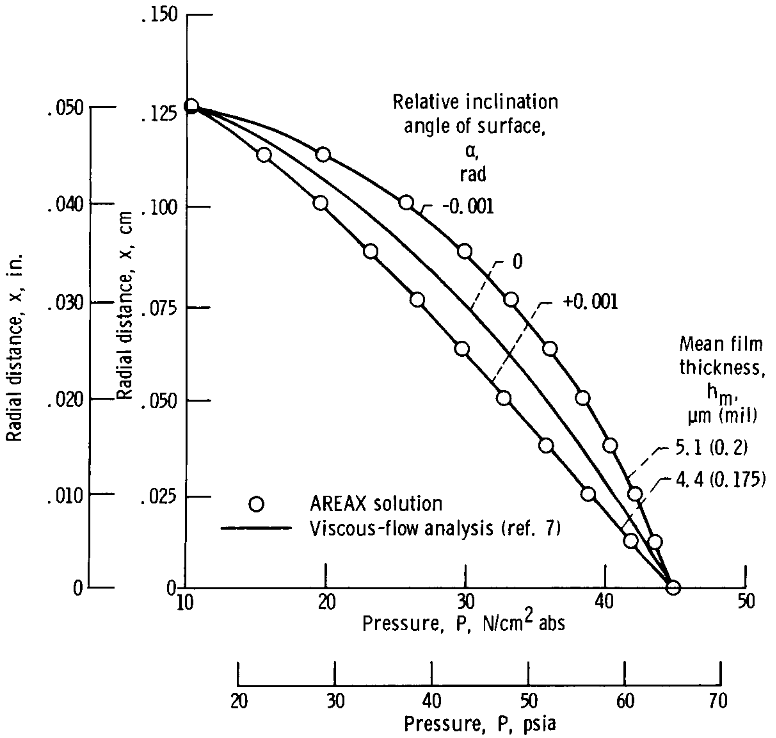

Figure 7. - Comparison of variable-area approximate analysis with exact viscous-compressible-flow solution. Positive and negative 1-milliradian tilt; sealed-gas-reservoir pressure, 45 N/cm^2 (65 psia); exit pressure, 10.3 N/cm^2 (15 psia); sealed-gas-reservoir temperature, 311 K (100^o F); inner radius, 8.300 centimeters (3.265 in.); outer radius, 8.410 centimeters (3.315 in.).

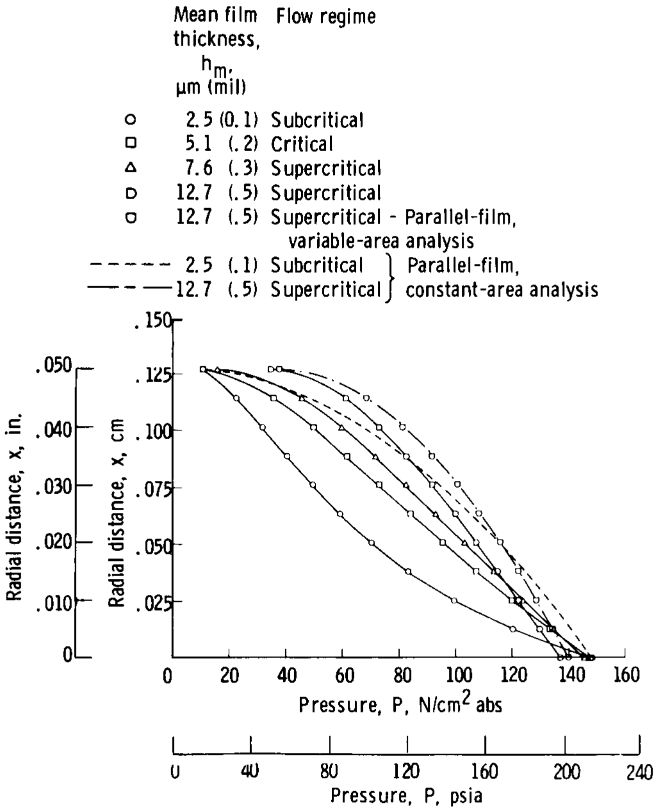

Figure 8. - Results obtained using variable-area approximate analysis for pressure distributions. Positive 2-milliradian tilt; conditions represent subcritical, critical, and supercritical flow; mean film thicknesses, 2.5, 5.1, 7.6, and 12.7 micrometers (0.1, 0.2, 0.3, and 0.5 mil); sealed-gas-reservoir pressure, 148 N/cm^2 (215 psia); exit pressure, 10.3 N/cm^2 (15 psia); sealed-gas-reservoir temperature, 700 K (800° F); inner radius, 8.300 centimeters (3.265 in.); outer radius, 8.410 centimeters (3.315 in.). Also shown are comparable parallel-film cases.

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