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QUASI-ONE-DIMENSIONAL COMPRESSIBLE FLOW ACROSS FACE SEALS AND NARROW SLOTS

II - Computer Program

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16. Abstract

A computer program is presented for compressible fluid flow with friction across face seals and through narrow slots. The computer program carries out a quasi-one-dimensional flow analysis which is valid for laminar and turbulent flows under both subsonic and choked flow conditions for parallel surfaces. The program is written in FORTRAN IV. The input and output variables are in either the International System of Units (SI) or the U. S. customary system.

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SUMMARY

The computer program presented in this report calculates the properties of compressible fluid flow with friction across shaft face seals and through narrow slots. The mathematical model on which this program is based is developed in a companion report. A summary of this analysis is included.

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

The program is written in FORTRAN IV. Input, internal calculations, and output are in either the International System of Units (SI) or the U. S. customary system. Automatic plotting of several of the output parameters is an available option.

This report includes a description of the program, details of the numerical techniques required to solve the set of equations in the mathematical model, flow charts of the main program and the essential subprograms, a complete description of the input variables, and sample input and output.

INTRODUCTION

The computer program presented in this report, QUASC, calculates the properties of compressible fluid flow with friction across shaft face seals and through narrow slots. It is based on a mathematical model which is developed in a companion report (ref. 1). A summary of this analysis and the governing equations of the model are given in the next section.

The analysis includes fluid inertia, viscous friction, and entrance losses. The model is valid for both completely subsonic flow and choked flow. It is also valid for both laminar and turbulent flow regimes.

The computer program has proved useful in seal design, where much of the physical information of interest is difficult to determine experimentally. A mathematical model tested on a computer can generate this needed information. The model on which QUASC is based has been shown to be a good model for conventional face seals which are pressure (force) balanced and for seals with self-acting lift pads. These two types of seals are shown in figures 1 and 2.

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 QUASC for specified seal geometries, 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.

Results of the computer analysis agree quite well with experimental results. The comparison of these results is discussed in detail in reference 1.

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

SUMMARY OF QUASI-ONE-DIMENSIONAL ANALYSIS

The mathematical model on which the program QUASC is based is for face seals which consist of two parallel, coaxial, circular rings separated by a very narrow gap (fig. 3). A pressure difference exists between the rings' inner and outer radii. The cavities on either side (i. d. and o. d.) of the sealing dam are assumed to be constant pressure reservoirs.

The flow is assumed to be entirely radial. It has been shown that the effects of rotation of the two seal faces are negligible for most applications (ref. 2). Since the radial distance across the seal is very small compared to the mean radius of the rings (i. d. /o. d. $\simeq$ 0.98), the area expansion is negligible. The analysis is also valid for flow through a narrow slot.

In reference 1, the analysis is separated into two parts. The first part is the flow in the passage itself, where the flow is assumed to behave as a constant-area adiabatic flow with friction. The second part is the flow in the entrance region. These two parts are discussed separately herein also.

Constant-Area Adiabatic Flow with Friction

It is assumed that the flow in the seal leakage flow region behaves as a constant-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 area expansion due to radius increase is neglected. (In most main-shaft face seals the i. d. /o. d. is about 0.98.) Hence, the analysis is also valid for narrow slots.

(2) The flow is adiabatic.

(3) No shaft work is done on or by the system.

(4) No potential energy difference is present such as caused by elevation differences.

(5) The fluid behaves as a perfect gas.

(6) The sealing surfaces are parallel.

With these assumptions, the flow is commonly known as Fanno line flow.

In reference 1, under the model assumptions, the governing conservation equations reduce to the following (all symbols are defined in appendix A):

Conservation of mass:

$$\frac{d\rho}{\rho} + \frac{1}{2}\frac{du^2}{u^2} = 0 \tag{1}$$

Conservation of momentum:

$$-A\,dP - \tau_w\,dA_w = \dot{M}\,du \tag{2}$$

Conservation of energy:

$$\frac{dT}{T} + \frac{\gamma - 1}{2} M^2 \frac{du^2}{u^2} = 0 \tag{3}$$

Perfect gas relation:

$$\frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dT}{T} \tag{4}$$

With the introduction of the mean Fanning friction factor $\bar{f}$

$$\bar{f} = \frac{-dP/dx}{2\rho u^2/D} \tag{5}$$

and the hydraulic diameter D

$$D = \frac{4A}{P_w} \tag{6}$$

the conservation equations can be combined into one equation

$$\frac{4\bar{f}}{D}\,dx = \frac{(1 - M^2)dM^2}{\gamma M^4\left[1 + \frac{1}{2}(\gamma - 1)M^2\right]} \tag{7}$$

Integrating equation (7) from the point of interest to the point of choking gives

$$-\int_x^L \frac{4\bar{f}}{D}\,dx = \int_M^1 \frac{(1 - M^2)dM^2}{\gamma M^4\left[1 + \frac{1}{2}(\gamma - 1)M^2\right]} \tag{8}$$

(Since eq. (7) is a first-order differential equation, one boundary condition must be specified. The only known condition is that Mach number is unity at the critical choking length L (fig. 4).) Carrying out the integration gives

$$\frac{4\bar{f}}{D}(L - x) = \frac{1}{\gamma}\,\frac{1 - M^2}{M^2} + \frac{\gamma + 1}{2\gamma}\ln\left[\frac{\frac{1}{2}(\gamma + 1)M^2}{1 + \frac{1}{2}(\gamma - 1)M^2}\right] \equiv B(M) \tag{9}$$

The mean Fanning friction factor does not vary with flow length and is known to vary with Reynolds number according to the relation (ref. 1)

$$\bar{f} = \frac{k}{Re^n} \tag{10}$$

The hydraulic diameter for both coaxial rings and parallel planes (narrow slots) is twice the film thickness,

$$D = 2h \tag{11}$$

Further manipulation of the conservation equations and the perfect-gas relation result in the following equations:

$$\frac{dP}{P} = -\frac{\frac{1}{2}\left[1 + (\gamma - 1)M^2\right]dM^2}{M^2\left[1 + \frac{1}{2}(\gamma - 1)M^2\right]} \tag{12}$$

$$\frac{dT}{T} = -\frac{\frac{1}{2}(\gamma - 1)dM^2}{1 + \frac{1}{2}(\gamma - 1)M^2} \tag{13}$$

which, when integrated from the point of interest to the point of choking, give

$$\frac{P}{P^*} = \frac{1}{M}\left[\frac{\frac{1}{2}(\gamma + 1)}{1 + \frac{1}{2}(\gamma - 1)M^2}\right]^{1/2} \tag{14}$$

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

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

$$Re = \frac{\rho_1 u_1 D}{\mu_1} \tag{16}$$

$$M = \frac{u}{c} = \frac{u}{\sqrt{\gamma \mathscr{R} T}} \tag{17}$$

Entrance Flow

As stated in reference 1, the entrance region flow can be assumed to be isentropic and adiabatic. 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 flow equations. The resulting entrance temperature equation is

$$T_1 = \frac{T_0}{1 + \frac{(\gamma - 1)M_1^2}{2C_L^2}} \tag{18}$$

while the entrance pressure equation is

$$P_1 = \frac{P_0}{\left[1 + \frac{(\gamma - 1)M_1^2}{2C_L^2}\right]^{\gamma/(\gamma-1)}} \tag{19}$$

When $C_L = 1$, the flow is isentropic.

Solution of Equations

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

$$\frac{P}{\rho} = \mathscr{R}T \tag{20}$$

must now be solved. The independent variable is chosen to be x, the distance across the face of the sealing dam (fig. 3). 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 film thickness

k, n constants in friction factor - Reynolds number relation

These two constants apply to laminar flow ($Re \leq Re_l$) and turbulent flow ($Re \geq Re_t$). For flow in the transition region ($Re_l < Re < Re_t$), variation of the friction factor with Reynolds number is determined by the method described in appendix B.

The set of equations in the mathematical model cannot be solved explicitly. Consequently, an implicit solution, that is, an iterative procedure, must be used.

There are three types of flow considered: (1) critical flow, when the exit Mach number is 1 and the exit pressure equals the ambient pressure; (2) supercritical flow, when the exit Mach number is 1 and the exit pressure is greater than the ambient pressure; and (3) subcritical flow, when the exit Mach number is less than 1 and the exit pressure is equal to the ambient pressure (flow is entirely subsonic). Since the boundary conditions on the mathematical model are slightly different for each type of flow, the solution of the equations is slightly different for each type. The simplest set of equations is for critical flow. Hence, this flow case is considered first.

Critical flow. - For critical flow, the boundary conditions are as follows:

$$\text{Exit pressure } P_2 = P_3$$

$$\text{Choking pressure } P^* = P_3$$

$$\text{Exit Mach number } M_2 = 1$$

$$\text{Flow length } L = \Delta R$$

For this case it is necessary to calculate choking film thickness h^*, entrance Mach number M_1, and mean friction factor $\bar{f}$.

Start the implicit solution of the equations by guessing a value for M_1. Substitute for M_1 in equations (14) and (19) giving

$$\left.\frac{P}{P^*}\right|_{M_1} = \frac{P_1}{P_3} = \frac{1}{M_1}\left[\frac{\frac{1}{2}(\gamma + 1)}{1 + \frac{1}{2}(\gamma - 1)M_1^2}\right]^{1/2} \tag{21}$$

and

$$\left.\frac{P}{P_0}\right|_{M_1} = \frac{P_1}{P_0} = \frac{1}{\left[1 + \frac{1}{2}(\gamma - 1)(M_1/C_L)^2\right]^{\gamma/(\gamma-1)}} \tag{22}$$

Dividing equation (21) by equation (22) gives

$$\frac{P_1/P_3}{P_1/P_0} = \frac{P_0}{P_3} = \sqrt{\frac{\gamma + 1}{2}}\,\frac{1}{M_1}\,\frac{\left[1 + \frac{1}{2}(\gamma - 1)(M_1/C_L)^2\right]^{\gamma/(\gamma-1)}}{\left[1 + \frac{1}{2}(\gamma - 1)M_1^2\right]^{1/2}} \tag{23}$$

Equation (23) can be solved for M_1 by the method of iteration, a standard numerical analysis technique (see appendix C). It should be noted that equation (23) does not have a solution for certain combinations of P_0, P_3, and γ. In that case, the flow is assumed to be subcritical. See appendix B for further discussion of this point.

Once M_1 has been found, it can be substituted into equation (9) giving

$$B(M_1) = B_1 = \frac{4\bar{f}\,\Delta R}{2h^*} \tag{24}$$

Since $x = 0$ at the entrance, the flow length L is equal to ΔR. In equation (24), both $\bar{f}$ and h^* are unknown. However, it is known that $\bar{f} = k/Re^n$ (eq. (10)). Substituting in equation (23) for $\bar{f}$, Reynolds number (eq. (16)), and hydraulic diameter (eq. (11)) gives

$$B_1 = \frac{2\,\Delta R}{h^*}\,k\left(\frac{\mu_1}{\rho_1 u_1 2h^*}\right)^n \tag{25}$$

Entrance density ρ_1 is calculated from the perfect-gas relation (eq. (20))

$$\rho_1 = \frac{\mathscr{R}T_1}{P_1}$$

where T_1 and P_1 are calculated from the entrance equations (18) and (19). Leakage flow velocity u_1 is calculated from the definition of Mach number (eq. (17)). Equation (25) can now be solved for h^*. Iteration is required to determine whether the flow is laminar, transition, or turbulent. A block diagram of this solution is shown in figure 5.

When M_1 and h^* have been found, it is then possible to calculate the distribution, across the face of the seal, of pressure, temperature, Mach number, velocity, density, and friction parameter B. First, calculate T^* from equation (15) for $M = M_1$. Choose a value of the independent variable and solve equations (1), (9), (14), (17), and (20) simultaneously. Since the solution cannot be obtained explicitly, an iterative solution must again be used. First, substitute for x in equation (9), giving

$$B_x = \frac{4\bar{f}(L - x)}{D} = B(M_x) \tag{26}$$

Solve equation (26) by the method of iteration for M_x. Once M_x has been determined, find T_x from equation (15). Substitute M_x and T_x in the definition of Mach number (eq. (17)) to give u_x. Substitute u_x, u_1, and ρ_1 into the conservation-of-mass equation

$$\rho_1 u_1 = \rho_x u_x \tag{27}$$

to give ρ_x. Determine P_x from the perfect-gas relation (eq. (20)).

Supercritical flow. - For supercritical flow, the film thickness h is greater than h^*. The boundary conditions for this type of flow are as follows:

$$\text{Exit Mach number } M_2 = 1$$

$$L = \Delta R$$

Again, the model equations cannot be solved explicitly. Start the implicit solution by guessing a value for M_1. Calculate T_1 and P_1 from the entrance equations (18) and (19). Calculate ρ_1 from the perfect-gas relation (eq. (20)) and u_1 from the definition of the Mach number (eq. (17)). Calculate the Reynolds number from equation (16). Use this Reynolds number to determine the friction factor $\bar{f}$. Substitute for h and $\bar{f}$ at $x = 0$ in equation (9), which gives

$$\frac{4\bar{f}\,\Delta R}{D} = B_1 \tag{23}$$

Substituting the value of B_1 into equation (9) and solving for M by the method of iteration gives a new value for M_1. If the new and old values of M_1 are equal, the set of equations is solved. If not, use the new value of M_1 as the guess for M_1 and repeat the procedure until the two values for M_1 are equal. A block diagram for this scheme is shown in figure 6. The distribution of pressure, temperature, Mach number, velocity, density, and friction parameter B are found in the same way as for critical flow.

Subcritical (subsonic) flow. - For subcritical flow, the film thickness h is less than h^*. For this type of flow, the boundary conditions are as follows:

$$L = L_2 + \Delta R$$

$$P_2 = P_3$$

where L_2 is the distance from the end of the seal to the imaginary point of choking. The additional unknown parameter L_2, which depends on M_2, is zero in the two other types of flow. The flow lengths involved in this type of flow are shown in figure 4.

As before, the set of equations in the model for subcritical flow cannot be solved explicitly. The implicit solution is similar to that for supercritical flow. Start by guessing M_1; then calculate T_1, P_1, ρ_1, u_1, Re, and $\bar{f}$. Now, however, calculate $B_1 = B(M_1)$ from equation (9). Calculate L from equation (9) at $x = 0$

$$L = \frac{B_1 D}{4\bar{f}} \tag{29}$$

From the second boundary condition, calculate L_2,

$$L_2 = L - \Delta R \tag{30}$$

Calculate B_2 from equation (9)

$$B_2 = \frac{4\bar{f}}{D} L_2 \tag{31}$$

Substitute B_2 into equation (9)

$$B_2 = B(M_2) \tag{32}$$

and solve equation (32) for M_2 by the method of iteration. Calculate P^* for M_1 from equation (14) and P_2 from equation (14) for P^* and M_2. If P_2 and P_3 are equal, that is, if the second boundary condition is satisfied, the set of equations is solved. If they are not equal, a new M_1 must be guessed and the procedure must be repeated. The successive values of M_1 and P_2 are saved, and the correct value of M_1 is determined graphically for $P_2 = P_3$. On the computer, a curve-fitting scheme is used to determine the correct M_1 from the stored values of M_1 and P_2. Figure 7 shows a detailed block diagram of this calculation scheme. The distributions, across the seal face, of pressure, temperature, Mach number, velocity, density, and friction parameter are determined the same way as for critical flow.

COMPUTER PROGRAM

The program QUASC which performs the analysis of quasi-one-dimensional compressible flow with friction across shaft face seals and narrow slots is written in FORTRAN IV for the computer at the Lewis Research Center. This computer is an IBM 7094II/7044 direct couple computer using IBSYS version 13.

QUASC is applicable for the type of seals shown in figures 1 and 2 and for narrow slots. The program must be supplied with the geometry of the seal, gas properties, reservoir conditions, constants for determining the variation of mean friction factor with Reynolds number, and certain logical variables which control output and plotting. Input and output can be in either the International System of Units (SI) or the U. S. customary system of units.

Automatic plotting of some of the output variables is an available option. The version of QUASC in use at the Lewis Research Center uses the DD80 microfilm plotter (ref. 3). Users of other computing systems would have to adapt that part of the program to fit the equipment available.

In general, QUASC 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, QUASC determines the minimum film thickness for choked flow h^*. Then, for each given film thickness h, QUASC determines which type of flow is associated with this h, that is, which solution of the equations is required as described in the section Solution of Equations (subsonic, critical, or supercritical).

When the type of flow has been determined, QUASC calculates the following parameters: entrance Mach number; mean friction factor; Reynolds number; distributions, across the seal face, of pressure, temperature, density, velocity, Mach number, and friction parameter $4\bar{f}(L - x)/D$; mass and volume flow rates; Knudsen number; sealing dam 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 for all the given film thicknesses, QUASC writes the output data with appropriate labels and headings.

To increase program efficiency and to facilitate program writing, QUASC includes a number of subprograms. Figure 8 shows the hierarchy of the subprogram calls. Variables are transmitted between the main program and the subprograms through labeled COMMON storage.

A more detailed description of QUASC and descriptions of the subprograms are found in appendix D.

The formulas for many of the parameters calculated by QUASC are listed in table I. Not listed are the formulas for h^*, M_1, $\bar{f}$, and Re, which are discussed in detail in the section Solution of Equations. It should be noted that when the flow is in 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 found in the program listing in appendix E. More details on the numerical integration by Simpson's rule, which is used to find the sealing dam force and center of pressure, and on the numerical differentiation, used to find film stiffness, are found in appendix D.

REMARKS ON ADDITIONAL PARAMETERS CALCULATED BY COMPUTER PROGRAM

As previously stated the program will calculate rotational Reynolds number, variables associated with power dissipation, and axial film stiffness. These additional parameters can be useful in selecting the seal design and seal operating design gap.

The rotational Reynolds number is determined by using the gap as the characteristic length, since gap film seals generally operate with merged rotational boundary layers

$$Re_{rot} = \frac{\bar{\rho} V h}{\bar{\mu}}$$

The Knudsen number can be found from (ref. 4)

$$Kn = \frac{\text{Molecular mean free path}}{\text{Mean film thickness}} \cong \frac{2.96\ M_{max}}{Re}$$

Under conditions of very small film thicknesses, the Knudsen number may be greater than 0.01, and this continuum analysis would no longer be valid. (In that case, a slip flow analysis must be used.)

The total power is found by considering the viscous shear due to rotation only

$$\text{Power} = \bar{R}\Omega \times \text{Shear force} = \frac{\bar{R}^2\Omega^2\mu}{h} \int_A dA = \frac{\mu\bar{R}^2\Omega^2 A}{h}$$

where $\bar{R}\Omega$ is the mean rotational velocity.

A rough estimate of the gas temperature rise through the film can be found by assuming that all the energy dissipated by viscous shear is added to the gas film:

$$T_{film,av} - T = \frac{\mu\bar{R}^2\Omega^2 A}{hc_p M}$$

This calculated film temperature rise will be higher than actually occurs since the predominant mode of heat transfer, conduction by the walls, is neglected.

INPUT DATA

Input to QUASC is by punched cards. The NAMELIST feature of FORTRAN IV is used to read data pertaining to the seal, the gas properties, and the reservoir conditions. The feature allows the individual variables to be named and eliminates complicated card formats. Also, it permits changing just a few variables on each READ statement, which keeps data cards at a minimum in parametric studies of candidate seal designs.

The first card required by QUASC 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 QUASC contain the parameters in NAMELIST/SDATA/. Variables in /SDATA/ are listed in table II. When the data from NAMELIST/SDATA/ have been read, QUASC checks the value of SKPH. If SKPH is . FALSE. , cards with film thickness data are needed. The first card contains the variable NJ, which is the number of film thicknesses. It must be in the first three columns of the card in format (I3). Then there must be NJ film thicknesses punched six to a card in format (6F12. 6).

The next cards required contain the variables from NAMELIST/PDATA/. The variables in /PDATA/ are listed in table III.

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 F.

Page one 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 seal face area and gas constant; a list of what optional parameters will be calculated, namely power, normalized force and center of pressure, and distributions across the seal face; and a list of parameters that will be plotted. The legend at the bottom of the page identifies the flow regime associated with a particular film thickness. The legend is as follows:

- * indicates the critical film thickness
- \+ indicates the flow is in the laminar-turbulent transitional regime
- / indicates the flow is in the turbulent regime

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

Page three and the following pages contain lists of parameters that vary with radial distance, namely, pressure, Mach number, friction parameter $4\bar{f}L/D$, density, velocity, and temperature. The film thickness to which each set of lists pertains is printed above the lists.

SAMPLE PROBLEM

An example of the use of the computer program is given here with the following conditions: Air at 4.48×10^5 N/m^2 (65.0 psia) is to be sealed from ambient air at 1.03×10^5 N/m^2 (15.0 psia) by a seal operating in the externally pressurized mode. The mean temperature of the pressurized air is 310.9 K (100° F). The sealing dam outside diameter is 0.1684 meter (6.630 in.), and the inside diameter is 0.1658 meter (6.530 in.). The design surface speed is 61 meters per second (200 ft/sec).

It is desired to find a design mean 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 2.54 to 25.4 micrometers (0.1 to 1.0 mils) in increments of 2.54 micrometers (0.1 mil). However, to give a sample output for transition flow and turbulent flow, the range of film thicknesses has been increased to 45.72 micrometers (1.8 mils). The output desired includes the mass and volume flow rates, sealing dam force due to the pressure drop, center of pressure, power loss, and approximate temperature rise due to shearing. A check on the validity of the analysis is made by examining the Knudsen number and the rotational flow Reynolds numbers. 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, kg/kg-mole (lbm/lb-mole)	28.9660 (28.9660)
Reservoir pressure (highest pressure), P_0, N/m^2 (psia)	4.48×10^{-5} (65.0)
Ambient pressure (lowest pressure), P_3, N/m^2 (psia)	1.03×10^{5} (15.0)
Specific heat at constant pressure, c_p, J/kg-K (Btu/lbm-$^{\circ}$R)	10^3 (0.24)
Film thickness (increase in increments of 2.54 μm (0.1 mil)), h, μm (mil)	2.54 to 45.72 (0.1 to 1.8)
Reservoir temperature, T_0, K ($^{\circ}$F)	310 (100)
Inner radius, R_1, m (in.)	0.0829 (3.265)
Flow length, m (in.)	1.29×10^{-3} (0.050)
Specific heat ratio, γ	1.4
k_l	24
n_l	1.00
k_t	0.079
n_t	0.25
Loss coefficient, C_L	1.00

The data sheet for this sample problem is given in table IV. The sample problem is shown in both SI and U.S. units. The choking film thickness is 13.104 micrometers (0.516 mil); film thicknesses of 27.94, 30.48, and 33.02 micrometers (1.1, 1.2, and 1.3 mils) are in the transition flow regime; and film thicknesses of 35.56 micrometers (1.4 mils) and greater are in the turbulent flow regime. The distributions of pressure, Mach number, friction parameter, density, radial velocity, and temperature are also shown. Plots (fig. 9) are shown for film thickness ratios and also for film thicknesses of 2.54, 13.1, and 45.72 micrometers (0.100, 0.516, and 1.80 mils). This problem ran in approximately 0.5 minute on the Lewis computer.

CONCLUDING REMARKS

A summary of the quasi-one-dimensional analysis of compressible flow with friction has been presented. Also, a detailed description of the computer program QUASC which performs this analysis is given. This computer program has proved to be very useful in seal design. An example mainshaft seal problem required about 0.5 minute to analyze 18 different film thickness conditions.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 29, 1972,
132-15.

APPENDIX A

SYMBOLS

A	area
B	friction parameter, $4\bar{f}(L - x)/D$
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	sealing dam force
$\bar{F}$	dimensionless sealing dam force
$\bar{f}$	mean Fanning friction factor
h	film thickness (gap)
k	numerical constant in friction factor - Reynolds number relation
Kn	Knudsen number
L	flow length from entrance to point of choking
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
P_w	wetted flow perimeter
Q	volume leakage flow rate
$\bar{R}$	mean radius
ΔR	sealing dam radial width (physical flow length), $R_2 - R_1$
$\mathscr{R}$	gas constant (universal gas constant/molecular weight)
Re	Reynolds number
Re(p)	Reynolds number of leakage flow (defined in table I)
Re(r)	Reynolds number of rotational flow (defined in table I)

r radius

T temperature

u leakage flow mean velocity (x-direction)

V mean rotational velocity

W flow width

x radial coordinate direction

x_c center of pressure

$\bar{x}_c$ dimensionless center of pressure

γ specific heat ratio

λ mean free path of gas molecules

μ absolute (dynamic) viscosity

ρ density

τ shear stress

Subscripts:

av average

l laminar flow

max maximum

rot rotational

t turbulent flow

w wetted surface area

x location along flow leakage length from entrance

0 sealed (reservoir) conditions

1 entrance conditions

2 exit conditions

3 ambient sump conditions

Superscript:

* critical flow condition

APPENDIX B

DERIVATIONS AND REMARKS

Transition Flow Friction Factor Derivation

For laminar flow

$$\bar{f} = k_l (Re)^{-n_l} \tag{B1}$$

For turbulent flow

$$\bar{f} = k_t (Re)^{-n_t} \tag{B2}$$

Equations (B1) and (B2) are straight lines when plotted on logarithmic graph paper.

Taking logs (to any arbitrary base) we have $\log \bar{f} = \log k_l - n_l \log Re$ and $\log \bar{f} = \log k_t - n_t \log Re$. Define $x = \log Re$ and $y = \log \bar{f}$. Therefore, for laminar flow, $y = \log k_l - n_l x$ and for turbulent flow, $y = \log k_t - n_t x$.

Let x_1 be the value of x such that flow is laminar for $x \leq x_1$. Let x_2 be the value of x such that flow is turbulent for $x \geq x_2$. Note that in general $x_1 \neq x_2$. To smooth the discontinuity between x_1 and x_2, define a new function y

$$y = ax^3 + bx^2 + cx + d$$

subject to the constraints

$$y\big|_{x_1} = \log k_l - n_l x_1$$

$$y\big|_{x_2} = \log k_t - n_t x_2$$

$$\left.\frac{dy}{dx}\right|_{x_1} = \left.\frac{dy}{dx}\right|_{x_2} = 0$$

These constraints result in four linear equations in a, b, c, and d which can be solved simultaneously. These equations are

$$ax_1^3 + bx_1^2 + cx_1 + d = \log k_l - n_l x_1$$

$$ax_2^3 + bx_2^2 + cx_2 + d = \log k_t - n_t x_2$$

$$3ax_1^2 + 2bx_1 + c = 0$$

$$3ax_2^2 + 2bx_2 + c = 0$$

The determinant of these equations is nonzero; and the solution for a, b, c, and d gives y as

$$y = \log k_t - n_t x_2 - \frac{2\left[\log(k_t/k_l) + (n_l x_1 - n_t x_2)\right]\left[x^3 - 3/2\, x^2(x_1 + x_2) + 3x_1 x_2 x - 1/2\, x_2^2(3x_1 - x_2)\right]}{(x_2 - x_1)^3}$$

Comment on Solution of Mach Number Equation for Critical Flow

It was mentioned in the main text that equation (23) does not always have a solution. To illustrate, if equation (23) is rewritten as

$$g(M_1) = -\sqrt{\frac{\gamma + 1}{2}}\,\frac{1}{M_1}\,\frac{\left[1 + \frac{1}{2}(\gamma - 1)(M_1/C_L)^2\right]^{\gamma/(\gamma-1)}}{\left[1 + \frac{1}{2}(\gamma - 1)M_1^2\right]^{1/2}} + \frac{P_0}{P_3} = 0 \qquad \text{(B3)}$$

and plotted for $P_0/P_3 = 3.0$, $\gamma = 1.4$, and $C_L = 0.8$, it is obvious that $g(M_1)$ does not cross the M_1-axis and, hence, does not have a solution in the range of acceptable M_1's (see fig. 10).

APPENDIX C

DETAILS OF NUMERICAL TECHNIQUES USED IN PROGRAM

Method of Iteration

This method is a standard numerical analysis technique that is used for finding the roots of an equation. It consists of writing an equation

$$g(x) = 0 \tag{C1}$$

in the form

$$x = G(x) \tag{C2}$$

Any x which satisfies equation (C2) is a root of equation (C1).

Equation (9) in the main text is an equation whose roots must be found numerically, so it can be used to illustrate the method of iteration. Equation (9) can be written as

$$g(M) = \frac{1}{\gamma}\frac{1 - M^2}{M^2} + \frac{\gamma + 1}{2\gamma}\ln\left[\frac{\frac{1}{2}(\gamma + 1)M^2}{1 + \frac{1}{2}(\gamma - 1)M^2}\right] - B = 0 \tag{C3}$$

where B is a constant

$$B = \frac{4\bar{f}(L - x)}{2h} \tag{C4}$$

Rewriting equation (C3) so it is in the form of equation (C2) gives

$$M = G(M) = \left\{\frac{1 - M^2}{\gamma B - \frac{1}{2}(\gamma + 1)\ln\left[\frac{\frac{1}{2}(\gamma + 1)M^2}{1 + \frac{1}{2}(\gamma - 1)M^2}\right]}\right\}^{1/2} \tag{C5}$$

The first step in finding an M which will satisfy equation (C5) is to guess a value for M. Then it must be substituted in G(M), which will give a new value for M. If the two values of M agree, the equation is satisfied. If they do not, the new value of M is substituted in G(M) to give yet another value for M. This procedure is repeated until M = G(M). Table V gives the steps in the solution of equation (C3) by the method of iteration for $\gamma = 1.4$, B = 1, and an initial guess for M of 0.1. By examining a plot of g(M) against M, as shown in figure 11, it is readily observed that g(M) crosses the M-axis at M = 0.5087. Hence, M = 0.5087 is a root of g(M).

The program QUASC uses the method of iteration to solve equations such as equation (C3).

Numerical Differentiation for Film Stiffness

The differentiation required for the calculation of axial film stiffness, -dF/dh, is performed numerically by Lagrange's method (ref. 5). The general formula for Lagrange differentiation is

$$L'(x) = \sum_{i=0}^{n} L_i'(x) y_i$$

where

$$L_i'(x) = \frac{P_i(x)}{P_i(x_i)} \left(\sum_{\substack{j=0 \\ j \neq i}}^{n} \frac{1}{x - x_j} \right)$$

and

$$P_i(x) = (x - x_i)^{-1} \prod_{j=0}^{n} (x - x_j)$$

For the special case of the derivative at one of the tabulated points x_k,

$$L'(x_k) = \prod_{\substack{j=0 \\ j \neq k}}^{n} (x_k - x_j) \left(\sum_{\substack{i=0 \\ i \neq k}}^{n} \frac{y_i}{D_{ik}} \right) + y_k \sum_{\substack{j=0 \\ j \neq k}}^{n} \frac{1}{x_k - x_j} \tag{C6}$$

where $D_{ik} = (x_k - x_i)P_i(x_i),\ i \neq k$.

Reference 5 describes a computing scheme which is followed in QUASC. A matrix is defined whose elements are $a_{ij} = x_i - x_j$. The product of the off-diagonal elements of each row is multiplied by $x_k - x_i$, except for the k^{th} row. This defines D_{ik}. The sum

$$\sum_{\substack{i=0 \\ i \neq k}}^{n} \frac{y_i}{D_{ik}}$$

is formed and multiplied by the product of the negative of the off-diagonal elements in the j^{th} column. This gives the first term in the formula. The second term is formed by summing the reciprocals of the off-diagonal elements in the k^{th} column and multiplying the sum by y_k.

Numerical Integration by Simpson's Rule

Simpson's rule is a common method of numerical integration. The formula is written

$$\int_{x_0}^{x_f} y\,dx = \frac{\Delta x}{6} \left[y(x_0) + 4y\left(x_0 + \frac{\Delta x}{2}\right) + y(x_f) \right] \tag{C7}$$

where $\Delta x = x_f - x_0$. The total interval of integration can be broken up into smaller subintervals. This is written as

$$\int_{x_0}^{x_f} y\,dx = \int_{x_0}^{x_2} y\,dx \int_{x_2}^{x_4} + \ldots + \int_{x_{f-2}}^{x_f} y\,dx$$

The total interval must be broken up into enough subintervals to ensure that the value of $\int_{x_0}^{x_f} y\,dx$ is accurate. The subroutine which does the numerical integration by Simpson's rule makes smaller subintervals where the value of the integrand is changing rapidly.

APPENDIX D

DETAILED DESCRIPTION OF PROGRAM

This section 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 section INPUT DATA or in the program listings.

Main Program QUASC

The main program QUASC 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 determine h^*; M_1; $\bar{f}$; Re; and the distributions across the seal face of pressure, temperature, density, velocity, Mach number, and friction parameter $4\bar{f}(L - x)/D$. It calculates the other parameters associated with the flow, such as mass flow rate, and writes the output. It then calls a subroutine to do the automatic plotting. QUASC then transfers to read new input data.

The labeled COMMON storage defined by QUASC contains constants needed by the subprograms and the output data. The variables in the COMMON blocks are listed in tables VI, VII, and VIII. The variable names and array names are not listed because the names are not the same in all the programs.

There are two kinds of parameters in the COMMON block /ARRAYS/ (table VII): one is the distributions across the face of the seal, the other includes some of the parameters that vary with film thickness. The arrays are dimensioned for 20 film thicknesses and 11 points across the seal face. The two exceptions are the distance array and the pressure array P. These are dimensioned for 101 points across the seal face. The finer mesh is necessary for the numerical integration of the pressure function in calculating force and center of pressure (see table VII).

The parameters in common block /CONVRT/ are the constants needed by the program for the internal calculations. The array CONV has dimension (12, 2). The first column contains constants for calculations in SI units. The second column contains constants for calculations in U. S. customary units. The variable IUNITS is 1 for SI units and 2 for U. S. units.

QUASC 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 R1IN, R2IN, and RDIFIN. Since only two are necessary, the third must be made consistent with the other two. The check is made as follows: If R1IN ≠ 0 and R2IN ≠ 0, QUASC sets R1 = R1IN and R2 = R2IN and then calculates RDIF = R2 - R1. If R1IN ≠ 0, R2IN = 0, and RDIFIN ≠ 0, QUASC sets R1 = R1IN and RDIF = RDIFIN and then calculates R2 = R1 + RDIF. If R1IN = 0, R2IN ≠ 0, and RDIFIN ≠ 0, QUASC sets R2 = R2IN and RDIF = RDIFIN and then calculates R1 = R2 - RDIF. Any other combination of R1IN, R2IN, and RDIFIN is considered an error since there is not enough information available to determine a nonzero flow length. If this error condition exists, QUASC writes a message and transfers to read new data from NAMELIST/SDATA/.

Another 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 P0IN ≠ 0 and P3IN ≠ 0, QUASC sets P0 = P0IN and P3 = P3IN and then calculates PRAT = P0/P3. If P0IN ≠ 0, P3IN = 0, and PRIN ≠ 0, QUASC sets P0 = P0IN and PRAT = PRIN and then calculates P3 = P0/PRAT. If P0IN = 0, P3IN ≠ 0, and PRIN ≠ 0, QUASC sets P3 = P3IN and PRAT = PRIN and then calculates P0 = PRAT*P3. Any other combination of P0IN, P3IN, and PRIN is considered an error. In that case, QUASC writes an error message and transfers to read new data according to the input code.

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

The final check for consistency is made on the logical variables. If any of the logical variables are set to .TRUE., which means a calculation is to be omitted, the corresponding element in the PLTSKP array must also be set to .TRUE.

QUASC also tests for pressure ratios which do not yield a solution to equation (23). In that case, the flow is assumed to be subcritical and h^* is set to 10^{30}.

For valid pressure ratios, QUASC determines the critical film thickness h^* by calling subroutine START. For other film thicknesses, QUASC compares h with h^*. If $h > h^*$, subroutine CHOKE is called to determine M_1, $\overline{f}$, and Re for supercritical flow. If $h < h^*$, subroutine NCHOKE is called to determine M_1, $\overline{f}$, and Re for subcritical flow. And subroutine DIST is called to calculate the distributions across the face of the seal. QUASC then calculates the other flow parameters. Function subprogram SIMPS2 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, QUASC calls subroutine STFNSS to determine the axial film stiffness.

When all the calculations are complete, QUASC writes the input data, the "checked" input data, and the output data with appropriate headings and labels. Then QUASC calls subroutine GRAFIC to do the automatic plotting.

The final command in the program is a transfer to read new input data.

Subroutine START

Subroutine START determines the critical film thickness h^* and M_1, $\bar{f}$, and Re(p) for h^*. It uses three arithmetic function statements which define P_1, T_1, and $4\bar{f}(L - x)/D$ (eqs. (19), (18), and (9)). The calculation scheme is described in the main text section Solution of Equations. There are some intermediate variables defined in the iteration procedure which are not mentioned in the solution of the equations. Their purpose is mainly to delineate the individual steps in the iterative solution.

Subroutine CHOKE

Subroutine CHOKE determines M_1, $\bar{f}$, and Re(p) for supercritical flow. It uses three arithmetic function statements which define P_1, T_1, and $4\bar{f}(L - x)/D$ (eqs. (19), (18), and (9)). The computing scheme is described in the section Solution of Equations. The iteration stops when $L = \Delta R$.

In the iteration to determine M_1, CHOKE saves three values of each L and M_1. It then does a linear curve fit (least squares) on the three points (L, M_1) and picks from the line a new value of M_1 that corresponds to $L = \Delta R$. This M_1 is used to generate a new L, which is checked against ΔR. If they are not equal, the point such that $|L - \Delta R|$ is largest is discarded and the new point is substituted for it. Then a new linear curve fit is made and the process is repeated until $|L - \Delta R| < 10^{-7}$

If the curve fit produces a new M_1 which is less than zero, M_1 is chosen to be one-half the smallest of the three existing M_1's.

As its final step, CHOKE calculates T^*, which will be needed in calculating the temperature distribution across the face of the seal.

Subroutine NCHOKE

Subroutine NCHOKE determines M_1, $\bar{f}$, and Re for subcritical flow. It uses five arithmetic function statements to define P_1, T_1, $4\bar{f}(L - x)/D$, P/P^*, and B_2 (eqs. (19), (18), (9), (14), and (32)). The computation scheme is described in the section Solution of Equations. The iteration stops when $P_2 = P_3$.

In its iteration, NCHOKE saves three values of each M_1 and P_2. It does a linear (least squares) curve fit on these three points (P_2, M_1) and picks from the line a new value of M_1 that corresponds to $P_2 = P_3$. Then a new P_2 is generated and checked against P_3. If they are not equal, the point such that $|P_2 - P_3|$ is largest is discarded and the new point is substituted for it. Then a new P_2 is calculated and the process is repeated until $|P_2 - P_3| < P_{tol}$.

A cut-off criterion of $P_{tol} = 5P_3 \times 10^{-6}$ is necessary because of roundoff errors on the computer. For the special cases of $h^* = 10^{30}$ and for h very close to h^* (approximately $|10^{-3}\ h^*|$), a three-point curve fit is not necessary. Two points were found to be sufficient for the straight-line curve fit since the Mach numbers involved are very low.

The values of M_1 used are screened systematically by the subroutine. If M_1 generates an $L < \Delta R$, M_1 is lowered by ΔM_1 until an M_1 is found which will produce an $L > \Delta R$.

The final calculation in NCHOKE determines T^*, which is needed in calculating the temperature distribution across the face of the seal.

Subroutine DIST

Subroutine DIST determines the distributions of pressure, temperature, density, Mach number, velocity, and friction parameter $4\bar{f}(L - x)/D$ across the face of the seal. The subroutine uses two arithmetic function statements to define T_1 and B_2 (eqs. (18) and (32)). The computation scheme is described in the section Solution of Equations.

Pressure is calculated at 101 points since a fine mesh is needed for the numerical integration in the force and center-of-pressure equations. The other parameters are calculated at 11 points across the face of the seal.

Subroutine STFNSS

Subroutine STFNSS performs the numerical differentiation of force with respect to film thickness, which gives the axial film stiffness.

There are four regions in which the differentiation is performed. These four regions are for subcritical laminar flow, subcritical turbulent flow, supercritical laminar flow, and supercritical turbulent flow. The four regions are necessary because the force varies differently with film thickness for the different types of flow. The axial film stiffness in the transition region is not computed because the exact values of the sealing dam force are unknown.

The subroutine first arranges the data in order of ascending x. It chooses the five data points x_i, y_i ($i = k - 2,\ k - 1,\ k,\ k + 1,\ k + 2$) for use in equation (C6). If there are less than five data points in the set, all are used in the differentiation.

The computation scheme for STFNSS is described in detail in appendix B.

Subroutine SIMPS2

Function subprogram SIMPS2 uses Simpson's rule to evaluate the integrals in the force and center-of-pressure equations. A statement such as

F = SIMPS2(J, XO, XF, G, K)

gives F as the definite integral

$$F = \int_{XO}^{XF} G(J,\ x)dx$$

The integrand is evaluated at interior points by the function subprogram G names in the calling vector. The parameter J is a constant needed by G. In the case of QUASC, J is the index of the film thickness being examined.

The range of the integration is not divided uniformly. More subdivisions are made in the region where the integrand is changing rapidly. If SIMPS2 cannot evaluate the integral to an accuracy of 10^{-5} times the value of the integrand with 200 subdivisions, the parameter K is raised by 2 to indicate the integral is inaccurate.

Subroutines FFUNC and XCFUNC

Function subprogram FFUNC evaluates the integrand in the force equation. Function subprogram XCFUNC evaluates the integrand in the center-of-pressure equation. Both FFUNC and XCFUNC call subroutine PRESS to evaluate the pressure for the j^{th} film thickness at any distance x across the seal face.

Subroutine PRESS

Function subprogram PRESS uses a three-point Lagrange interpolation to determine the pressure at any distance x across the face of the seal. One-hundred and one values of x and P are stored for this interpolation. Subprogram PRESS first searches the x array to find the three stored values of x closest to the given x and then uses these three points in the interpolation.

Subroutine GRAFIC

Subroutine GRAFIC makes the following plots:

(1) Power against film thickness

(2) Center of pressure against film thickness

(3) Force against film thickness

(4) Pressure against x

(5) Temperature against x

(6) Density against x

(7) Mach number against x

(8) Friction parameter $4\bar{f}(L - x)/D$ against x

All the plots are dimensionless. The film thickness is normalized by the maximum h. Radial coordinate direction x is normalized by ΔR. Power is normalized by the maximum power. Center of pressure is normalized by ΔR. Force is normalized by $(P_0 - P_3)\Delta R\pi\bar{R}$. Pressure is normalized by P_0. Temperature is normalized by T_0. Density is normalized by $\rho_0 = P_0/RT_0$. Mach number and friction parameter are already dimensionless.

The subroutine presented here is just a skeleton. It has no commands that will produce plots. Each user can add the plotting commands appropriate to the equipment available. The subroutine does, however, include commands for the normalization of the plotting parameters and labels for the plots as they appear in this report.

Subroutine SORT

Subroutine SORT 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.

APPENDIX E

PROGRAM LISTING AND FLOW CHARTS

```
C
C      PROGRAM FOR QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW WITH FRICTION
C      AND PARALLEL FILMS
C
C
C      INPUT VARIABLES
C      ***************
C
C       TITLE - ALPHA-NUMERIC IDENTIFICATION OF THE DATA
C
C        R1IN - INNER RADIUS OF SEAL
C        R2IN - OUTER RADIUS OF SEAL
C      RDIFIN - FLOW LENGTH
C       WIDTH - FLOW WIDTH
C       MOLWT - MOLECULAR WEIGHT
C          CP - SPECIFIC HEAT
C          MJ - RESERVOIR VISCOSITY
C       GAMMA - RATIO OF SPECIFIC HEATS
C       SPEED - ROTATIONAL SPEED
C        CAPV - SURFACE VELOCITY
C        XLAM - EXPONENT IN RE - F RELATION FOR LAMINAR FLOW
C      CONLAM - CONSTANT IN RE - F RELATION FOR LAMINAR FLOW
C       XTURB - EXPONENT IN RE - F RELATION FOR TURBULENT FLOW
C      CONTRB - CONSTANT IN RE - F RELATION FOR TURBULENT FLOW
C       RELAM - UPPER LIMIT OF REYNOLDS NUMBER FOR LAMINAR FLOW
C      RETURB - LOWER LIMIT OF REYNOLDS NUMBER FOR TURBULENT FLOW
C      PWRSKP - LOGICAL VARIABLE. IF TRUE, SKIP POWER CALCULATIONS
C      NRMSKP - LOGICAL VARIABLE. IF TRUE, SKIP NORMALIZATION OF FORCE
C                  AND CENTER OF PRESSURE
C      PRSSKP - LOGICAL VARIABLE. IF TRUE, SKIP PRINTOUT OF DISTRIBUTIONS
C      PLTSKP - LOGICAL ARRAY. IF TRUE, SKIP THE APPROPRIATE PLOT
C                  PLTSKP(1) -  POWER VS FILM THICKNESS
C                  PLTSKP(2) -  CENTER OF PRESSURE VS FILM THICKNESS
C                  PLTSKP(3) -  FORCE VS FILM THICKNESS
C                  PLTSKP(4) -  PRESSURE VS DISTANCE ACROSS SEAL
C                  PLTSKP(5) -  TEMPERATURE VS DISTANCE ACROSS SEAL
C                  PLTSKP(6) -  DENSITY VS DISTANCE ACROSS SEAL
C                  PLTSKP(7) -  MACH NUMBER VS DISTANCE ACROSS SEAL
C                  PLTSKP(8) - 4FL/D VS DISTANCE ACROSS SEAL
C        SKPH - LOGICAL VARIABLE. IF TRUE, SKIP READING OF FILM THICKNESS
C                  DATA
C        NOSI - LOGICAL VARIABLE. IF TRUE, INPUT AND OUTPUT ARE IN U.S.
C                  CUSTOMARY UNITS. IF FALSE, INPUT AND OUTPUT ARE IN
C                  INTERNATIONAL UNITS.
C
C          NJ - NUMBER OF FILM THICKNESS IN ADDITION TO H*
C           H - ARRAY OF FILM THICKNESS
C
C        POIN - SUPPLY PRESSURE
C        P3IN - AMBIENT PRESSURE
C        PRIN - SUPPLY TO AMBIENT PRESSURE RATIO
```

```
C         TOIN - TOTAL TEMPERATURE
C         LOSS - VELOCITY LOSS COEFFICIENT
C       INCODE - INPUT CODE
C                   INCODE = 1 MEANS TRANSFER TO READ NEW TITLE CARD
C                   INCODE = 2 MEANS TRANSFER TO READ NEW FILM THICKNESS
C                              DATA
C                   INCODE = 3 MEANS TRANSFER TO READ NEW RESERVOIR DATA
C
C       OUTPUT VARIABLES
C       ****************
C
C           R1 - INNER RADIUS OF SEAL
C           R2 - OUTER RADIUS OF SEAL
C         RDIF - FLOW LENGTH, R2-R1
C           PO - SUPPLY PRESSURE
C           P3 - AMBIENT PRESSURE
C         PRAT - PRESSURE RATIO, PO/P3
C           TO - TOTAL TEMPERATURE
C         AREA - SURFACE AREA OF SEAL
C         RGAS - GAS CONSTANT
C
C         MDOT - MASS FLOW RATE
C            Q - VOLUME FLOW RATE
C           KN - KNUDSEN NUMBER
C        LAMDA - MEAN FREE PATH OF GAS MOLECULES
C        STIFF - AXIAL FILM STIFFNESS
C        FORCE - SEALING DAM FORCE
C           XC - CENTER OF PRESSURE
C        XCBAR - NORMALIZED CENTER OF PRESSURE
C         FBAR - NORMALIZED FORCE
C        FRICT - MEAN FRICTION FACTOR
C          REP - PRESSURE REYNOLDS NUMBER
C          RER - ROTATIONAL REYNOLDS NUMBER
C        PSTAR - PRESSURE AT POINT OF CHOKING
C        LSTAR - DISTANCE FROM ENTRANCE TO POINT OF CHOKING
C        POWER - POWER DUE TO VISCOUS SHEARING
C       HSHEAR - SHEAR HEAT
C         DELT - APPARENT TEMPERATURE RISE DUE TO POWER DISSIPATION
C       TORQUE - TORQUE DUE TO POWER
C
C            X - DISTANCE ACROSS SEAL
C            P - PRESSURE DISTRIBUTION ACROSS SEAL
C         MACH - MACH NUMBER DISTRIBUTION ACROSS SEAL
C           FF - FRICTION PARAMETER 4FL/D DISTRIBUTION ACROSS SEAL
C          RHO - DENSITY DISTRIBUTION ACROSS SEAL
C            V - VELOCITY DISTRIBUTION ACROSS SEAL
C            T - TEMPERATURE DISTRIBUTION ACROSS SEAL
C         CALC - ARRAY OF LABELS
C
C       PROGRAM VARIABLES
C       *****************
C
C            C - PERMANENTLY STORED ARRAY OF LABELS
C           PI - 3.1415927
C        RUNIV - UNIVERSAL GAS CONSTANT
C
C         TEMP - TEMPORARY STORAGE FOR A CONSTANT
C        CRITM - MACH NUMBER FOR WHICH P3/PO IS A MAXIMUM
C           CC - TEMPORARY STORAGE IN COMPUTING CRITICAL PRESSURE RATIO
```

```
C      PRCRIT - PRESSURE RATIO THAT CORRESPONDS TO CRITM = MAXIMUM
C                    PRESSURE RATIO FOR WHICH EQ. 23 HAS A SOLUTION
C
C           N - CHARACTERISTIC OF LOG(10) OF P3
C        PTOL - TOLERANCE FOR ROUND-OFF ERROR IN ITERATIVE SOLUTION OF
C                    EQUATIONS FOR SUB-CRITICAL FLOW
C        DELX - STEP SIZE ACROSS FACE OF SEAL
C
C         MUM - VISCOSITY AT MID-SEAL
C           K - INDICATOR THAT NUMERICAL INTEGRATION IN FORCE CALCULATION
C                    IS INACCURATE
C          KK - INDICATOR THAT NUMERICAL INTEGRATION IN CENTER OF
C                    PRESSURE CALCULATION IS INACCURATE
C           J - FILM THICKNESS INDEX
C                    H(J=1) IS THE CRITICAL FILM THICKNESS H*
C
      REAL MOLWT,MDOT,KN,LAMDA,MUM,MACH,LSTAR,LOSS
      LOGICAL PWRSKP,NRMSKP,PRSSKP,PLTSKP(8),SKPH,NOSI
      REAL MU
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1       RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2       REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
      COMMON/CONSTS/GAMMA,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
     1       RGAS,LOSS,RELAM,RETURB,MU,TSTAR
      COMMON/CONVRT/CONV(12,2),IUNITS
      NAMELIST/SDATA/R1IN,R2IN,RDIFIN,WIDTH,MOLWT,CP,MU,GAMMA,SPEED,
     1       CAPV,XLAM,CONLAM,XTURB,CONTRB,RELAM,RETURB,PWRSKP,NRMSKP,
     2       PRSSKP,PLTSKP,SKPH,NOSI
      NAMELIST/PDATA/POIN,P3IN,PRIN,TOIN,LOSS,INCODE
      DIMENSION TITLE(12),C1(4),C2(4),C3(4),C4(4),C5(4),C6(4),C7(4)
      DIMENSION CALC(7,4),RUNIV(2),MDOT(20),Q(20),KN(20),LAMDA(20),
     1       RER(20),DELT(20),HSHEAR(20),TORQUE(20),XC(20)
      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     4,6HFL/D  /
      DATA BLANK/6H      /
      DATA PI,RUNIV(1),RUNIV(2)/ 3.1415927, 8.31436E3, 1545.4 /
      EXTERNAL FFUNC,XCFUNC
      MU = 0.
C
C     READ INPUT DATA - SEAL IDENTIFICATION
C                       SEAL DIMENSIONS, PLOTTING CODES, PHYSICAL
C                            PROPERTIES OF GAS
C                       SEVERAL GAPS BETWEEN PLATES
C
  100 READ (5,1) TITLE
      READ (5,SDATA)
      IUNITS=1
      IF(NOSI) IUNITS=2
C
C     CHECK CONSISTANCY OF SEAL DIMENSIONS AND LOGICAL VARIABLES
C
      IF(R1IN.EQ.0.) GO TO 101
      IF(R2IN.EQ.0.) GO TO 102
      R1 = R1IN
```

```
      R2 = R2IN
      RDIF= R2-R1
      GO TO 104
C
  101 IF(R2IN.EQ.0.)  GO TO 103
      IF (RDIFIN.EQ.0.)   GO TO 103
      RDIF= RDIFIN
      R2 = R2IN
      R1 = R2-RDIF
      GO TO 104
C
  102 IF (RDIFIN.EQ.0.)   GO TO 103
      RDIF= RDIFIN
      R1 = R1IN
      R2 = R1+RDIF
      GO TO 104
C
  103 WRITE (6,32) R1IN,R2IN,RDIFIN
      IF (S<PH)   GO TO 106
      READ (5,2) NJ
      NJ = NJ+1
      IF (NJ.GT.1)   READ (5,3) (H(J),J=2,NJ)
  106 READ (5,PDATA)
      GO TO 700
C
  104 IF(NRMSKP)  PLTSKP(3)= .TRUE.
      IF(.NOT.PRSSKP)  GO TO 110
      DO 105 I=4,8
  105 PLTSKP(I)= .TRUE.
C
  110 IF (SKPH)   GO TO 120
      READ (5,2) NJ
      NJ = NJ+1
      IF (NJ.GT.1)   READ (5,3) (H(J),J=2,NJ)
  120 READ (5,PDATA)
      H(1)= 1.E-3
      IF (NJ.LT.2)   GO TO 130
      DO 125 J=2,NJ
  125 H(1) = AMIN1(H(1),H(J))
      DEBUG H(1)
C
C     WRITE INPUT DATA
C
  130 WRITE (6,10) TITLE
      IF(NOSI) WRITE(6,11) R1IN,POIN,MOLWT,R2IN,P3IN,CP,CONLAM,RDIFIN,
     1       PRIN,GAMMA,XLAM,WIDTH,TOIN,MU,RELAM,LOSS,SPEED,CONTRB,CAPV,
     2       XTURB,RETURB
      IF(.NOT.NOSI) WRITE(6,13) R1IN,POIN,MOLWT,R2IN,P3IN,CP,CONLAM,
     1       RDIFIN,PRIN,GAMMA,XLAM,WIDTH,TOIN,MU,RELAM,LOSS,SPEED,
     2       CONTRB,CAPV,XTURB,RETURB
C
C     CHECK CONSISTANCY OF PRESSURE DATA
C
  200 IF (POIN.NE.0.)   GO TO 240
      IF (P3IN.NE.0.)   GO TO 210
      WRITE (6,30)
      GO TO (100,110,120),INCODE
C
  210 IF (PRIN.NE.0.)   GO TO 230
```

```
  220 WRITE (6,31) POIN,P3IN
      GO TO (100,110,120),INCODE
C
  230 PO = PRIN*P3IN
      P3 = P3IN
      PRAT = PRIN
      GO TO 260
C
  240 IF (P3IN.NE.0.)   GO TO 250
      IF (PRIN.EQ.0.)   GO TO 220
      P3 = POIN/PRIN
      PO = POIN
      PRAT = PRIN
      GO TO 260
C
  250 PO = POIN
      P3 = P3IN
      PRAT = PO/P3
C
C     CALCULATE CRITICAL PRESSURE RATIO
C     H* CANNOT BE DETERMINED FOR P3/PO(GIVEN) GREATER THAN P3/PO
C     (CRITICAL) - I.E., EQ. 23 DOES NOT HAVE A SOLUTION
C     ASSUME NON-CHOKED FLOW FOR THIS CONDITION
C
  260 IF (GAMMA.EQ.1.)   GO TO 300
      TEMP = (GAMMA+1.)/2./(GAMMA-1.)
      CRITM = SQRT(LOSS**2-TEMP+SQRT(TEMP**2+LOSS**2*(LOSS**2-1.)))
      CC = CRITM*SQRT(1.+.5*(GAMMA-1.)*CRITM**2)/(LOSS**2+.5*(GAMMA-1.)
     1       *CRITM**2)**(GAMMA/(GAMMA-1.))
      PRCRIT = CC*SQRT(2./(GAMMA+1.))*LOSS**(2.*GAMMA/(GAMMA-1.))
      IF(P3/PO.LT.PRCRIT)  GO TO 300
      WRITE (6,56)   PO,P3,GAMMA,LOSS
      H(1) = 1.E30
C
C            WRITE PROGRAM CONSTANTS AND RESERVOIR CONDITIONS
C
  300 RGAS = RUNIV(IUNITS)/MOLWT
      TO = TOIN+CONV(1,IUNITS)
C
C     FOR AIR, CALCULATE RESERVOIR VISCOSITY FROM SUTHERLANDS FORMULA
C
      IF(GAMMA.EQ.1.4) MU=CONV(2,IUNITS)*TO**1.5/(TO+CONV(3,IUNITS))
      TO = TO-CONV(1,IUNITS)
      N = ALOG10(P3)
      PTOL = 5.*10.**(N-6)
      IF (SPEED.EQ.0.)  GO TO 330
      CAPV= PI*SPEED*(R1+R2)/CONV(4,IUNITS)
      GO TO 340
  330 IF (CAPV.EQ.0.)   GO TO 335
      SPEED= CONV(4,IUNITS)*CAPV/PI/(R2+R1)
      GO TO 340
  335 PWRSKP = .TRUE.
      CP = 0.
  340 IF (PWRSKP)   PLTSKP(1)=.TRUE.
      AREA = PI*(R2**2-R1**2)
      IF (WIDTH.EQ.0.)   WIDTH=PI*(R1+R2)
      DELX = RDIF/100.
      DO 350 I=1,101
  350 X(I) = FLOAT(I-1)*DELX
      IF (PWRSKP)   PLTSKP(1)=.TRUE.
```

```
C
      DO 360  I=1,7
      DO 360  J=1,4
  360 CALC(I,J)= BLANK
      DO 380  I=1,7
      GO TO (361,362,363,364,365,366,367),I
  361 IF(PWRSKP)  GO TO 380
      DO 1361  J=1,4
 1361 CALC(I,J)= C1(J)
      GO TO 380
  362 IF(NRMSKP)  GO TO 380
      DO 1362  J=1,4
 1362 CALC(I,J)= C2(J)
      GO TO 380
  363 IF(PRSSKP)  GO TO 380
      DO 1363  J=1,4
 1363 CALC(I,J)= C3(J)
      GO TO 380
  364 IF(PLTSKP(1))  GO TO 1364
      CALC(I,1)= C4(1)
      CALC(I,2)= C4(2)
 1364 IF(PLTSKP(2))  GO TO 380
      CALC(I,3)= C4(3)
      CALC(I,4)= C4(4)
      GO TO 380
  365 IF(PLTSKP(3))  GO TO 1365
      CALC(I,1)= C5(1)
      CALC(I,2)= C5(2)
 1365 IF(PLTSKP(4))  GO TO 380
      CALC(I,3)= C5(3)
      CALC(I,4)= C5(4)
      GO TO 380
  366 IF(PLTSKP(5)) GO TO 1366
      CALC(I,1)= C6(1)
      CALC(I,2)= C6(2)
 1366 IF(PLTSKP(6)) GO TO 380
      CALC(I,3)= C6(3)
      CALC(I,4)= C6(4)
      GO TO 380
  367 IF(PLTSKP(7))  GO TO 1367
      CALC(I,1)= C7(1)
      CALC(I,2)= C7(2)
 1367 IF(PLTSKP(8)) GO TO 380
      CALC(I,3)= C7(3)
      CALC(I,4)= C7(4)
  380 CONTINUE
C
      IF(NOSI) WRITE(6,12) R1,PO,MOLWT,(CALC(1,I),I=1,4), R2,P3,CP,
     1      (CALC(2,I),I=1,4),RDIF,PRAT,GAMMA,(CALC(3,I),I=1,4),WIDTH,
     2      TO,MU,(CALC(4,I),I=1,4),AREA,RGAS,SPEED,(CALC(5,I),I=1,4),
     3      LOSS,CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4)
      IF(.NOT.NOSI) WRITE(6,14) R1,PO,MOLWT,(CALC(1,I),I=1,4),R2,P3,CP,
     1      (CALC(2,I),I=1,4),RDIF,PRAT,GAMMA,(CALC(3,I),I=1,4),WIDTH,
     2      TO,MU,(CALC(4,I),I=1,4),AREA,RGAS,SPEED,(CALC(5,I),I=1,4),
     3      LOSS,CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4)
C
      TO = TO + CONV(1,IUNITS)
C
C     H(1) IS H*, THE CRITICAL FILM THICKNESS.  CALCULATE IT FIRST.
```

```
C     IF H(J) IS GREATER THAN H*, ASSUME CHOKED FLOW.  IF H(J) IS LESS
C     THAN H*, ASSUME NON-CHOKED FLOW.
C
  400 DO 470 J=1,NJ
      IF (J.NE.1)   GO TO 410
      IF (H(1).GE.1.E30)   GO TO 470
      CALL START
      IF(H(1) .LT. 1.E30) GO TO 415
      GO TO 470
  410 IF (H(J).GT.H(1))   GO TO 420
  412 CALL NCHOKE(J)
      GO TO 415
  420 CALL CHOKE(J)
  415 CALL DIST(J)
C
  440 MDOT(J) = WIDTH*H(J)*RHO(J,1) * V(J,1)*CONV(5,IUNITS)
      Q(J)= MDOT(J)*CONV(6,IUNITS)
      KN(J)  = 2.96*MACH(J,11)/REP(J)
      LAMDA(J) = KN(J)*H(J)
      MUM = MU
      IF(GAMMA.EQ.1.4)  MUM=CONV(2,IUNITS)*(T(J,6)+CONV(1,IUNITS))**1.5
     1       /(T(J,6)+CONV(1,IUNITS)+CONV(3,IUNITS))
      RER(J)= RHO(J,6)*CAPV*H(J)/MUM*2./CONV(7,IUNITS)
      IF (PWRSKP)        GO TO 460
C
C     CALCULATE POWER, SHEAR HEAT, TORQUE, AND TEMPERATURE RISE DUE TO
C     POWER DISSIPATION
C
      IF(REP(J).LE.RELAM)  POWER(J)=MUM*AREA*CAPV**2/H(J)*CONV(8,IUNITS)
      DELT(J)= CONV(9,IUNITS)*POWER(J)/ABS(MDOT(J))/CP
      HSHEAR(J)= CONV(9,IUNITS)*POWER(J)
      TORQUE(J)= POWER(J)*CONV(10,IUNITS)/SPEED
C
C     CALCULATE FORCE AND CENTER OF PRESSURE
C
  460 K=0
      KK = 0
      FORCE(J) = SIMPS2(J,0.,RDIF,FFUNC,K)*WIDTH
      XC(J) = SIMPS2(J,0.,RDIF,XCFUNC,KK)/FORCE(J)*WIDTH
      IF(K.NE.0.OR.KK.NE.0)  WRITE(6,63) J,K,KK
  470 CONTINUE
      CALL STFNSS(NJ)
C
C     WRITE OUTPUT DATA
C
  500 WRITE(6,10) TITLE
      WRITE(6,17)
      IF (.NOT.NRMSKP)   WRITE(6,51)
      IF (NOSI)   WRITE (6,18)
      IF (.NOT.NOSI)   WRITE (6,15)
      IF (.NOT.NRMSKP)   WRITE(6,52)
      DO 510 J=1,NJ
      IF (H(J).GE.1.E30)   GO TO 510
      WRITE(6,19) H(J),MDOT(J),Q(J),KN(J),LAMDA(J),STIFF(J),
     1       FORCE(J), XC(J)
      IF(J.EQ.1) WRITE(6,58)
      IF (REP(J).GE.RETURB)   WRITE (6,60)
      IF(REP(J).GT.RELAM.AND.REP(J).LT.RETURB)  WRITE(6,59)
      IF (NRMSKP)   GO TO 510
```

```
      XCBAR(J)= XC(J)/RDIF
      FBAR(J)= FORCE(J)/(PO-P3)/WIDTH/RDIF
      WRITE (6,20) FBAR(J),XCBAR(J)
  510 CONTINUE
C
      WRITE(6,21)
      IF (.NOT.PWRSKP)    WRITE(6,53)
      IF (NOSI)   WRITE (6,22)
      IF (.NOT.NOSI)   WRITE (6,16)
      IF (.NOT.PWRSKP.AND.NOSI)   WRITE (6,54)
      IF (.NOT.PWRSKP.AND..NOT.NOSI)   WRITE (6,33)
      DO 520 J=1,NJ
      IF (H(J).GE.1.E30)   GO TO 520
      WRITE(6,19) H(J), FRICT(J),REP(J),RER(J)
      IF (J.EQ.1)   WRITE (6,58)
      IF(REP(J).GT.RELAM.AND.REP(J).LT.RETURB)  WRITE(6,59)
      IF (REP(J).GE.RETURB)   WRITE (6,60)
      IF(H(J).LE.H(1)) WRITE(6,57) PSTAR(J), LSTAR(J)
      IF (.NOT.PWRSKP.AND.REP(J).LE.RELAM)   WRITE (6,24) POWER(J),
     1             HSHEAR(J),DELT(J),TORQUE(J)
  520 CONTINUE
C
      IF (PRSSKP)   GO TO 600
      DO 533 J=1,NJ
      IF (MOD(J,3).EQ.1)   WRITE (6,26)
      IF (H(J).GE.1.E30)   GO TO 533
      IF (NOSI)   WRITE (6,25) H(J)
      IF (.NOT.NOSI)   WRITE (6,34) H(J)
      IF (J.EQ.1)   WRITE (6,58)
  531 WRITE(6,27)
      IF (NOSI)   WRITE (6,35)
      IF (.NOT.NOSI)   WRITE (6,36)
      DO 532 I=1,101,10
      IJ = I/10+1
      WRITE (6,23) X(I),P(J,I),MACH(J,IJ),FF(J,IJ),RHO(J,IJ),
     1      V(J,IJ),T(J,IJ)
  532 CONTINUE
  533 CONTINUE
C
C     MAKE PLOTS OF - POWER, CENTER OF PRESSURE, AND FORCE VS FILM
C     THICKNESS AND OF PRESSURE, TEMPERATURE, DENSITY, MACH NUMBER, AND
C     FRICTION PARAMETER 4FL/D VS RADIUS
C
  600 CALL GRAFIC(PLTSKP,NJ,TITLE)
  700 GO TO (100,110,120), INCODE
C
C     END OF PROGRAM
C
    1 FORMAT (12A6)
    2 FORMAT (I3)
    3 FORMAT (6F12.0)
   10 FORMAT (1H1,52HQUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRA
     1M,5X,12A6)
   11 FORMAT (1H0,12HINPUT DATA -,/,1H0,10X,9HR1,INCHES,22X,7HPO,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,7HP3,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,5HPO/P3,24X,
     5       5HGAMMA,23X,10HN(LAMINAR),/,1H ,F18.4,F29.3,F29.3,F30.2/,
```

```
     6      1H0,6X,17HFLOW WIDTH,INCHES,17X,8HTO,DEG F,16X,
     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)
  12 FORMAT (1H0,13HOUTPUT DATA -,/,1H0,10X,9HR1,INCHES,22X,7HP0,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,5HP0/P3,24X,
     5      5HGAMMA,/,1H ,F18.4,F29.3,F29.3,16X,4A6,/1H0,6X,
     6      17HFLOW WIDTH,INCHES,17X,8HTO,DEG F,16X,
     7      20HVISCOSITY,LB-SEC/IN2,18X,4HPLOT,/,1H ,F18.4,F29.3,G32.4,
     8      14X,22H**********************,/,1H0,10X,8HAREA,IN2,14X,
     9      24HGAS CONSTANT,LB-FT/LBM-R,14X,9HSPEED,RPM,14X,4A6,/,1H ,
     X      F18.4,F29.5,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      1H0,44X,30H******************************,/,1H ,44X,1H*,
     3      28X,1H*,/,1H ,44X,30H* * - CHOKING FILM THICKNESS *,/,1H ,
     4      44X,30H* + - TRANSITION REGION      *,/,1H ,44X,
     5      30H* / - TURBULENT FLOW         *,/,1H ,44X,1H*,28X,
     6      1H*,/,1H ,44X,30H******************************)
  13 FORMAT (1H0,12HINPUT DATA -,/,1H0,10X,9HR1,METERS,22X,7HP0,NSMA,
     1      18X,16HMOLECULAR WEIGHT,17X,9HF=K/RE**N,/,1H ,E18.3,E30.3,
     2      E29.3,22X,9H*********,/,1H0,10X,9HR2,METERS,22X,7HP3,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      5HP0/P3,24X,5HGAMMA,23X,10HN(LAMINAR),/,1H ,E18.3,E29.3,
     6      F29.3,E30.2,/,1H0,6X,17HFLOW WIDTH,METERS,17X,8HTO,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)
  14 FORMAT (1H0,13HOUTPUT DATA -,/,1H0,10X,9HR1,METERS,22X,7HP0,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,5HP0/P3,24X,
     5      5HGAMMA,/,1H ,E18.3,F29.3,F29.3,16X,4A6,/,1H0,6X,
     6      17HFLOW WIDTH,METERS,17X,8HTO,DEG K,17X,
     7      18HVISCOSITY,N-SEC/M2,19X,4HPLOT,/,1H ,E18.3,F29.3,G32.4,
     8      14X,22H**********************,/,1H0,11X,7HAREA,M2,12X,
     9      28HGAS CONSTANT,JOULES/KG-DEG K,12X,9HSPEED,RPS,14X,4A6,/,
     X      1H ,E18.3,E29.3,G32.4,/,1H ,93X,4A6,/,1H ,39X,10HLOSS COEF.,
     1      21X,7HV,M/SEC,/,1H ,F47.2,E30.3,16X,4A6,/,1H0,93X,4A6,/,
     2      1H0,44X,30H******************************,/,1H ,44X,1H*,28X,
     3      1H*,/1H ,44X,30H* * - CHOKING FILM THICKNESS *,/,1H ,44X,
     4      30H* + - TRANSITION REGION      *,/,1H ,44X,
     5      30H* / - TURBULENT FLOW         *,/,1H ,44X,1H*,28X,1H*,/,
     6      1H ,44X,30H******************************)
  15 FORMAT (1H ,5X,6HMETERS,7X,6HKG/SEC,7X,4HSCMS,8X,6HNUMBER,6X,
     1      6HMETERS,7X,3HN/M,10X,1HN,9X,6HMETERS)
  16 FORMAT (1H ,5X,6HMETERS,8X,6HFACTOR,30X,4HNSMA,7X,6HMETERS)
  17 FORMAT (1H0,15H FILM THICKNESS,3X,6HM(DOT),9X,1HQ,9X,7HKNUDSEN,
     1      5X,6HLAMBDA,4X,9HSTIFFNESS,5X,5HFORCE,9X,2HXC)
  18 FORMAT (1H ,5X,6HINCHES,7X,6HLB/MIN,7X,4HSCFM,8X,6HNUMBER,6X,
     1      6HINCHES,6X,5HLB/IN,8X,2HLB,9X,6HINCHES)
```

```
   19 FORMAT (1H ,G15.5,7G12.3)
   20 FORMAT (1H+,102X,2G12.3)
   21 FORMAT (1H0,15H FILM THICKNESS,3X,8HFRICTION,4X,5HRE(P),7X,
     1        5HRE(R),8X,4HP(*),8X,4HL(*))
   22 FORMAT (1H ,5X,6HINCHES,8X,6HFACTOR,30X,4HPSIA,7X,6HINCHES)
   23 FORMAT (1H ,7G12.3)
   24 FORMAT (1H+,77X,4G12.3)
   25 FORMAT (1H0,18H  FILM THICKNESS =,G12.5,2X,6HINCHES)
   26 FORMAT (1H1)
   27 FORMAT (1H0,6X,1HX,10X,1HP,10X,4HMACH,8X,5H4FL/D,7X,7HDENSITY,7X,
     1        1HV,11X,1HT)
   30 FORMAT (1H0,11HPO = P3 = 0)
   31 FORMAT (1H0,4HPO =,F10.3,5X,4HP3 =,F10.3,5X,9HPO/P3 = 0)
   32 FORMAT(1H0,39HSEAL DIMENSION DATA INCONSISTANT - R1 =,F10.4,5X,
     1        4HR2 =,F10.4,5X,6HRDIF =,F10.4)
   33 FORMAT (1H+,81X,5HWATTS,6X,5HWATTS,7X,5HDEG K,9X,3HN-M)
   34 FORMAT (1H0,18H  FILM THICKNESS =,G12.5,2X,6HMETERS)
   35 FORMAT (1H ,4X,6HINCHES,5X,4HPSIA,8X,6HNUMBER,17X,11HLB-SEC2/FT4,
     1        2X,6HFT/SEC,7X,5HDEG F)
   36 FORMAT (1H ,4X,6HMETERS,5X,4HNSMA,8X,6HNUMBER,20X,5HKG/M3,6X,
     1        5HM/SEC,6X,5HDEG K)
   51 FORMAT (1H+,105X,5HFORCE,8X,2HXC)
   52 FORMAT (1H+,106X,3HBAR,9X,3HBAR)
   53 FORMAT (1H+,81X,5HPOWER,4X,9HHEAT LOSS,4X,6HDEL(T),7X,6HTORQUE)
   54 FORMAT (1H+,82X,4HH.P.,5X,7HBTU/MIN,5X,5HDEG F,9X,5HLB/FT)
   56 FORMAT (1H0,23HCANNOT FIND H* FOR PO =,G14.5,6H, P3 =,G14.5,
     1        9H, GAMMA =,G14.5,18H, AND LOSS COEF. =,G14.5,/,1H ,
     2        22HASSUME NON-CHOKED FLOW)
   57 FORMAT (1H+,51X,2G12.3)
   58 FORMAT (1H+,1H*)
   59 FORMAT (1H+,2H +)
   60 FORMAT (1H+,2H /)
   63 FORMAT (1H0,35HERROR IN NUMERICAL INTEGRATION J =,I5,5X,3HK =,
     1        I5,5X,4HKK =,I5)
C
      END
```

```
$IBFTC STRT
C
C     FIND CRITICAL FILM THICKNESS AND ENTRANCE CONDITIONS FOR CRITICAL
C     FLOW
C
C     PROGRAM VARIABLES
C     *****************
C
C         M1 - ENTRANCE MACH NUMBER
C         C1 - CONSTANT IN SEVERAL EQUATIONS - TEMPORARY STORAGE
C      MTEST - NEW VALUE OF M1 IN ITERATIVE SOLUTION OF EQ. 23
C         B1 - FRICTION PARAMETER AT M1 (EQ. 9)
C         TT - ENTRANCE TEMPERATURE
C         MJ - ENTRANCE VISCOSITY
C         VV - ENTRANCE VELOCITY
C        PP3 - ENTRANCE PRESSURE RATIO, P1/PO
```

```
C        RRHO - ENTRANCE DENSITY
C          C2 - CONSTANT IN H* EQUATION
C          EX - EXPONENT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                  FOR LAMINAR OR TURBULENT FLOW
C         CON - CONSTANT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                  FOR LAMINAR OR TURBULENT FLOW
C      ******
C        X1 *
C        X2 * - INTERMEDIATE VARIABLES IN FRICTION FACTOR - REYNOLDS
C        XY *      NUMBER RELATION FOR TRANSITION REGION
C        X2 *
C      ******
C           P - PRESSURE
C         REP - ENTRANCE PRESSURE REYNOLDS NUMBER
C       FRICT - MEAN FRICTION FACTOR
C        HNEW - TRIAL VALUE FOR H*
C           N - CHARACTERISTIC OF LOG(10) OF HNEW
C        HTOL - ROUND-OFF ERROR TOLERANCE IN CALCULATION OF H*
C
      SUBROUTINE START
      DOUBLE PRECISION X1,X2,XX,Y2
      REAL MU,MUO,MACH,M1,MTEST,LSTAR,LOSS
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1       RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2       REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
      COMMON/CONSTS/G,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
     1       RGAS,LOSS,RELAM,RETURB,MUO,TSTAR
      COMMON/CONVRT/CONV(12,2),IUNITS
      EQ1(G,X) = 1./(1.+.5*(G-1.)*X**2)**(G/(G-1.))
      EQ2(G,X) = 1./(1.+.5*(G-1.)*X**2)
      EQ3(G,X) = (1./X**2-1.+.5*(G+1.)*ALOG((G+1.)*X**2/(2.+(G-1.)
     1       *X**2)))/G
C
      IF (G.NE.1.)   GO TO 90
      M1 = P3/PO
      GO TO 110
C
C
C     ITERATE FOR M1 BASED ON FORMULA USING M2=1, P2=P3, AND L**=R2-R1
C
   90 M1 = 0.
      C1 = P3*SQRT(.5*(G+1.))/PO
  100 MTEST = C1*SQRT(EQ2(G,M1))/EQ1(G,M1/LOSS)
      IF (M1.GT.1.)   GO TO 160
      IF (ABS(M1-MTEST).LT.1.E-7)   GO TO 110
      M1 = MTEST
      GO TO 100
  110 B1 = EQ3(G,M1)
      C1 = 2.*RDIF/B1
C
C     CALCULATE TEMPERATURE, VISCOSITY, VELOCITY, PRESSURE, DENSITY,
C     AND REYNOLDS NUMBER AT ENTRANCE.
C
      TT = EQ2(G,M1/LOSS)*TO
      MU = MUO
      IF(G.EQ.1.4) MU=CONV(2,IUNITS)*TT**1.5/(TT+CONV(3,IUNITS))
      VV= M1*SQRT(TT*RGAS*G*CONV(11,IUNITS))
      PPO = 1.
      IF (G.NE.1.)  PPO=EQ1(G,M1/LOSS)
```

```
      P(1,1) = PPO*PO
      RRHO= P(1,1)*CONV(12,IUNITS)/RGAS/TT
      C2   = 2.*VV*RRHO/MU/CONV(7,IUNITS)
  120 REP(1) = C2*H(1)
C
C     FOR LAMINAR OR TURBULENT FLOW, CALCULATE FRICTION FACTOR = K/RE**N
C     FOR TRANSITION FLOW, USE SPECIAL FORMULA
C
      IF(REP(1).GT.RELAM)  GO TO 130
      EX = XLAM
      CON = CONLAM
      GO TO 140
  130 IF(REP(1).GT.RETURB)  GO TO 135
      X1 = ALOG(RELAM)
      X2 = ALOG(RETURB)
      XX= ALOG(REP(1))
      Y2 = ALOG(CONTRB)-XTURB*X2-2.*(ALOG(CONTRB/CONLAM)+XLAM*X1-
     1      XTURB*X2)*(XX*(XX*(XX-1.5*(X1+X2))+3.*X1*X2)-.5*X2**2
     2      *(3. *X1-X2))/(X2-X1)**3
      FRICT(1)= DEXP(Y2)
      GO TO 145
  135 EX= XTURB
      CON = CONTRB
  140 FRICT(1) = CON/REP(1)**EX
C
C     ITERATE FOR H(1)=H*
C
  145 HNEW= C1*FRICT(1)
      N = ALOG10(HNEW)
      HTOL = 10.**(N-7)
      IF (ABS(H(1)-HNEW).LT.HTOL)    GO TO 150
      H(1) = .5*(H(1)+HNEW)
      GO TO 120
C
C     SATISFACTORY H* FOUND - STORE L*, P*, MACH NUMBER, FRICTION
C     PARAMETER 4FL/D, DENSITY, TEMPERATURE, AND VELOCITY.
C     CALCULATE T*.
C
  150 LSTAR(1) = RDIF
      PSTAR(1) = P3
      MACH(1,1) = M1
      FF(1,1) = B1
      RHO(1,1) = RRHO
      T(1,1)= TT-CONV(1,IUNITS)
      V(1,1) = VV
      TSTAR = TT/EQ2(G,M1)/.5/(G+1.)
      RETURN
C
C     ERROR CONDITION - SUPERSONIC ENTRANCE CONDITIONS.
C
  160 H(1) = 1.E30
      WRITE (6,10)
   10 FORMAT (1H0,61HSUPERSONIC ENTRANCE CONDITIONS FOR H*, ASSUME NON-C
     1HOKED FLOW)
      RETURN
C
      END
```

```
$IBFTC CSTRT
C
C     STARTING ROUTINE FOR SUPERCRITICAL FLOW
C
C     PROGRAM VARIABLES
C     *****************
C
C         KNT - COUNTER FOR NUMBER OF TIMES THROUGH THE ITERATION
C          M1 - ENTRANCE MACH NUMBER
C          TT - ENTRANCE TEMPERATURE
C          MU - ENTRANCE VISCOSITY
C         PPO - PRESSURE RATIO, P1/PO
C           P - PRESSURE
C         RHO - DENSITY
C           V - VELOCITY
C         REP - ENTRANCE PRESSURE REYNOLDS NUMBER
C
C          EX - EXPONENT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                  FOR LAMINAR AND TURBULENT FLOW
C         CON - CONSTANT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                  FOR LAMINAR AND TURBULENT FLOW
C     ******
C        X1 *
C        X2 * - INTERMEDIATE VARIABLES IN FRICTION FACTOR - REYNOLDS
C        XX *       NUMBER RELATION FOR TRANSITION REGION
C        Y2 *
C     ******
C       FRICT - MEAN FRICTION FACTOR
C          FF - FRICTION PARAMETER  4FL/D BY EQ. 9
C         FL1 - FLOW LENGTH CALCULATED FROM EQ. 9
C
C          SM - MACH NUMBER (DEPENDENT VARIABLE) FOR CURVE FIT
C          SL - FLOW LENGTH (INDEPENDENT VARIABLE) FOR CURVE FIT
C       FLMAX - MAXIMUM DIFFERENCE BETWEEN NEW FLOW LENGTH AND SL
C                  VALUES
C          II - INDEX OF ELEMENT OF SL ARRAY FOR WHICH FLMAX IS LARGEST,
C                  REPLACE THE II(TH) POINT BY THE NEW POINT
C        SUM3 - SUM OF SQUARES OF INDEPENDENT VARIABLE
C        SUM2 - SUM OF INDEPENDENT VARIABLE
C        SUM1 - SUM OF PRODUCT OF INDEPENDENT AND DEPENDENT VARIABLES
C        SUM0 - SUM OF INDEPENDENT VARIABLE
C         DET - DETERMINANT IN CURVE FIT
C           A - SLOPE OF FITTED STRAIGHT LINE
C           B - INTERCEPT OF FITTED STRAIGHT LINE
C          FM - VALUE OF MACH NUMBER FROM STRAIGHT LINE THAT
C                  CORRESPONDS TO L = R2-R1
C           T - TEMPERATURE
C       TSTAR - TEMPERATURE AT POINT OF CHOKING
C
C
      SUBROUTINE CHOKE(J)
      REAL MU,MUO,M1,MTEST,MACH,LSTAR,LOSS
      DOUBLE PRECISION SL,SM,DET,SUM3,SUM2,SUM1,SUMO,A,B,X1,X2,XX,Y2
      DIMENSION SM(3),SL(3)
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1      RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2      REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
      COMMON/CONSTS/G,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
     1      RGAS,LOSS,RELAM,RETURB,MUO,TSTAR
```

```
      COMMON/CONVRT/CONV(12,2),IUNITS
      EQ1(G,X) = 1./(1.+.5*(G-1.)*X**2)**(G/(G-1.))
      EQ2(G,X) = 1./(1.+.5*(G-1.)*X**2)
      EQ3(G,X) = (1./X**2-1.+.5*(G+1.)*ALOG(.5*(G+1.)*X**2/(1.+.5*(G-1.)
     1      *X**2)))/G
C
C     GUESS M1
C
      M1 = MACH(1,1)
      KNT = 0
C
C     CALCULATE TEMPERATURE, VISCOSITY, PRESSURE, VELOCITY, AND
C     REYNOLDS NUMBER AT ENTRANCE
C
  100 TT = TO*EQ2(G,M1/LOSS)
      MU = MUO
      IF(G.EQ.1.4) MU=CONV(2,IUNITS)*TT**1.5/(TT+CONV(3,IUNITS))
      V(J,1) = M1*SQRT(TT*RGAS*G*CONV(11,IUNITS))
      PPO = 1.
      IF (G.NE.1.)   PPO=EQ1(G,M1/LOSS)
      P(J,1) = PO*PPO
      RHO(J,1)= P(J,1)*CONV(12,IUNITS)/RGAS/TT
      REP(J)= V(J,1)*RHO(J,1)*2.*H(J)/MU/CONV(7,IUNITS)
C
C     FOR LAMINAR OR TURBULENT FLOW, CALCULATE FRICTION FACTOR = K/RE**N
C     FOR TRANSITION FLOW, USE SPECIAL FORMULA
C
      IF(REP(J).GT.RELAM)  GO TO 110
      EX = XLAM
      CON = CONLAM
      GO TO 120
  110 IF(REP(J).GT.RETURB)  GO TO 115
      X1 = ALOG(RELAM)
      X2 = ALOG(RETURB)
      XX= ALOG(REP(J))
      Y2 = ALOG(CONTRB)-XTURB*X2-2.*(ALOG(CONTRB/CONLAM)+XLAM*X1-
     1      XTURB*X2)*(XX*(XX*(XX-1.5*(X1+X2))+3.*X1*X2)-.5*X2**2
     2      *(3. *X1-X2))/(X2-X1)**3
      FRICT(J)= DEXP(Y2)
      GO TO 125
  115 EX= XTURB
      CON = CONTRB
  120 FRICT(J)= CON/REP(J)**EX
C
C     CALCULATE FRICTION PARAMTER 4FL/D FOR M1
C
  125 FF(J,1) = EQ3(G,M1)
      FL1 = FF(J,1)*H(J)/2./FRICT(J)
C
C     CHECK FOR CHOKING LENGTH = R2-R1.
C     IF NOT EQUAL, STORE M1 AND FL1 FOR CURVE FIT
C
      IF (ABS(FL1-RDIF).LT.1.E-7)   GO TO 130
      KNT = KNT+1
      IF (KNT.GT.3)   GO TO 126
      SM(KNT) = M1
      SL(KNT) = FL1
      IF (KNT.EQ.3)   GO TO 128
```

```
      M1 = M1*RDIF/ABS(FL1)
      GO TO 100
  126 FLMAX = 0.
      DO 127 I=1,3
      IF (ABS(SL(I)-FL1).LT.FLMAX)   GO TO 127
      II = I
      FLMAX = ABS(SL(I)-FL1)
  127 CONTINUE
      SL(II) = FL1
      SM(II) = M1
  128 CONTINUE
C
C     DO LINEAR CURVE FIT WITH 3 POINTS TO DETERMINE NEW VALUE OF M1
C     CORRESPONDING TO L=R2-R1
C
      SUM3 = 0.
      SUM2 = 0.
      SUM1 = 0.
      SUM0 = 0.
      DO 129 I=1,3
      SUM3 = SUM3+SL(I)**2
      SUM2 = SUM2+SL(I)
      SUM1 = SUM1+SM(I)*SL(I)
      SUM0 = SUM0+SM(I)
  129 CONTINUE
      DET = 3.*SUM3-SUM2**2
      A = (SUM1*3.-SUM2*SUM0)/DET
      B = (SUM3*SUM0-SUM2*SUM1)/DET
      FM = A*RDIF+B
      IF (KNT.GT.3)    M1=.5*(M1+FM)
      IF (M1.LT.0.)    M1=ABS(M1)
      GO TO 100
C
C     SATISFACTORY M1 FOUND
C
  130 T(J,1)= TT-CONV(1,IUNITS)
      TSTAR = TT/EQ2(G,M1)/.5/(G+1.)
      MACH(J,1) = M1
C
      RETURN
      END




$IBFTC NCSTRT

C
C     STARTING CONDITIONS FOR SUBCRITICAL FLOW
C
C     PROGRAM VARIABLES
C     *****************
C
C        LIM - NUMBER OF POINTS IN THE CURVE FIT OF M1 VS P2
C        CUT - FACTOR BY WHICH M1 IS CUT IN SEARCHING FOR AN M1
C                 THAT GIVES L GREATER THAN R2-R1
C         M1 - ENTRANCE MACH NUMBER
```

```
C          M2 - EXIT MACH NUMBER
C        DELM - MACH NUMBER INCREMENT TO GET THE ITERATION STARTED
C         KNT - COUNTER FOR THE NUMBER OF TIMES THROUGH THE ITERATION
C
C          TT - ENTRANCE TEMPERATURE
C          MU - ENTRANCE VISCOSITY
C          VV - ENTRANCE VELOCITY
C         PPO - PRESSURE RATIO, P1/PO
C           P - PRESSURE
C        RRHO - ENTRANCE DENSITY
C         REP - ENTRANCE REYNOLDS NUMBER
C
C          EX - EXPONENT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                 FOR LAMINAR AND TURBULENT FLOW
C         CON - CONSTANT IN FRICTION FACTOR - REYNOLDS NUMBER RELATION
C                 FOR LAMINAR AND TURBULENT FLOW
C     ******
C        X1  *
C        X2  * - INTERMEDIATE VARIABLES IN FRICTION FACTOR - REYNOLDS
C        XX  *       NUMBER RELATION FOR TRANSITION REGION
C        Y2  *
C     ******
C          FR - MEAN FRICTION FACTOR FOR TRANSITION REGION. IF FR
C                 IS NOT A GOOD NUMBER, ALTER M1 BY DELM.
C       FRICT - MEAN FRICTION FACTOR
C
C          B1 - FRICTION PARAMETER 4FL/D FROM EQ. 9
C      L1STAR - FICTITIOUS FLOW LENGTH FROM ENTRANCE TO POINT OF
C                 CHOKING
C       PSTAR - PRESSURE AT POINT OF CHOKING
C          L2 - DISTANCE FROM END OF SEAL TO POINT OF CHOKING
C          B2 - FRICTION PARAMETER 4FL2/D
C       MTEST - NEW VALUE OF M2 FROM ITERATIVE SOLUTION OF EQ. 9
C          P2 - EXIT PRESSURE
C
C          SM - MACH NUMBER (DEPENDENT VARIABLE) FOR CURVE FIT
C          SP - EXIT PRESSURE (INDEPENDENT VARIABLE) FOR CURVE FIT
C        PMAX - MAXIMUM DIFFERENCE BETWEEN NEW P2 AND STORED P2 VALUES
C          II - INDEX OF ELEMENT OF SP ARRAY FOR WHICH PMAX IS LARGEST,
C                 REPLACE THE II(TH) POINT BY THE NEW POINT
C        SUM3 - SUM OF SQUARES OF INDEPENDENT VARIABLE
C        SUM2 - SUM OF INDEPENDENT VARIABLE
C        SUM1 - SUM OF PRODUCT OF INDEPENDENT AND DEPENDENT VARIABLES
C        SUM0 - SUM OF DEPENDENT VARIABLE
C         DET - DETERMINANT IN CURVE FIT
C           A - SLOPE OF FITTED STRAIGHT LINE
C           B - INTERCEPT OF FITTED STRAIGHT LINE
C
C        PDIF - MINIMUM DIFFERENCE BETWEEN P3 AND STORED VALUES OF P2 FOR
C                 THE CONDITION WHEN P2 CANNOT BE DETERMINED WITHIN PTOL
C                 TOLERANCE OF P3
C       TSTAR - TEMPERATURE AT CHOKING
C
C
      SUBROUTINE NCHOKE(J)
      DOUBLE PRECISION SM,SP,A,B,DET,SUM3,SUM2,SUM1,SUM0,X1,X2,XX,Y2
      REAL MU,L1STAR,M1,M2,MTEST,L2,MACH,LSTAR,LOSS,MUO
      DIMENSION SP(3),SM(3)
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
```

```
1       RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
2       REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
  COMMON/CONSTS/G,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
1       RGAS,LOSS,RELAM,RETURB,MUO,TSTAR
  DIMENSION SP(3),SM(3)
  EQ1(G,X) = 1./(1.+.5*(G-1.)*X**2)**(G/(G-1.))
  EQ2(G,X) = 1./(1.+.5*(G-1.)*X**2)
  EQ3(G,X) = (1./X**2-1.+.5*(G+1.)*ALOG((G+1.)*X**2/(2.+(G-1.)
1       *X**2)))/G
  EQ5(G,X) = SQRT((G+1.)/(2.+(G-1.)*X**2))/X
  EQ8(G,B,X)= 1./SQRT(G*B+1.-.5*(G+1.)*ALOG((G+1.)*X**2/(2.+(G-1.)*X
1       **2)))
C
C     SET CONSTANTS AND MAKE INITIAL GUESS FOR M1.  FOR P3/PO GREATER
C     THAN P3/PO (CRITICAL), USE A TWO POINT FIT.  FOR P3/PO LESS THAN
C     P3/PO (CRITICAL), USE A THREE POINT FIT.
C
      LIM = 3
      IF (H(1).GE.1.E30)   LIM=2
      IF (ABS(1.0-H(1)/H(J)).LE.2.0E-2)   LIM=2
      CUT = .98
      MTEST = 0.
      M1 = .75
      DELM = M1/2.
      M2 = 1.
      KNT = 0
   90 IF (MTEST.GT..9)   CUT=.9999
      IF (KNT.GT.50)   CUT=.9999
      IF (KNT.GT.100)   CUT=.9999999
C
C     CALCULATE TEMPERATURE, VISCOSITY, VELOCITY, PRESSURE, DENSITY,
C     AND REYNOLDS NUMBER AT ENTRANCE.
C
  100 TT = EQ2(G,M1/LOSS)*TO
      MU = MUO
      IF (G.EQ.1.4)   MU=2.27E-8*TT**1.5/(TT+198.6)
      VV = M1*SQRT(TT*RGAS*32.174*G)
      PPO = 1.
      IF (G.NE.1.)   PPO=EQ1(G,M1/LOSS)
      P(J,1) = PPO*PO
      RRHO = P(J,1)*144./RGAS/TT/32.174
  120 REP(J)= VV*RRHO*2.*H(J)/MU/12.
C
C     FOR LAMINAR OR TURBULENT FLOW, CALCULATE FRICTION FACTOR = K/RE**N
C     FOR TRANSITION FLOW, USE SPECIAL FORMULA
C
      IF(REP(J).GT.RELAM)   GO TO 130
      EX = XLAM
      CON = CONLAM
      GO TO 140
  130 IF(REP(J).GT.RETURB)   GO TO 135
      X1 = ALOG(RELAM)
      X2 = ALOG(RETURB)
```

```
      XX= ALOG(REP(J))
      Y2 = ALOG(CONTRB)-XTURB*X2-2.*(ALOG(CONTRB/CONLAM)+XLAM*X1-
     1       XTURB*X2)*(XX*(XX*(XX-1.5*(X1+X2))+3.*X1*X2)-.5*X2**2
     2       *(3. *X1-X2))/(X2-X1)**3
      IF (KNT.EQ.0)   GO TO 131
      FR = DEXP(Y2)
      IF (FR.NE.FRICT(J))   GO TO 131
      M1 = M1+DELM
      GO TO 100
  131 FRICT(J)= DEXP(Y2)
      GO TO 145
  135 EX= XTURB
      CON = CONTRB
  140 FRICT(J)= CON/REP(J)**EX
C
C     CALCULATE FRICTION PARAMETER B1, L1*, AND P* FOR M1.   DETERMINE
C     L2*, FRICTION PARAMETER B2, M2, AND P2
C
  145 B1 = EQ3(G,M1)
      L1STAR = B1*H(J)/2./FRICT(J)
      PSTAR(J) = P(J,1)/EQ5(G,M1)
      L2 = L1STAR-RDIF
      IF (L2.GE.0.)   GO TO 150
      M1 = M1*CUT
      DELM = DELM*CUT
      GO TO 100
  150 B2 = 2.*FRICT(J)*L2/H(J)
  160 MTEST = EQ8(G,B2,M2)
      IF(ABS(M2-MTEST).LT.1.E-7)   GO TO 170
      M2 = MTEST
      GO TO 160
  170 P2 = PSTAR(J)*EQ5(G,M2)
C
C     CHECK FOR P2=P3.   IF NOT EQUAL, STORE M1 AND P2 FOR CURVE FIT.
C
      IF (ABS(P2-P3).LT.PTOL)   GO TO 180
      IF (DELM.EQ.0.)   GO TO 180
      IF (DELM.LT.1.E-7)   GO TO 175
      KNT = KNT+1
      IF (KNT.GT.LIM)   GO TO 171
      SM(KNT) = M1
      SP(KNT) = P2
      IF (KNT.EQ.LIM)   GO TO 173
      M1 = M1+DELM
      GO TO 100
  171 PMAX = 0.
      DO 172 I=1,LIM
      IF (ABS(SP(I)-P3).LT.PMAX)   GO TO 172
      II = I
      PMAX = ABS(SP(I)-P3)
  172 CONTINUE
      SP(II) = P2
      SM(II) = M1
  173 CONTINUE
C
C     DO TWO OR THREE POINT LINEAR CURVE FIT TO DETERMINE NEW VALUE OF
C     M1 CORRESPONDING TO P2=P3
```

```
C
      SUM3 = 0.D0
      SUM2 = 0.D0
      SUM1 = 0.D0
      SUM0 = 0.D0
      DO 174 I=1,LIM
      SUM3 = SUM3+SP(I)**2
      SUM2 = SUM2+SP(I)
      SUM1 = SUM1+SM(I)*SP(I)
      SUM0 = SUM0+SM(I)
  174 CONTINUE
      DET = FLOAT(LIM)*SUM3-SUM2**2
      A = (SUM1*FLOAT(LIM)-SUM2*SUM0)/DET
      B = (SUM3*SUM0-SUM2*SUM1)/DET
      M1 = A*P3+B
      IF (M1.LT.0.)   M1=.5*SM(1)
      DELM = AMIN1(ABS(M1-SM(1)),ABS(M1-SM(2)),ABS(M1-SM(3)),DELM)
      GO TO 90
C
C     ERROR CONDITION - CANNOT DETERMINE P2 WITHIN TOLERANCE PTOL OF P3
C
  175 DELM = 0.0
      PDIF = ABS(SP(1)-P3)
      M1 = SM(1)
      IF (ABS(SP(2)-P3).GT.PDIF)   GO TO 176
      PDIF = ABS(SP(2)-P3)
      M1 = SM(2)
  176 IF (ABS(SP(3)-P3).LT.PDIF)   M1=SM(3)
      GO TO 90
C
C     SATISFACTORY M1 FOUND - STORE CURRENT VALUES OF VELOCITY,
C     TEMPERATURE, DENSITY, FRICTION PARAMETER, MACH NUMBER, AND L*
C     CALCULATE T*
C
  180 V(J,1) = VV
      T(J,1)= TT-CONV(1,IUNITS)
      RHO(J,1) = RRHO
      FF(J,1) = B1
      MACH(J,1) = M1
      LSTAR(J) = L1STAR
      TSTAR = TT/EQ2(G,M1)/.5/(G+1.)
      RETURN
C
      END




$IBFTC DISTS

C
C     PRESSURE, TEMPERATURE, VELOCITY, MACH NUMBER, DENSITY, AND
C     FRICTION PARAMETER PROFILES VS X
C
C     PROGRAM VARIABLES
C     *****************
```

```
C
C           X - DISTANCE ACROSS THE FACE OF THE SEAL
C           K - POINT COUNTER FOR VARIABLES OTHER THAN X AND P
C          MX - MACH NUMBER AT X
C          LX - DISTANCE FROM X TO POINT OF CHOKING
C          BX - FRICTION PARAMETER 4FLX/D
C       MTEST - NEW VALUE OF MX IN ITERATIVE SOLUTION OF EQ. 23
C          TT - TEMPERATURE AT X
C          VV - VELOCITY AT X
C        RRHO - DENSITY AT X
C           P - PRESSURE AT X
C
C           I - POINT INDEX FOR X AND P
C          II - I(MODULO 10) - WHEN II=1, INCREASE K
C           J - FILM THICKNESS INDEX
C
      SUBROJTINE DIST(J)
      REAL LX,MX,MACH,MTEST,LOSS,LSTAR
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1      RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2      REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
      COMMON/CONSTS/G,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
     1      RGAS,LOSS,RELAM,RETURB,FMU,TSTAR
      COMMON/CONVRT/CONV(12,2),IUNITS
      EQ2(G,X) = 1./(1.+.5*(G-1.)*X**2)
      EQ8(G,B,X) = 1./SQRT(G*B+1.-.5*(G+1.)*ALOG((G+1.)*X**2/
     1      (2.+(G-1.)*X**2)))
C
      K=1
      MX= MACH(J,1)
      DO 120  I=2,101
      II= MOD(I,10)
      IF (H(J).LT.H(1))   GO TO 90
      IF (I.NE.101)   GO TO 90
      MX = 1.
      LX = 0.
      BX = 0.
      GO TO 110
   90 MX= MX*(1.04+.2E-3*FLOAT(I))
      IF (MX.GT.1.)   MX=1.
      LX= RDIF-X(I)
      IF (H(J).LT.H(1))   LX=LSTAR(J)-X(I)
      BX= 2.*FRICT(J)*LX/H(J)
  100 MTEST= EQ8(G,BX,MX)
      IF(ABS(MTEST-MX) .LT. 1.E-7) GO TO 110
      MX= MTEST
      GO TO 100
  110 TT = TSTAR*.5*(G+1.)*EQ2(G,MX)
  116 VV= MX*SQRT(G*RGAS*TT*CONV(11,IUNITS))
      RRHO= RHO(J,1) *V(J,1)/VV
      P(J,I)= RRHO*RGAS*TT/CONV(12,IUNITS)
C
C     STORE EVERY 10-TH VALUE OF TEMPERATURE, DENSITY, VELOCITY, MACH
C     NUMBER, AND FRICTION PARAMETER
C
      IF(II.NE.1) GO TO 120
      K= K+1
      T(J,K)= TT-CONV(1,IUNITS)
      V(J,K)= VV
      MACH(J,K)= MX
```

```
      FF(J,K)= BX
      RHO(J,K)= RRHO
  120 CONTINUE
C
      RETURN
      END
```

```
$IBFTC PX

C
C     INTEGRAND OF FORCE INTEGRAL
C
      FUNCTION FFUNC(J,X)
      COMMON/CONSTS/D(8),P3,DD(7)
C
      FFUNC=PRESS(J,X)-P3
      RETURN
      END
```

```
$IBFTC PXX

C
C     INTEGRAND OF CENTER OF PRESSURE INTEGRAL
C
      FUNCTION XCFUNC(J,X)
      COMMON/CONSTS/D(8),P3,DD(7)
C
      XCFUNC = (PRESS(J,X)-P3)*X
      RETURN
      END
```

```
$IBFTC PRSS

C
C      INTERPOLATION ROUTINE FOR PRESSURE
C
C      CALL VECTOR VARIABLES
C      *********************
C
C            J - FILM THICKNESS INDEX
C           XX - DISTANCE ACROSS FACE OF SEAL
C
      FUNCTION PRESS(J,XX)
      REAL MACH,LSTAR
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1       RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2       REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
C
      DX = X(2)-X(1)
      DO 100 I=1,101
      II = I
      IF (XX-X(I))   110,120,100
  100 CONTINUE
  110 IF (II.LT.2)   II=2
      IF (II.GT.100) II=100
      PRESS = (P(J,II-1)*(XX-X(II))*(XX-X(II+1))-P(J,II)*
     1       (XX-X(II-1))*(XX-X(II+1))*2.+P(J,II+1)*(XX-X(II-1))*
     2       (XX-X(II)))/2./DX**2
      RETURN
  120 PRESS = P(J,II)
      RETURN
      END
```

```
$IBFTC DERIV

C
C      LAGRANGE NUMERICAL DIFFERENTIATION OVER MAXIMUM OF 5 POINTS
C      TO DETERMINE AXIAL FILM STIFFNESS
C
C
C      CALL VECTOR VARIABLES
C      *********************
C
C        MMAX - NUMBER OF FILM THICKNESSES
C
C      PROGRAM VARIABLES
C      *****************
C
C          XX - FILM THICKNESSES
C          YY - FORCE
C         DDY - AXIAL FILM STIFFNESS
C
C           X - WORKING ARRAY FOR FILM THICKNESSES
C           Y - WORKING ARRAY FOR FORCE
C          DY - WORKING ARRAY FOR AXIAL FILM STIFFNESS
```

```
C
C        IND - INDEX OF TYPE OF FLOW
C                  IND = 1 MEANS CHOKED LAMINAR FLOW
C                  IND = 2 MEANS CHOKED TURBULENT FLOW
C                  IND = 3 MEANS NON-CHOKED LAMINAR FLOW
C                  IND = 4 MEANS NON-CHOKED TURBULENT FLOW
C
C          M - POINT INDEX
C         MM - POINT COUNTER FOR EACH TYPE OF FLOW
C
C     ******
C          N *
C        IST *
C         IN *
C          K * - AUXILLIARY INDEXES IN SETTING UP MATRIX A
C         II *
C         JJ *
C          J *
C     ******
C
C          A - MATRIX OF DIFFERENCES DEFINED BY EQ.-
C
C     ******
C         S1 *
C         S2 * - SUMS AND PRODUCTS DEFINED BY EQS. -
C         P1 *
C         P2 *
C     ******
C
C         KY - DERIVATIVE (AXIAL FILM STIFFNESS) ROUNDED OFF TO
C                  NEAREST WHOLE NUMBER
C
      SUBROUTINE STFNSS(MAX)
      DIMENSION X(20), Y(20), DY(20),A(5,5)
      COMMON/CONSTS/D1(12),RELAM,RETURB,FMU,TSTAR
      COMMON/ARRAYS/D2(3221),XX(20),D3(60),REP(20),D4(40),YY(20),
     1       DDY(20),D5(20)
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
      IF (XX(M).GE.1.E30)   GO TO 110
      GO TO (1,2,3,4),IND
    1 IF (XX(M).GT.XX(1).AND.REP(M).LE.RELAM)   GO TO 105
      GO TO 110
    2 IF (XX(M).GT.XX(1).AND.REP(M).GE.RETURB)   GO TO 105
      GO TO 110
    3 IF (XX(M).LE.XX(1).AND.REP(M).LE.RELAM)   GO TO 105
      GO TO 110
    4 IF (XX(M).LE.XX(1).AND.REP(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 = MAXO(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
      CDY(M) = -DY(II)
      GO TO 320
  311 CDY(M) = DY(II)
      GO TO 320
```

```
  310 CONTINUE
  320 CONTINUE
  400 CONTINUE
C
      RETURN
      END
```

```
$IBFTC SRT
C
C     ARRANGE POINTS (X,Y) IN ORDER OF ASCENDING X
C
C     CALL VECTOR VARIABLES
C     *********************
C
C          X - INDEPENDENT VARIALBE
C          Y - DEPENDENT VARIABLE
C          N - NUMBER OF POINTS TO BE SORTED
C
C     PROGRAM VARIABLES
C     *****************
C
C          T - TEMPORARY STORAGE
C          I - POINT INDEX
C          J - POINT INDEX
C         NN - N-1
C
      SUBROUTINE SORTXX(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
```

```
$IBFTC SMPS32

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 SIMPS2(J,XMIN,XMAX,FUNC2,KER)
      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)=FUNC2(J,XMIN)
      B(1)=FUNC2(J,XMIN+H(1))
      C(1)=FUNC2(J,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
C
C     BEGIN INTEGRATION USING MORE SUBINTERVALS WHERE VALUE OF INTEGRAND
C     IS CHANGING RAPIDLY
C
    1 FRAC=0.5*FRAC
    2 TEST=ABS(FRAC*ANS)
      K=N
      DO 7 I=1,K
      IF (NTEST.GT.IABS(NE(I)))  GO TO 7
      N = N+1
      V(N)=V(I)+H(I)
      H(N)=0.5*H(I)
      A(N)=B(I)
      B(N)=FUNC2(J,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)=FUNC2(J,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+2
C
C     ACCUMULATE FINAL ANSWER
C
   14 ANS=0.0
      DO 16 I=1,N
   16 ANS=ANS+P(I)
      SIMPS2=(ANS+Q/30.0)/3.0
C
      RETURN
      END
```

```
$IBFTC GRAFS
C
C     MICROFILM PLOTTING ROUTINE
C
C
C     CALL VECTOR VARIABLES
C     *********************
C
C     PTLSKP - ARRAY OF LOGICAL VARIABLES THAT TELL WHICH PLOTS TO OMIT
C         NJ - NUMBER OF FILM THICKNESSES
C      TITLE - ALPHA-NUMERIC IDENTIFICATION OF DATA = PLOT TITLE
C
C     PROGRAM VARIABLES
C     *****************
C
C       HLEG - FILM THICKNESS LEGEND FOR ABSCISSA OF FIRST 3 PLOTS
C     PWRLEG - POWER LEGEND FOR ORDINATE OF FIRST PLOT
C      XCLEG - CENTER OF PRESSURE LEGEND FOR ORDINATE OF SECOND PLOT
C       FLEG - FORCE LEGEND FOR ORDINATE OF THIRD PLOT
C
C       XLEG - X LEGEND FOR ABSCISSA OF LAST 5 PLOTS
C       PLEG - PRESSURE LEGEND FOR ORDINATE OF FOURTH PLOT
C       TLEG - TEMPERATURE LEGEND FOR ORDINATE OF FIFTH PLOT
C       RLEG - DENSITY LEGEND FOR ORDINATE OF SIXTH PLOT
C       MLEG - MACH NUMBER LEGEND FOR ORDINATE OF SEVENTH PLOT
C       BLEG - FRICTION PARAMETER LEGEND FOR ORDINATE OF EIGHT PLOT
C
C     NORMALIZING PARAMETERS
C     **********************
C
C       HMAX - MAXIMUM FILM THICKNESS
C     PWRMAX - MAXIMUM POWER
C       RDIF - FLOW LENGTH
C         P0 - SUPPLY PRESSURE
C         T0 - TOTAL TEMPERATURE
C         R0 - DENSITY OF SUPPLY RESERVOIR
C         XX - AUXILLIARY ARRAY FOR INDEPENDENT VARIABLE IN EACH PLOT
C         YY - AUXILLIARY ARRAY FOR DEPENDENT VARIABLE IN EACH PLOT
C         IJ - POINT COUNTER
C
      SUBROUTINE GRAFIC(PLTSKP,NJ,TITLE)
      LOGICAL PLTSKP
      REAL MACH,LSTAR
      DIMENSION PLTSKP(8),TITLE(12),XX(25),YY(200)
      DIMENSION HLEG(10),PWRLEG(10),XCLEG(10),XLEG(10),PLEG(10),
     1      TLEG(10),RLEG(10),MLEG(10),BLEG(10),FLEG(10)
      COMMON/ARRAYS/X(101),P(20,101),MACH(20,11),V(20,11),T(20,11),
     1      RHO(20,11),FF(20,11),H(20),XCBAR(20),LSTAR(20),PSTAR(20),
     2      REP(20),FRICT(20),POWER(20),FORCE(20),STIFF(20),FBAR(20)
      COMMON/CONSTS/G,RDIF,XLAM,CONLAM,XTURB,CONTRB,TO,PO,P3,PTOL,
     1      RGAS,LOSS,RELAM,RETURB,FMUO,TSTAR
      COMMON/CONVRT/CONV(12,2),IUNITS
C
C     ALL PLOTS ARE DIMENSIONLESS
C
      HMAX = H(1)
      PWRMAX = POWER(1)
      DO 100 J=2,NJ
```

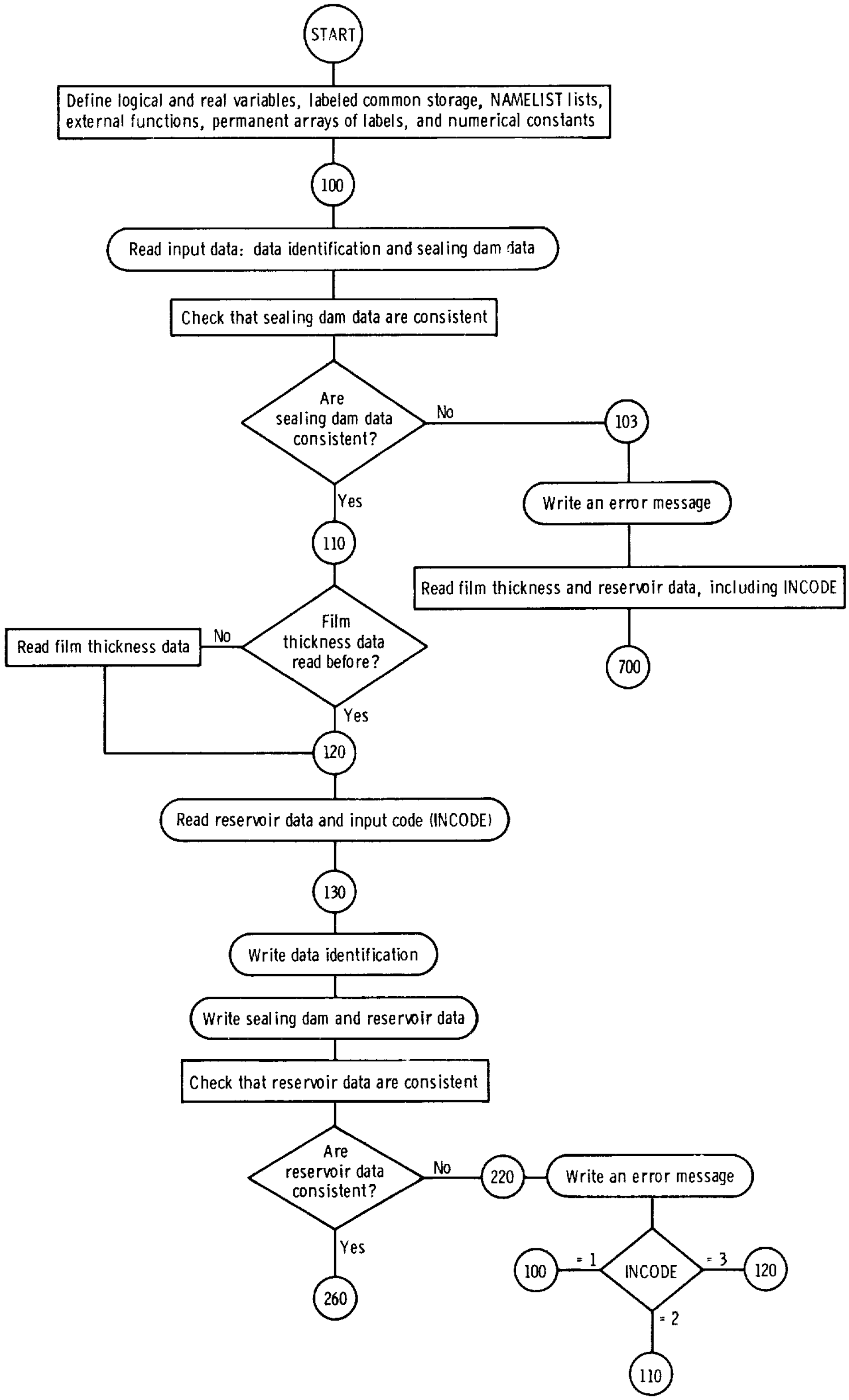
```
      HMAX = AMAX1(HMAX,H(J))
      PWRMAX = AMAX1(PWRMAX,POWER(J))
  100 CONTINUE
      DO 110 J=1,NJ
  110 XX(J) = H(J)/HMAX
C
      IF(PLTSKP(1))     GO TO 210
      DO 200 J=1,NJ
  200 YY(J) = POWER(J)/PWRMAX
C
C**** CALL PLOT ROUTINE TO PLOT POWER VS FILM THICKNESS ****************
C
  210 IF (PLTSKP(2))    GO TO 220
C
C**** CALL PLOT ROUTINE TO PLOT CENTER OF PRESSURE VS FILM THICKNESS ***
C
  220 IF (PLTSKP(3))    GO TO 300
C
C**** CALL PLOT ROUTINE TO PLOT FORCE VS FILM THICKNESS ****************
C
C     MULTIPLE PLOTS OF PARAMETERS THAT VARY WITH X
C
  300 IJ = 0
      DO 301 J=1,NJ
      DO 301 I=1,101,10
      IJ = IJ+1
  301 XX(IJ) = X(I)/RDIF
      IF (PLTSKP(4))    GO TO 310
      IJ = 0
      DO 302 J=1,NJ
      DO 302 I=1,101,10
      IJ = IJ+1
  302 YY(IJ) = P(J,I)/PO
C
C**** CALL PLOT ROUTINE TO PLOT PRESSURE VS DISTANCE *******************
C
  310 IF (PLTSKP(5))    GO TO 320
      IJ = 0
      DO 311 J=1,NJ
      DO 311 I=1,11
      IJ = IJ+1
  311 YY(IJ) = (T(J,I)+CONV(1,IUNITS))/TO
C
C**** CALL PLOT ROUTINE TO PLOT TEMPERATURE VS DISTANCE ****************
C
  320 IF (PLTSKP(6))    GO TO 330
      IJ = 0
      RO = PO*CONV(12,IUNITS)/RGAS/TO
      DO 321 J=1,NJ
      DO 321 I=1,11
      IJ = IJ+1
  321 YY(IJ) = RHO(J,I)/RO
C
C**** CALL PLOT ROUTINE TO PLOT DENSITY VS DISTANCE ******************
C
  330 IF (PLTSKP(7))    GO TO 340
      IJ = 0
      DO 331 J=1,NJ
```

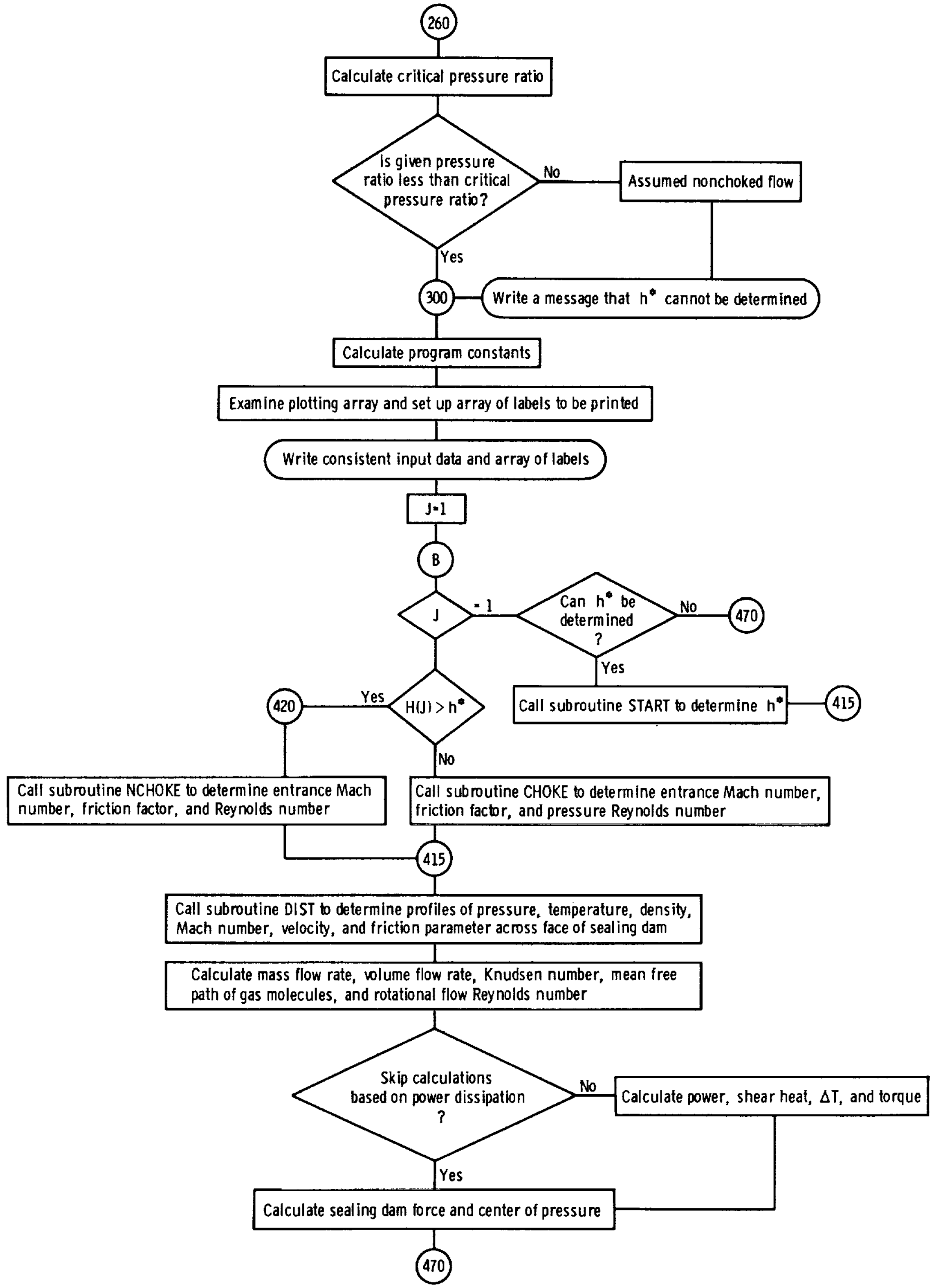
```
      DO 331 I=1,I1
      IJ = IJ+1
  331 YY(IJ) = MACH(J,I)
C
C**** CALL PLOT ROUTINE TO PLOT MACH NUMBER VS DISTANCE ****************
C
  340 IF (PLTSKP(8))    RETURN
      IJ = 0
      DO 341 J=1,NJ
      DO 341 I=1,I1
      IJ = IJ+1
  341 YY(IJ) = FF(J,I)
C
C**** CALL PLOT ROUTINE TO PLOT FRICTION PARAMETER VS DISTNACE *********
C
      RETURN
      END
```

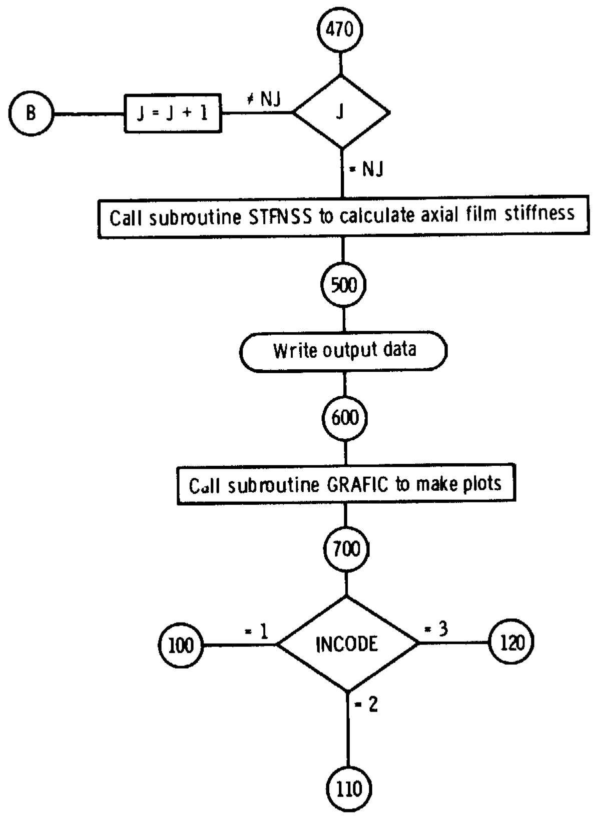
```
$IBFTC BDATA

C
C     UNITS CONVERSION DATA
C
      BLOCK DATA
      COMMON/CONVRT/CONV(12,2),IUNITS
      DATA (CONV(I,1),I=1,12)/0., .14591E-5, 110.33333, 2*1.,
     1      .5051554E-2, 6*1. /
      DATA (CONV(I,2),I=1,12)/ 460., 1.57639E-10, 198.6, 720.,
     1      13.405833, 13.083, 1728., .021818182, 42.42, 3.3E4, 32.174,
     2      4.4756636 /
C
      END
```

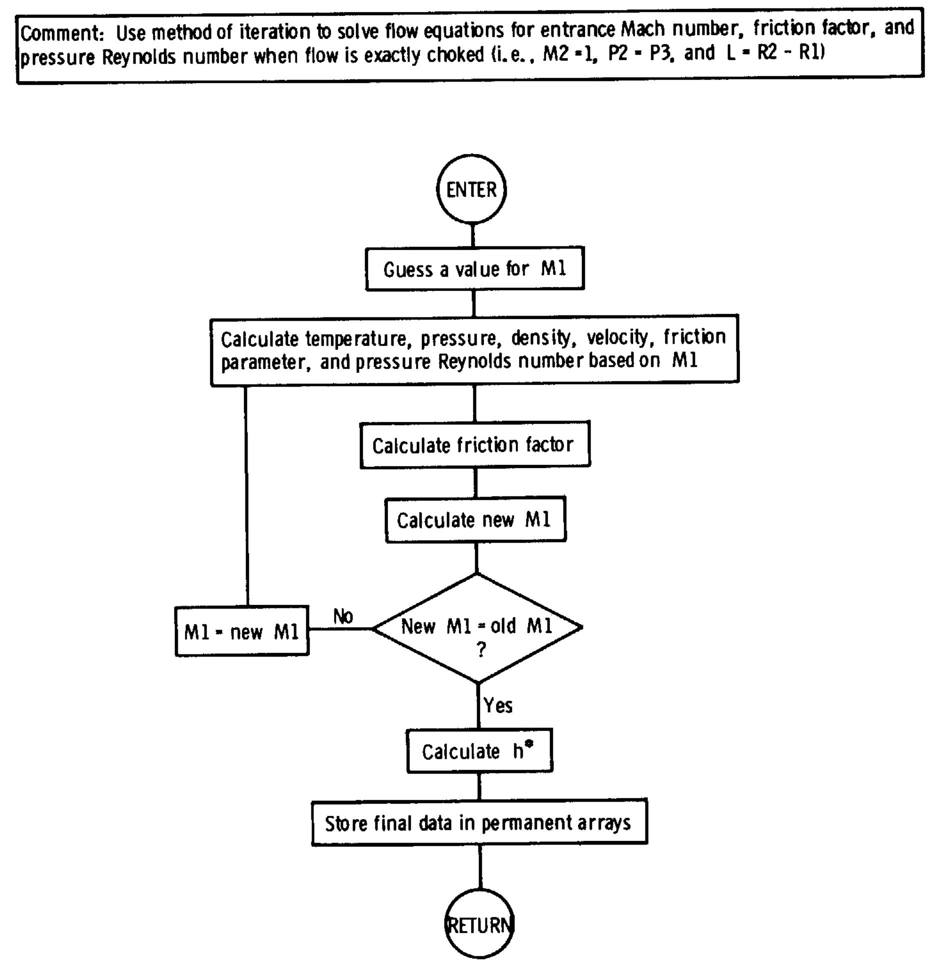
QUASC


START
Define logical and real variables, labeled common storage, NAMELIST lists, external functions, permanent arrays of labels, and numerical constants
100
Read input data: data identification and sealing dam data
Check that sealing dam data are consistent
Are sealing dam data consistent?
No
103
Write an error message
Read film thickness and reservoir data, including INCODE
700
Yes
110
Film thickness data read before?
No
Read film thickness data
Yes
120
Read reservoir data and input code (INCODE)
130
Write data identification
Write sealing dam and reservoir data
Check that reservoir data are consistent
Are reservoir data consistent?
No
220
Write an error message
INCODE
= 1
100
= 3
120
= 2
110
Yes
260


260
Calculate critical pressure ratio
Is given pressure ratio less than critical pressure ratio?
No
Assumed nonchoked flow
Yes
300
Write a message that h* cannot be determined
Calculate program constants
Examine plotting array and set up array of labels to be printed
Write consistent input data and array of labels
J=1
B
J
= 1
Can h* be determined ?
No
470
Yes
Call subroutine START to determine h*
415
420
Yes
H(J) > h*
No
Call subroutine NCHOKE to determine entrance Mach number, friction factor, and Reynolds number
Call subroutine CHOKE to determine entrance Mach number, friction factor, and pressure Reynolds number
415
Call subroutine DIST to determine profiles of pressure, temperature, density, Mach number, velocity, and friction parameter across face of sealing dam
Calculate mass flow rate, volume flow rate, Knudsen number, mean free path of gas molecules, and rotational flow Reynolds number
Skip calculations based on power dissipation ?
No
Calculate power, shear heat, ΔT, and torque
Yes
Calculate sealing dam force and center of pressure
470

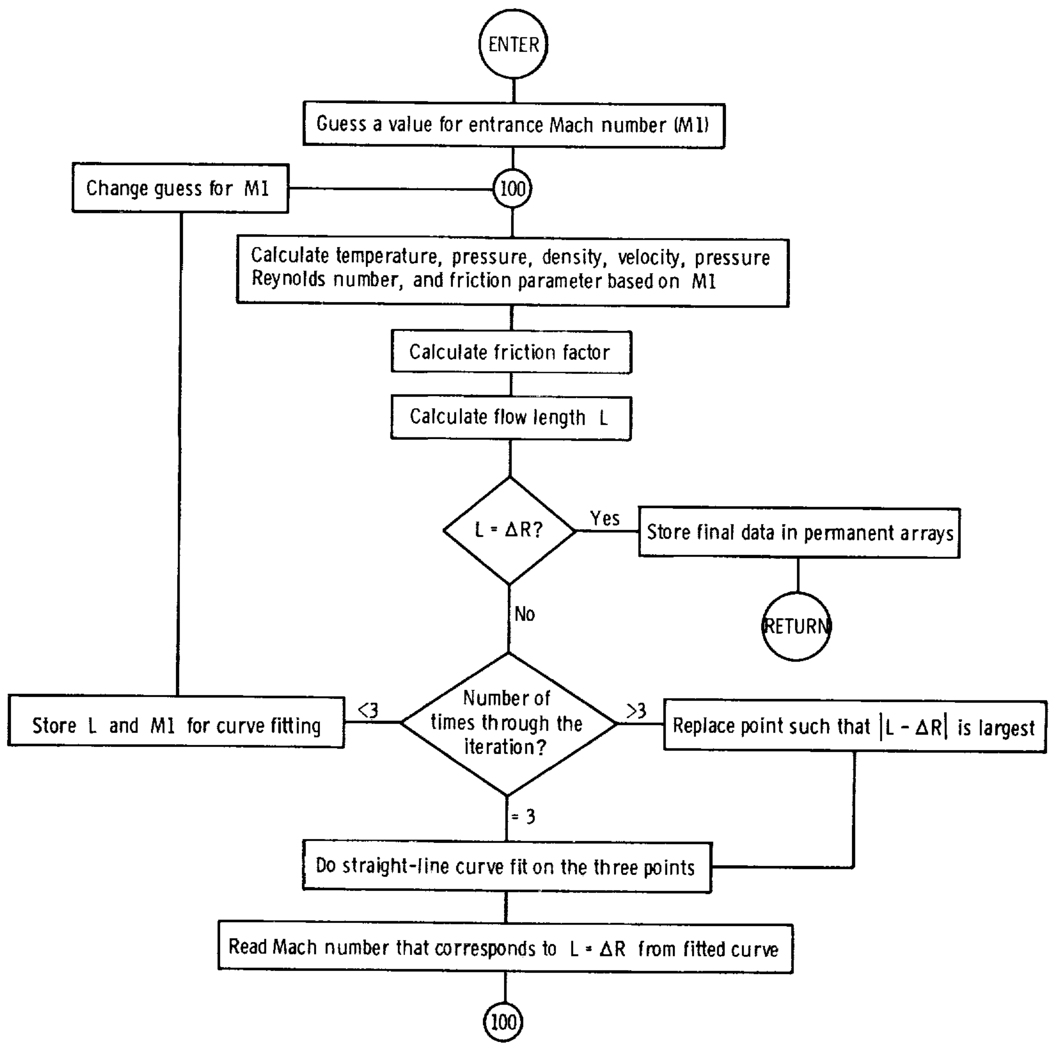

470
J
≠ NJ
J = J + 1
B
= NJ
Call subroutine STFNSS to calculate axial film stiffness
500
Write output data
600
Call subroutine GRAFIC to make plots
700
INCODE
= 1
100
= 3
120
= 2
110

START


Comment: Use method of iteration to solve flow equations for entrance Mach number, friction factor, and pressure Reynolds number when flow is exactly choked (i.e., M2 = 1, P2 = P3, and L = R2 - R1)
ENTER
Guess a value for M1
Calculate temperature, pressure, density, velocity, friction parameter, and pressure Reynolds number based on M1
Calculate friction factor
Calculate new M1
New M1 = old M1
?
No
M1 = new M1
Yes
Calculate h*
Store final data in permanent arrays
RETURN

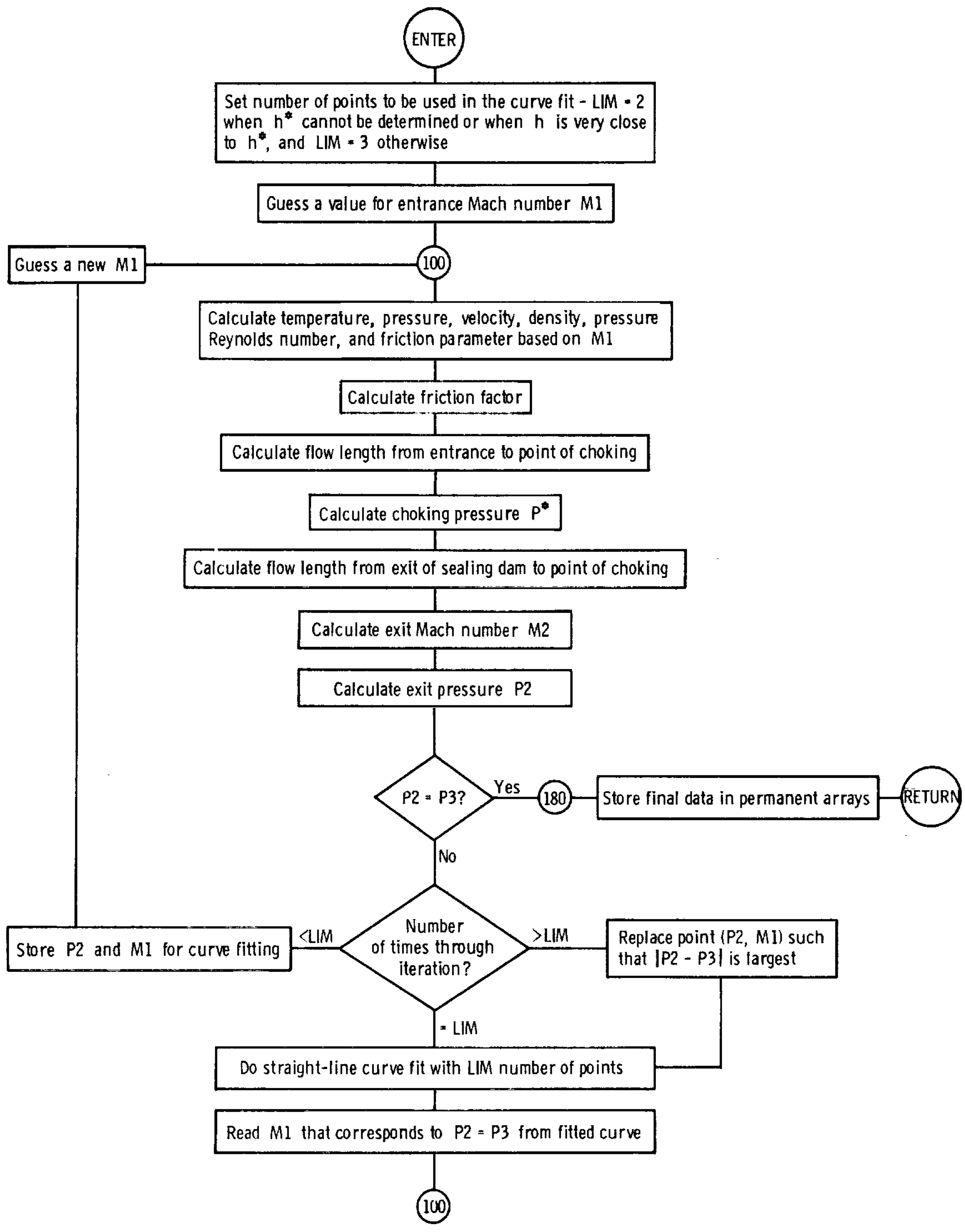
CHOKE

Comment: Use method of iteration to solve flow equations for entrance Mach number, friction factor, and pressure Reynolds number when flow is choked (i.e., M2 = 1, h > h*, L = R2 - R1, P2 > P3)

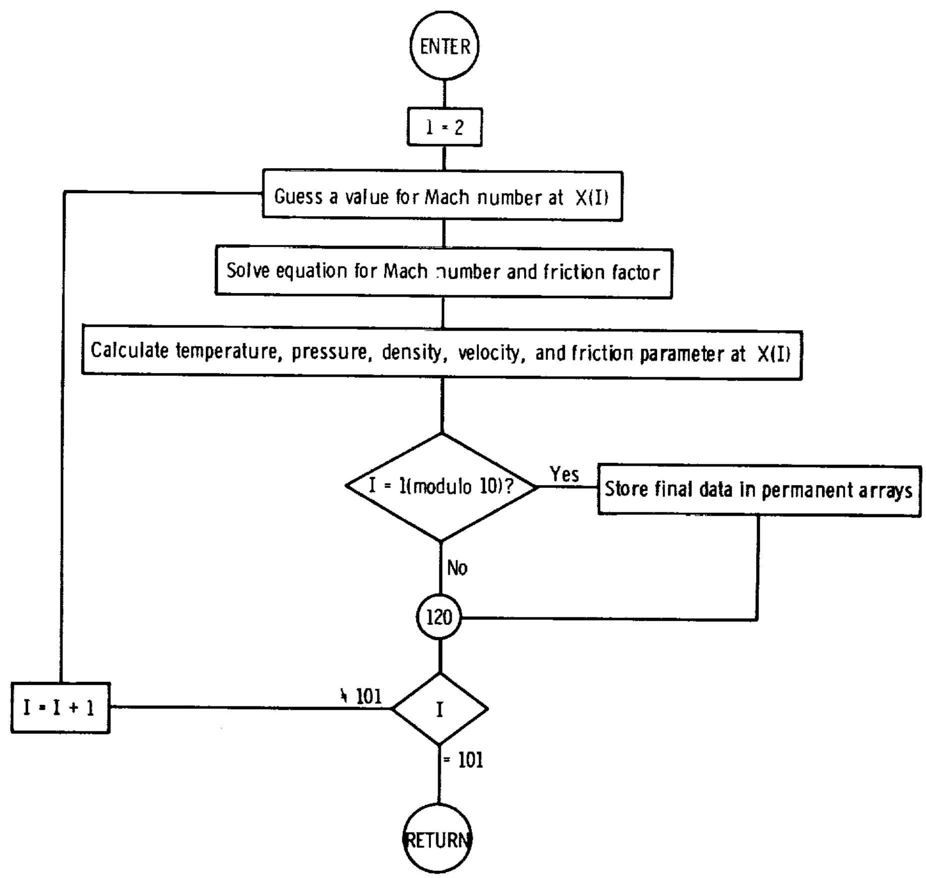


NCHOKE

Comment: Use method of iteration to solve flow equations for entrance Mach number, friction factor, and pressure Reynolds number when flow is not choked (i.e., M2 < 1, P2 = P3, L > R2 - R1, h < h*)

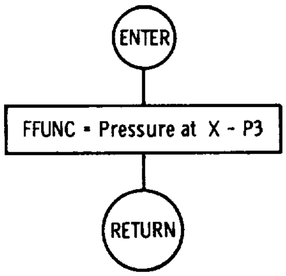


DISTS

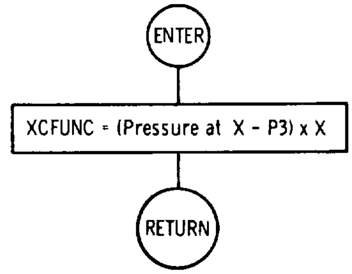


ENTER
I = 2
Guess a value for Mach number at X(I)
Solve equation for Mach number and friction factor
Calculate temperature, pressure, density, velocity, and friction parameter at X(I)
I = 1(modulo 10)?
Yes
Store final data in permanent arrays
No
120
I
≠ 101
= 101
I = I + 1
RETURN

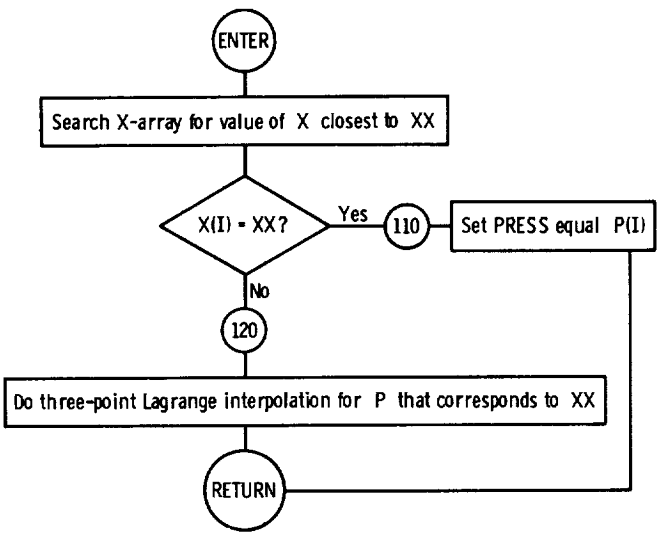
FFUNC



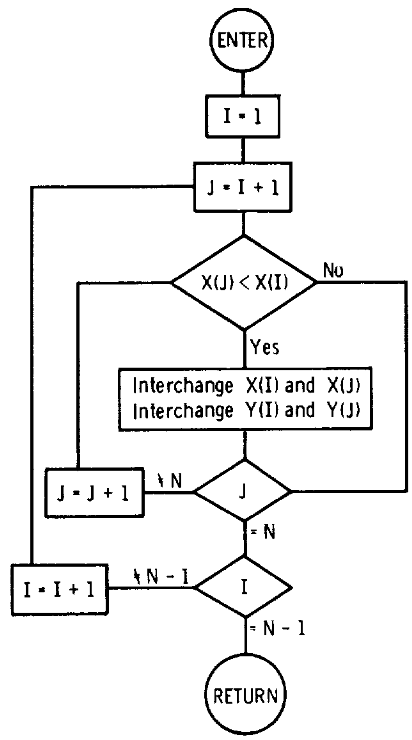
XCFUNC

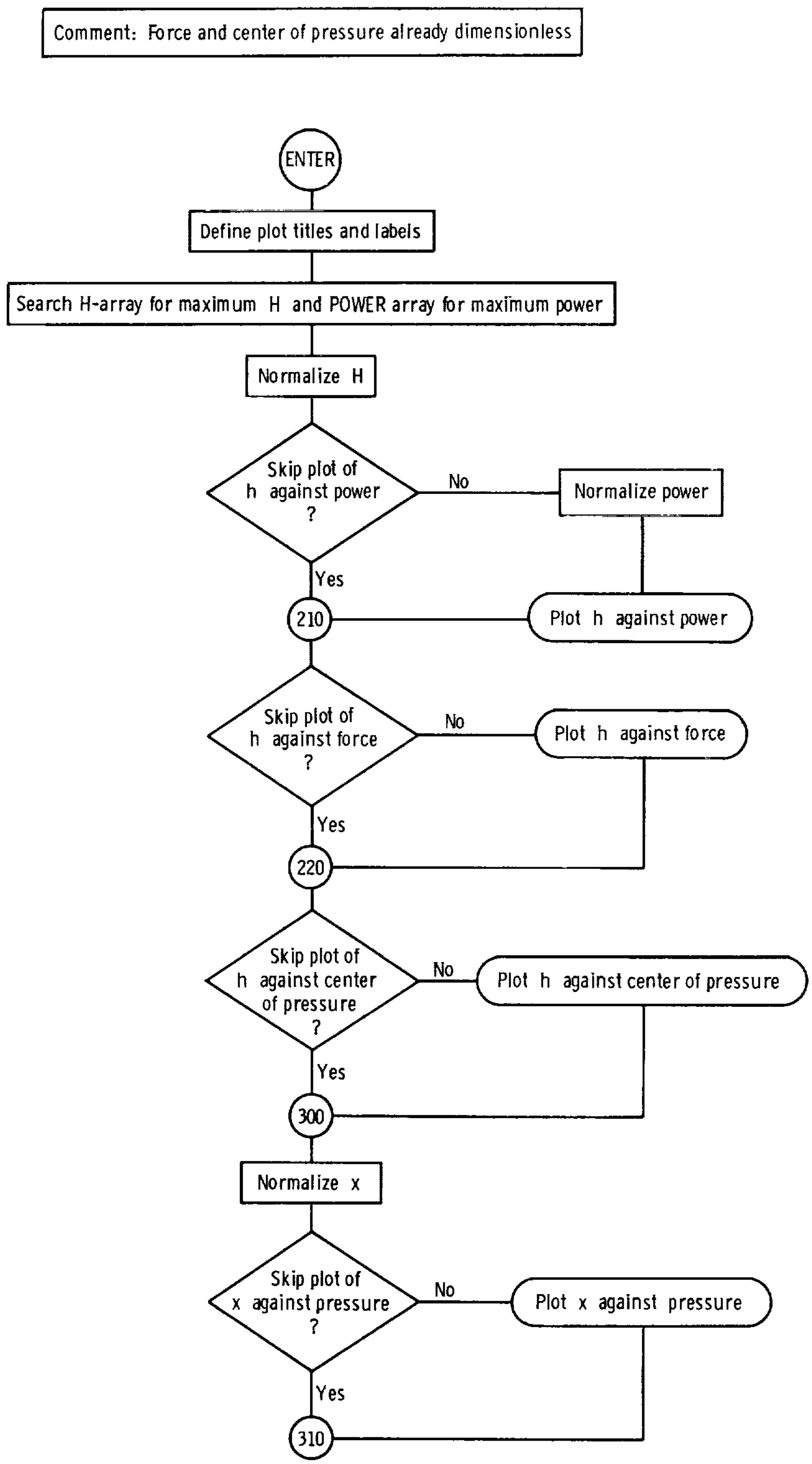


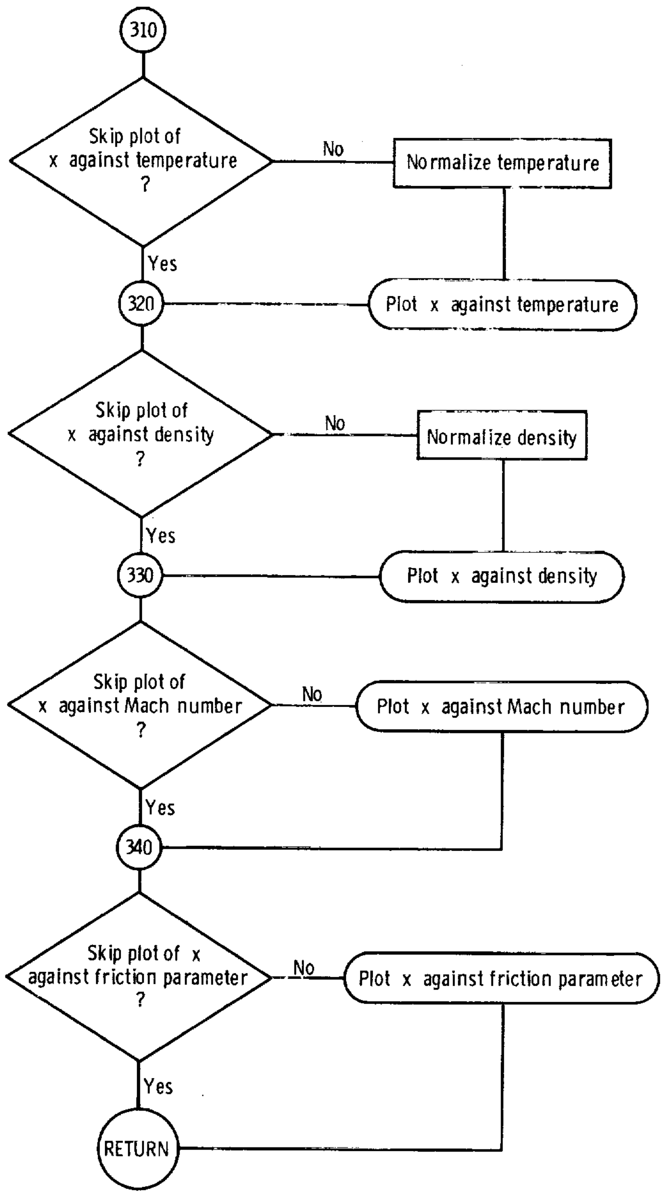
PRESS



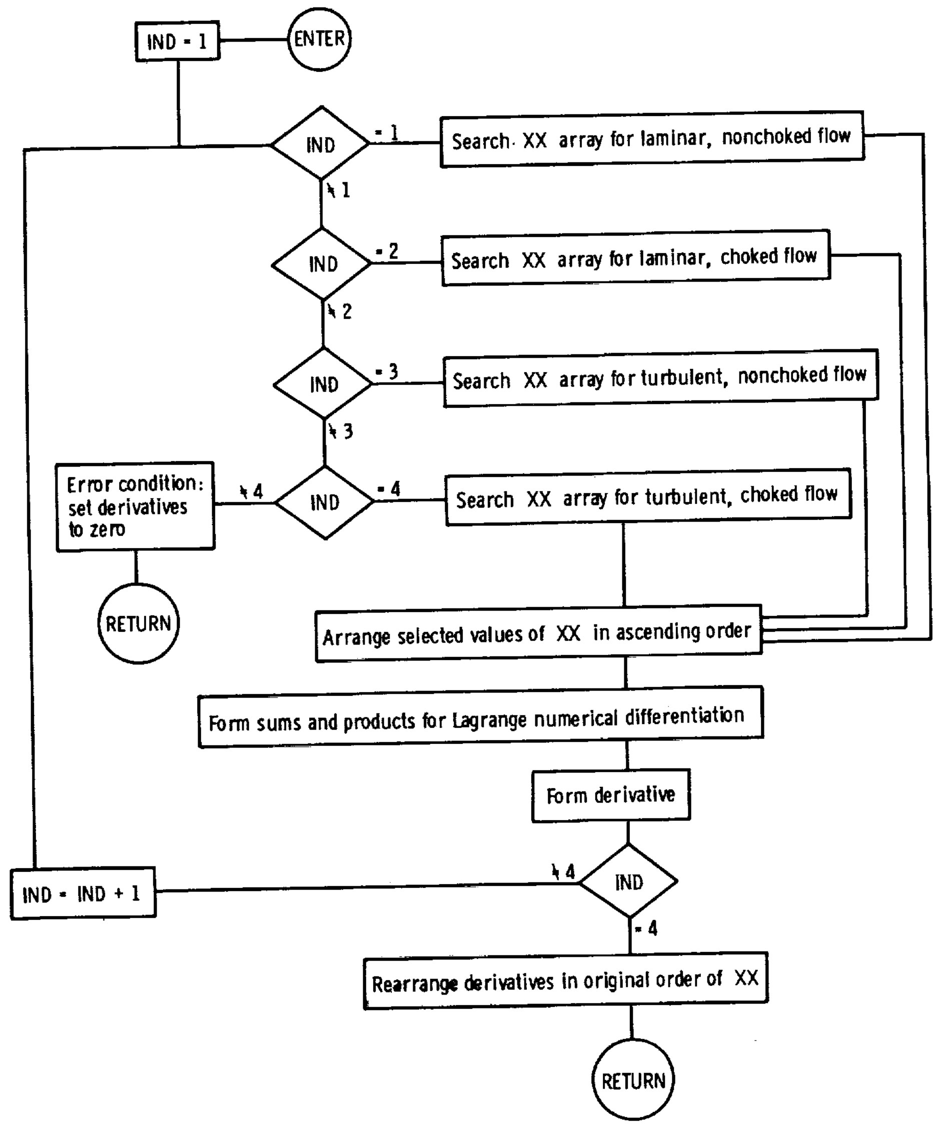
SORT

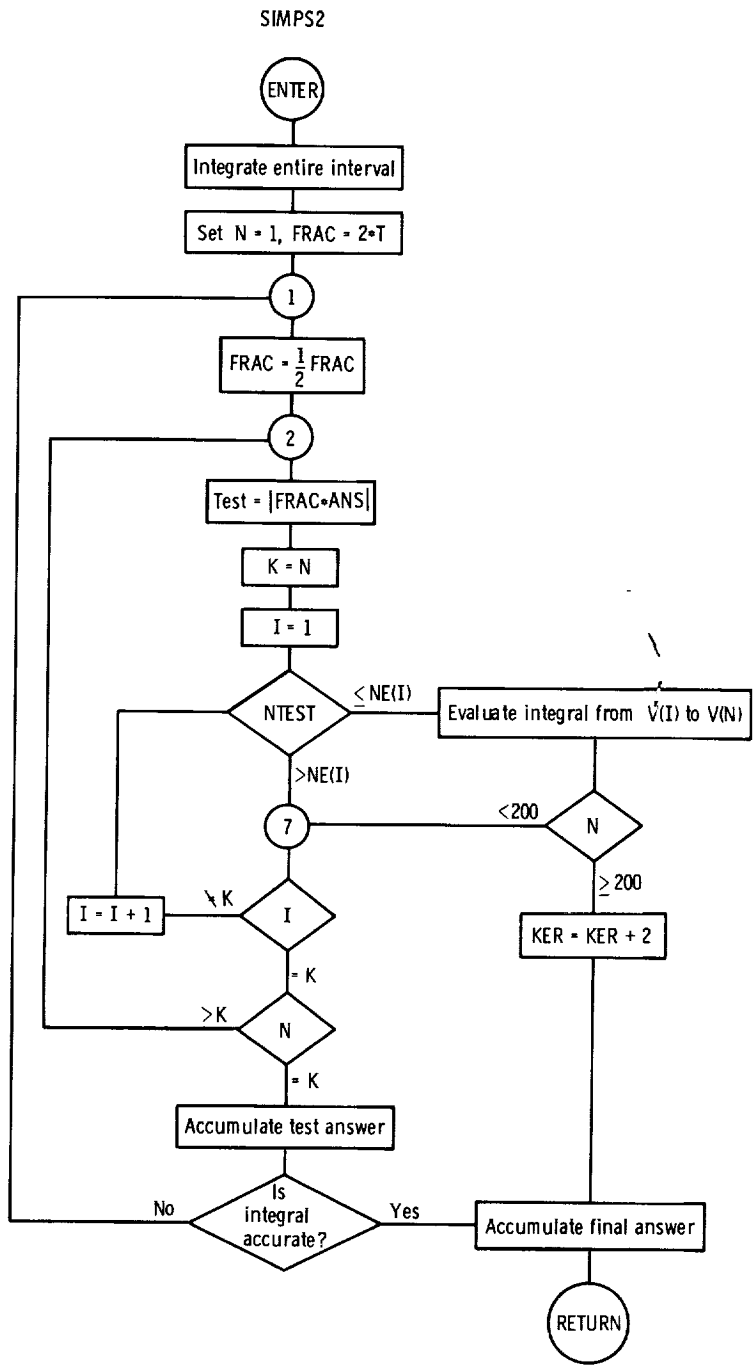



Comment: Force and center of pressure already dimensionless
ENTER
Define plot titles and labels
Search H-array for maximum H and POWER array for maximum power
Normalize H
Skip plot of h against power ?
No
Normalize power
Yes
210
Plot h against power
Skip plot of h against force ?
No
Plot h against force
Yes
220
Skip plot of h against center of pressure ?
No
Plot h against center of pressure
Yes
300
Normalize x
Skip plot of x against pressure ?
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 friction parameter ?
No
Plot x against friction parameter
Yes
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
IND
= 4
Search XX array for turbulent, choked flow
≠ 4
Error condition: set derivatives to zero
RETURN
Arrange selected values of XX in ascending order
Form sums and products for Lagrange numerical differentiation
Form derivative
IND
≠ 4
IND = IND + 1
= 4
Rearrange derivatives in original order of XX
RETURN


SIMPS2
ENTER
Integrate entire interval
Set N = 1, FRAC = 2•T
1
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 + 2
I = I + 1
≠ K
I
= K
>K
N
= K
Accumulate test answer
No
Is integral accurate?
Yes
Accumulate final answer
RETURN

APPENDIX F

SAMPLE PROBLEM

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   SAMPLE PROBLEM - INTERNATIONAL UNITS

INPUT DATA -

R1,METERS 0.929E-01	PO,NSMA 0.448E+06	MOLECULAR WEIGHT 0.290E-01	F=K/RE**N *********
R2,METERS 0.842E-01	P3,NSMA 0.103E+06	CP,JOULES/KG-DEG K 0.100E+04	K(LAMINAR) 24.000
FLOW LENGTH,METERS 0.	PO/P3 0.	GAMMA 1.400	N(LAMINAR) 0.10E+01
FLOW WIDTH,METERS 0.	TO,DEG K 310.9	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 0.929E-01	PO,NSMA 0.448E+06	MOLECULAR WEIGHT 0.029	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	PO/P3 4.333	GAMMA 1.400	PRESSURE DISTRIBUTIONS
FLOW WIDTH,METERS 0.525E+00	TO,DEG K 310.928	VISCOSITY,N-SEC/M2 0.1899E-04	PLOT **********************
AREA,M2 0.567E-03	GAS CONSTANT,JOULES/KG-DEG K 0.287E+06	SPEED,RPS 116.10	POWER XC(BAR)
	LOSS COEF. 1.00	V,M/SEC 0.610E+02	FORCE PRESSURE
			TEMPERATURE DENSITY
			MACH NUMBER 4FL/D

```
******************************
*                            *
* * - CHOKING FILM THICKNESS *
* + - TRANSITION REGION      *
* / - TURBULENT FLOW         *
*                            *
******************************
```

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   SAMPLE PROBLEM - INTERNATIONAL UNITS

	FILM THICKNESS METERS	M(DOT) KG/SEC	Q SCMS	KNUDSEN NUMBER	LAMBDA METERS	STIFFNESS N/M	FORCE N	XC METERS	FORCE BAR	XC BAR
*	0.73690E-04	0.549E-03	0.277E-05	0.266E-01	0.196E-05	-0.743E+05	141.7	0.504E-03	0.616	0.397
	0.25400E-05	0.317E-07	0.160E-09	0.855	0.217E-05	-0.412E+04	138.9	0.473E-03	0.604	0.373
	0.50800E-05	0.253E-06	0.128E-08	0.427	0.217E-05	-0.177E+04	138.9	0.474E-03	0.604	0.373
	0.76200E-05	0.855E-06	0.432E-08	0.285	0.217E-05	-589.0	138.9	0.474E-03	0.604	0.373
	0.10160E-04	0.203E-05	0.102E-07	0.214	0.217E-05	-838.0	138.9	0.474E-03	0.604	0.373
	0.12700E-04	0.396E-05	0.200E-07	0.171	0.217E-05	-0.209E+04	138.9	0.474E-03	0.604	0.373
	0.15240E-04	0.683E-05	0.345E-07	0.142	0.217E-05	-0.346E+04	138.9	0.474E-03	0.604	0.373
	0.17780E-04	0.108E-04	0.548E-07	0.122	0.217E-05	-0.524E+04	138.9	0.474E-03	0.604	0.373
	0.20320E-04	0.162E-04	0.816E-07	0.107	0.217E-05	-0.779E+04	138.9	0.474E-03	0.604	0.373
	0.22860E-04	0.230E-04	0.116E-06	0.947E-01	0.216E-05	-0.109E+05	138.9	0.474E-03	0.604	0.373
	0.25400E-04	0.314E-04	0.159E-06	0.851E-01	0.216E-05	-0.147E+05	139.0	0.474E-03	0.605	0.373
	0.27940E-04	0.416E-04	0.210E-06	0.773E-01	0.216E-05	-0.191E+05	139.0	0.475E-03	0.605	0.374
	0.30480E-04	0.537E-04	0.272E-06	0.707E-01	0.215E-05	-0.239E+05	139.1	0.475E-03	0.605	0.374
	0.33020E-04	0.679E-04	0.343E-06	0.651E-01	0.215E-05	-0.291E+05	139.1	0.476E-03	0.605	0.375
	0.35560E-04	0.841E-04	0.425E-06	0.602E-01	0.214E-05	-0.346E+05	139.2	0.476E-03	0.606	0.375
	0.38100E-04	0.102E-03	0.518E-06	0.560E-01	0.213E-05	-0.401E+05	139.3	0.477E-03	0.606	0.376
	0.40640E-04	0.123E-03	0.621E-06	0.523E-01	0.213E-05	-0.454E+05	139.4	0.478E-03	0.607	0.377
	0.43180E-04	0.146E-03	0.735E-06	0.490E-01	0.212E-05	-0.504E+05	139.6	0.479E-03	0.607	0.378
	0.45720E-04	0.170E-03	0.860E-06	0.461E-01	0.211E-05	-0.551E+05	139.7	0.481E-03	0.608	0.379

FILM THICKNESS METERS	FRICTION FACTOR	RE(P)	RE(R)	P(*) NSMA	L(*) METERS	POWER WATTS	HEAT LOSS WATTS	DEL(T) DEG K	TORQUE N-M
* 0.73690E-04	0.216	111.3	1.812	0.103E+06	0.127E-02	0.627	0.627	1.137	0.540E-02
0.25400E-05	0.378E+04	0.635E-02	0.594E-01	173.1	0.134E-02	18.53	18.53	0.582E+06	0.160
0.50800E-05	472.2	0.508E-01	0.119	692.4	0.134E-02	9.263	9.263	0.364E+05	0.798E-01
0.76200E-05	139.9	0.172	0.178	0.156E+04	0.134E-02	6.175	6.175	0.719E+04	0.532E-01
0.10160E-04	59.04	0.406	0.238	0.277E+04	0.134E-02	4.632	4.632	0.227E+04	0.399E-01
0.12700E-04	30.24	0.794	0.297	0.432E+04	0.134E-02	3.705	3.705	932.0	0.319E-01
0.15240E-04	17.51	1.371	0.357	0.622E+04	0.134E-02	3.088	3.088	449.7	0.266E-01
0.17780E-04	11.04	2.174	0.416	0.846E+04	0.134E-02	2.646	2.646	243.0	0.228E-01
0.20320E-04	7.405	3.241	0.476	0.110E+05	0.134E-02	2.315	2.315	142.6	0.199E-01
0.22860E-04	5.212	4.605	0.535	0.139E+05	0.133E-02	2.058	2.058	89.22	0.177E-01
0.25400E-04	3.811	6.298	0.595	0.172E+05	0.133E-02	1.852	1.852	58.71	0.159E-01
0.27940E-04	2.874	8.351	0.655	0.207E+05	0.133E-02	1.683	1.683	40.25	0.145E-01
0.30480E-04	2.225	10.79	0.715	0.245E+05	0.132E-02	1.542	1.542	28.56	0.133E-01
0.33020E-04	1.761	13.63	0.776	0.285E+05	0.132E-02	1.423	1.423	20.86	0.123E-01
0.35560E-04	1.421	16.89	0.837	0.328E+05	0.132E-02	1.321	1.321	15.63	0.114E-01
0.38100E-04	1.166	20.58	0.898	0.373E+05	0.131E-02	1.232	1.232	11.97	0.106E-01
0.40640E-04	0.971	24.71	0.960	0.420E+05	0.131E-02	1.154	1.154	9.343	0.994E-02
0.43180E-04	0.820	29.26	1.022	0.468E+05	0.130E-02	1.086	1.086	7.422	0.935E-02
0.45720E-04	0.701	34.24	1.085	0.517E+05	0.130E-02	1.025	1.025	5.988	0.882E-02

* FILM THICKNESS = 0.73690E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.427E+06	0.263	7.433	0.485E-02	0.292E+04	306.7
0.127E-03	0.410E+06	0.275	6.690	0.466E-02	0.305E+04	306.3
0.254E-03	0.391E+06	0.287	5.947	0.446E-02	0.318E+04	305.9
0.381E-03	0.372E+06	0.302	5.203	0.424E-02	0.335E+04	305.4
0.508E-03	0.351E+06	0.320	4.460	0.401E-02	0.354E+04	304.7
0.635E-03	0.328E+06	0.341	3.717	0.376E-02	0.377E+04	303.9
0.762E-03	0.304E+06	0.368	2.973	0.349E-02	0.406E+04	302.7
0.889E-03	0.276E+06	0.404	2.230	0.319E-02	0.445E+04	301.1
0.102E-02	0.243E+06	0.457	1.487	0.284E-02	0.500E+04	298.5
0.114E-02	0.201E+06	0.547	0.743	0.239E-02	0.594E+04	293.4
0.127E-02	0.103E+06	1.000	0	0.139E-02	0.102E+05	259.1

FILM THICKNESS = 0.25400E-05 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.423E-03	0.399E+07	0.502E-02	4.730	310.9
0.127E-03	0.426E+06	0.445E-03	0.361E+07	0.478E-02	4.971	310.9
0.254E-03	0.404E+06	0.470E-03	0.323E+07	0.452E-02	5.253	310.9
0.381E-03	0.379E+06	0.500E-03	0.286E+07	0.425E-02	5.590	310.9
0.508E-03	0.353E+06	0.537E-03	0.248E+07	0.396E-02	6.000	310.9
0.635E-03	0.325E+06	0.583E-03	0.210E+07	0.364E-02	6.518	310.9
0.762E-03	0.295E+06	0.644E-03	0.172E+07	0.330E-02	7.197	310.9
0.889E-03	0.260E+06	0.729E-03	0.135E+07	0.292E-02	8.144	310.9
0.102E-02	0.221E+06	0.859E-03	0.968E+06	0.247E-02	9.603	310.9
0.114E-02	0.172E+06	0.110E-02	0.590E+06	0.193E-02	12.30	310.9
0.127E-02	0.103E+06	0.183E-02	0.212E+06	0.116E-02	20.51	310.9

FILM THICKNESS = 0.50800E-05 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.169E-02	0.249E+06	0.502E-02	18.92	310.9
0.127E-03	0.426E+06	0.178E-02	0.226E+06	0.478E-02	19.88	310.9
0.254E-03	0.404E+06	0.188E-02	0.202E+06	0.452E-02	21.01	310.9
0.381E-03	0.379E+06	0.200E-02	0.179E+06	0.425E-02	22.36	310.9
0.508E-03	0.353E+06	0.215E-02	0.155E+06	0.396E-02	24.00	310.9
0.635E-03	0.325E+06	0.233E-02	0.131E+06	0.364E-02	26.07	310.9
0.762E-03	0.295E+06	0.257E-02	0.108E+06	0.330E-02	28.78	310.9
0.889E-03	0.260E+06	0.291E-02	0.841E+05	0.292E-02	32.57	310.9
0.102E-02	0.221E+06	0.344E-02	0.605E+05	0.247E-02	38.41	310.9
0.114E-02	0.172E+06	0.440E-02	0.369E+05	0.193E-02	49.19	310.9
0.127E-02	0.103E+06	0.733E-02	0.133E+05	0.116E-02	81.99	310.9

FILM THICKNESS = 0.76200E-05 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.381E-02	0.493E+05	0.502E-02	42.56	310.9
0.127E-03	0.426E+06	0.400E-02	0.446E+05	0.478E-02	44.73	310.9
0.254E-03	0.404E+06	0.423E-02	0.399E+05	0.452E-02	47.27	310.9
0.381E-03	0.379E+06	0.450E-02	0.353E+05	0.425E-02	50.30	310.9
0.508E-03	0.353E+06	0.483E-02	0.306E+05	0.396E-02	53.99	310.9
0.635E-03	0.325E+06	0.525E-02	0.259E+05	0.364E-02	58.65	310.9
0.762E-03	0.295E+06	0.579E-02	0.213E+05	0.330E-02	64.76	310.9
0.889E-03	0.260E+06	0.656E-02	0.166E+05	0.292E-02	73.28	310.9
0.102E-02	0.221E+06	0.773E-02	0.119E+05	0.247E-02	86.41	310.9
0.114E-02	0.172E+06	0.990E-02	0.728E+04	0.193E-02	110.7	310.9
0.127E-02	0.103E+06	0.165E-01	0.262E+04	0.116E-02	184.4	310.9

FILM THICKNESS = 0.10160E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.677E-02	0.156E+05	0.502E-02	75.65	310.9
0.127E-03	0.426E+06	0.711E-02	0.141E+05	0.478E-02	79.51	310.9
0.254E-03	0.403E+06	0.752E-02	0.126E+05	0.452E-02	84.02	310.9
0.381E-03	0.379E+06	0.800E-02	0.112E+05	0.425E-02	89.41	310.9
0.508E-03	0.353E+06	0.859E-02	0.968E+04	0.396E-02	95.97	310.9
0.635E-03	0.325E+06	0.933E-02	0.820E+04	0.364E-02	104.2	310.9
0.762E-03	0.295E+06	0.103E-01	0.673E+04	0.330E-02	115.1	310.9
0.889E-03	0.260E+06	0.117E-01	0.525E+04	0.292E-02	130.3	310.9
0.102E-02	0.221E+06	0.137E-01	0.378E+04	0.247E-02	153.6	310.9
0.114E-02	0.172E+06	0.176E-01	0.230E+04	0.193E-02	196.7	310.9
0.127E-02	0.103E+06	0.293E-01	824.0	0.116E-02	327.8	310.9

FILM THICKNESS = 0.12700E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.106E-01	0.638E+04	0.502E-02	118.2	310.9
0.127E-03	0.426E+06	0.111E-01	0.578E+04	0.478E-02	124.2	310.9
0.254E-03	0.403E+06	0.117E-01	0.517E+04	0.452E-02	131.2	310.9
0.381E-03	0.379E+06	0.125E-01	0.457E+04	0.425E-02	139.7	310.9
0.508E-03	0.353E+06	0.134E-01	0.396E+04	0.396E-02	149.9	310.9
0.635E-03	0.325E+06	0.146E-01	0.336E+04	0.364E-02	162.8	310.9
0.762E-03	0.295E+06	0.161E-01	0.275E+04	0.330E-02	179.8	310.9
0.889E-03	0.260E+06	0.182E-01	0.215E+04	0.292E-02	203.4	310.9
0.102E-02	0.221E+06	0.215E-01	0.154E+04	0.247E-02	239.8	310.9
0.114E-02	0.172E+06	0.275E-01	939.5	0.193E-02	307.1	310.9
0.127E-02	0.103E+06	0.458E-01	334.7	0.116E-02	511.8	310.8

FILM THICKNESS = 0.15240E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.152E-01	0.308E+04	0.502E-02	170.1	310.9
0.127E-03	0.426E+06	0.160E-01	0.279E+04	0.478E-02	178.7	310.9
0.254E-03	0.403E+06	0.169E-01	0.249E+04	0.452E-02	188.9	310.9
0.381E-03	0.379E+06	0.180E-01	0.220E+04	0.425E-02	201.0	310.9
0.508E-03	0.353E+06	0.193E-01	0.191E+04	0.396E-02	215.7	310.9
0.635E-03	0.325E+06	0.210E-01	0.162E+04	0.364E-02	234.3	310.9
0.762E-03	0.295E+06	0.231E-01	0.133E+04	0.330E-02	258.7	310.9
0.889E-03	0.260E+06	0.262E-01	0.103E+04	0.292E-02	292.7	310.9
0.102E-02	0.221E+06	0.309E-01	742.9	0.247E-02	345.1	310.9
0.114E-02	0.172E+06	0.395E-01	451.1	0.193E-02	441.8	310.8
0.127E-02	0.103E+06	0.659E-01	159.3	0.116E-02	736.3	310.7

FILM THICKNESS = 0.17780E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.207E-01	0.166E+04	0.502E-02	231.3	310.9
0.127E-03	0.426E+06	0.217E-01	0.150E+04	0.478E-02	243.1	310.9
0.254E-03	0.403E+06	0.230E-01	0.135E+04	0.452E-02	256.8	310.9
0.381E-03	0.379E+06	0.244E-01	0.119E+04	0.425E-02	273.3	310.9
0.508E-03	0.353E+06	0.262E-01	0.103E+04	0.396E-02	293.3	310.9
0.635E-03	0.325E+06	0.285E-01	872.7	0.365E-02	318.6	310.9
0.762E-03	0.295E+06	0.315E-01	715.0	0.330E-02	351.7	310.9
0.889E-03	0.260E+06	0.356E-01	557.4	0.292E-02	397.9	310.8
0.102E-02	0.221E+06	0.420E-01	399.7	0.248E-02	469.0	310.8
0.114E-02	0.173E+06	0.537E-01	242.0	0.193E-02	600.2	310.7
0.127E-02	0.103E+06	0.896E-01	84.34	0.116E-02	0.100E+04	310.4

FILM THICKNESS = 0.20320E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.270E-01	973.8	0.502E-02	301.7	310.9
0.127E-03	0.426E+06	0.284E-01	881.2	0.478E-02	317.0	310.9
0.254E-03	0.403E+06	0.300E-01	788.7	0.452E-02	335.0	310.9
0.381E-03	0.379E+06	0.319E-01	696.1	0.425E-02	356.4	310.9
0.508E-03	0.353E+06	0.342E-01	603.5	0.396E-02	382.5	310.9
0.635E-03	0.325E+06	0.372E-01	511.0	0.365E-02	415.4	310.8
0.762E-03	0.295E+06	0.410E-01	418.4	0.330E-02	458.5	310.8
0.889E-03	0.260E+06	0.464E-01	325.8	0.292E-02	518.6	310.8
0.102E-02	0.221E+06	0.547E-01	233.3	0.248E-02	611.1	310.7
0.114E-02	0.173E+06	0.700E-01	140.7	0.194E-02	781.9	310.6
0.127E-02	0.103E+06	0.117	48.16	0.116E-02	0.130E+04	310.1

FILM THICKNESS = 0.22860E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.341E-01	608.2	0.502E-02	381.1	310.9
0.127E-03	0.426E+06	0.358E-01	550.2	0.478E-02	400.4	310.8
0.254E-03	0.403E+06	0.379E-01	492.3	0.452E-02	423.1	310.8
0.381E-03	0.379E+06	0.403E-01	434.4	0.425E-02	450.1	310.8
0.508E-03	0.353E+06	0.432E-01	376.5	0.396E-02	483.0	310.8
0.635E-03	0.325E+06	0.469E-01	318.6	0.365E-02	524.4	310.8
0.762E-03	0.295E+06	0.518E-01	260.7	0.330E-02	578.7	310.8
0.889E-03	0.261E+06	0.586E-01	202.8	0.292E-02	654.5	310.7
0.102E-02	0.221E+06	0.690E-01	144.9	0.248E-02	770.9	310.6
0.114E-02	0.173E+06	0.883E-01	86.98	0.194E-02	985.8	310.4
0.127E-02	0.103E+06	0.147	29.07	0.116E-02	0.164E+04	309.6

FILM THICKNESS = 0.25400E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.448E+06	0.420E-01	399.3	0.502E-02	469.2	310.8
0.127E-03	0.426E+06	0.441E-01	361.2	0.477E-02	492.9	310.8
0.254E-03	0.403E+06	0.466E-01	323.1	0.452E-02	520.8	310.8
0.381E-03	0.379E+06	0.496E-01	285.0	0.425E-02	553.9	310.8
0.508E-03	0.353E+06	0.532E-01	246.9	0.396E-02	594.4	310.8
0.635E-03	0.325E+06	0.577E-01	208.8	0.365E-02	645.2	310.7
0.762E-03	0.295E+06	0.637E-01	170.7	0.331E-02	711.9	310.7
0.889E-03	0.261E+06	0.720E-01	132.6	0.292E-02	804.8	310.6
0.102E-02	0.221E+06	0.848E-01	94.49	0.248E-02	947.5	310.5
0.114E-02	0.173E+06	0.108	56.39	0.194E-02	0.121E+04	310.2
0.127E-02	0.103E+06	0.181	18.28	0.117E-02	0.202E+04	308.9

FILM THICKNESS = 0.27940E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.447E+06	0.506E-01	273.1	0.502E-02	565.6	310.8
0.127E-03	0.426E+06	0.532E-01	247.0	0.477E-02	594.2	310.8
0.254E-03	0.403E+06	0.562E-01	220.9	0.452E-02	627.7	310.7
0.381E-03	0.379E+06	0.597E-01	194.8	0.425E-02	667.5	310.7
0.508E-03	0.353E+06	0.641E-01	168.6	0.396E-02	716.1	310.7
0.635E-03	0.325E+06	0.696E-01	142.5	0.365E-02	777.2	310.6
0.762E-03	0.295E+06	0.767E-01	116.4	0.331E-02	857.2	310.6
0.889E-03	0.261E+06	0.867E-01	90.24	0.293E-02	968.6	310.5
0.102E-02	0.222E+06	0.102	64.11	0.249E-02	0.114E+04	310.3
0.114E-02	0.173E+06	0.130	37.99	0.195E-02	0.145E+04	309.9
0.127E-02	0.103E+06	0.218	11.86	0.117E-02	0.242E+04	308.0

FILM THICKNESS = 0.30480E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.447E+06	0.600E-01	193.3	0.501E-02	670.0	310.7
0.127E-03	0.426E+06	0.630E-01	174.7	0.477E-02	703.8	310.7
0.254E-03	0.403E+06	0.665E-01	156.2	0.452E-02	743.3	310.7
0.381E-03	0.379E+06	0.707E-01	137.7	0.425E-02	790.3	310.6
0.508E-03	0.353E+06	0.759E-01	119.1	0.396E-02	847.6	310.6
0.635E-03	0.326E+06	0.823E-01	100.6	0.365E-02	919.5	310.5
0.762E-03	0.295E+06	0.908E-01	82.04	0.331E-02	0.101E+04	310.4
0.889E-03	0.261E+06	0.103	63.50	0.293E-02	0.114E+04	310.3
0.102E-02	0.222E+06	0.121	44.95	0.250E-02	0.135E+04	310.0
0.114E-02	0.174E+06	0.154	26.41	0.196E-02	0.172E+04	309.5
0.127E-02	0.103E+06	0.258	7.872	0.117E-02	0.286E+04	306.9

FILM THICKNESS = 0.33020E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.447E+06	0.700E-01	140.8	0.501E-02	781.7	310.6
0.127E-03	0.425E+06	0.735E-01	127.2	0.477E-02	821.0	310.6
0.254E-03	0.403E+06	0.776E-01	113.7	0.452E-02	866.8	310.6
0.381E-03	0.379E+06	0.825E-01	100.1	0.425E-02	921.4	310.5
0.508E-03	0.353E+06	0.884E-01	86.60	0.396E-02	987.9	310.4
0.635E-03	0.326E+06	0.959E-01	73.05	0.366E-02	0.107E+04	310.4
0.762E-03	0.295E+06	0.106	59.50	0.332E-02	0.118E+04	310.2
0.889E-03	0.262E+06	0.119	45.96	0.294E-02	0.133E+04	310.0
0.102E-02	0.223E+06	0.140	32.41	0.250E-02	0.156E+04	309.7
0.114E-02	0.174E+06	0.179	18.86	0.197E-02	0.199E+04	309.0
0.127E-02	0.103E+06	0.300	5.317	0.118E-02	0.332E+04	305.4

FILM THICKNESS = 0.35560E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.446E+06	0.806E-01	105.1	0.501E-02	900.1	310.5
0.127E-03	0.425E+06	0.846E-01	94.98	0.477E-02	945.1	310.5
0.254E-03	0.402E+06	0.893E-01	84.83	0.452E-02	997.6	310.4
0.381E-03	0.379E+06	0.949E-01	74.68	0.425E-02	0.106E+04	310.4
0.508E-03	0.353E+06	0.102	64.53	0.397E-02	0.114E+04	310.3
0.635E-03	0.326E+06	0.110	54.38	0.366E-02	0.123E+04	310.2
0.762E-03	0.296E+06	0.121	44.24	0.332E-02	0.136E+04	310.0
0.889E-03	0.262E+06	0.137	34.09	0.295E-02	0.153E+04	309.8
0.102E-02	0.223E+06	0.161	23.94	0.251E-02	0.179E+04	309.3
0.114E-02	0.175E+06	0.205	13.79	0.198E-02	0.228E+04	308.3
0.127E-02	0.103E+06	0.344	3.635	0.119E-02	0.380E+04	303.7

FILM THICKNESS = 0.38100E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.446E+06	0.917E-01	80.25	0.500E-02	0.102E+04	310.4
0.127E-03	0.424E+06	0.963E-01	72.47	0.476E-02	0.108E+04	310.4
0.254E-03	0.402E+06	0.102	64.70	0.451E-02	0.113E+04	310.3
0.381E-03	0.378E+06	0.108	56.92	0.425E-02	0.121E+04	310.2
0.508E-03	0.353E+06	0.116	49.15	0.397E-02	0.129E+04	310.1
0.635E-03	0.326E+06	0.125	41.38	0.366E-02	0.140E+04	310.0
0.762E-03	0.296E+06	0.138	33.60	0.333E-02	0.154E+04	309.7
0.889E-03	0.263E+06	0.155	25.83	0.296E-02	0.173E+04	309.4
0.102E-02	0.224E+06	0.182	18.05	0.252E-02	0.203E+04	308.9
0.114E-02	0.176E+06	0.231	10.28	0.199E-02	0.257E+04	307.6
0.127E-02	0.103E+06	0.390	2.506	0.119E-02	0.429E+04	301.8

FILM THICKNESS = 0.40640E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.445E+06	0.103	62.45	0.499E-02	0.115E+04	310.3
0.127E-03	0.424E+06	0.108	56.38	0.476E-02	0.121E+04	310.2
0.254E-03	0.402E+06	0.114	50.31	0.451E-02	0.128E+04	310.1
0.381E-03	0.378E+06	0.121	44.24	0.425E-02	0.136E+04	310.0
0.508E-03	0.353E+06	0.130	38.16	0.397E-02	0.145E+04	309.9
0.635E-03	0.326E+06	0.141	32.09	0.367E-02	0.157E+04	309.7
0.762E-03	0.296E+06	0.155	26.02	0.334E-02	0.173E+04	309.4
0.889E-03	0.263E+06	0.174	19.95	0.297E-02	0.19[illegible]E+04	309.0
0.102E-02	0.225E+06	0.204	13.88	0.254E-02	0.227E+04	308.4
0.114E-02	0.177E+06	0.258	7.307	0.201E-02	0.287E+04	306.8
0.127E-02	0.103E+06	0.437	1.736	0.120E-02	0.479E+04	299.5

FILM THICKNESS = 0.43180E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.444E+06	0.115	49.45	0.499E-02	0.129E+04	310.1
0.127E-03	0.423E+06	0.121	44.62	0.476E-02	0.135E+04	310.0
0.254E-03	0.401E+06	0.128	39.80	0.451E-02	0.142E+04	309.9
0.381E-03	0.378E+06	0.135	34.98	0.425E-02	0.151E+04	309.8
0.508E-03	0.353E+06	0.145	30.15	0.397E-02	0.162E+04	309.6
0.635E-03	0.326E+06	0.157	25.33	0.367E-02	0.175E+04	309.4
0.762E-03	0.297E+06	0.172	20.50	0.335E-02	0.192E+04	309.1
0.889E-03	0.264E+06	0.194	15.68	0.298E-02	0.216E+04	308.6
0.102E-02	0.226E+06	0.226	10.85	0.255E-02	0.251E+04	307.8
0.114E-02	0.178E+06	0.286	6.028	0.203E-02	0.317E+04	305.9
0.127E-02	0.103E+06	0.485	1.203	0.121E-02	0.529E+04	297.0

FILM THICKNESS = 0.45720E-04 METERS

X METERS	P NSMA	MACH NUMBER	4FL/D	DENSITY KG/M3	V M/SEC	T DEG K
0	0.443E+06	0.128	39.77	0.498E-02	0.142E+04	309.9
0.127E-03	0.422E+06	0.134	35.86	0.475E-02	0.149E+04	309.8
0.254E-03	0.401E+06	0.141	31.98	0.451E-02	0.157E+04	309.7
0.381E-03	0.378E+06	0.150	28.09	0.425E-02	0.167E+04	309.5
0.508E-03	0.353E+06	0.160	24.20	0.398E-02	0.178E+04	309.3
0.635E-03	0.326E+06	0.173	20.30	0.368E-02	0.193E+04	309.1
0.762E-03	0.297E+06	0.190	16.41	0.335E-02	0.211E+04	308.7
0.889E-03	0.265E+06	0.213	12.51	0.299E-02	0.237E+04	308.1
0.102E-02	0.227E+06	0.248	8.620	0.257E-02	0.276E+04	307.1
0.114E-02	0.179E+06	0.313	4.726	0.205E-02	0.346E+04	305.0
0.127E-02	0.103E+06	0.533	0.832	0.122E-02	0.579E+04	294.2

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM SAMPLE PROBLEM - U. S. CUSTOMARY UNITS

INPUT DATA -

R1,INCHES
3.2650

R2,INCHES
3.3150

FLOW LENGTH,INCHES
0.

FLOW WIDTH,INCHES
0.

PO,PSIA
65.000

P3,PSIA
15.000

PO/P3
0.

TO,DEG F
100.0

LOSS COEF.
1.00

MOLECULAR WEIGHT
28.966

CP,BTU/LBM-DEG R
0.240

GAMMA
1.400

VISCOSITY,LB-SEC/IN2
0

SPEED,RPM
0.

V,FT/SEC
200.00

F=K/RE**N
****

K(LAMINAR)
24.000

N(LAMINAR)
1.00

UPPER LIMIT RE (LAMINAR)
2300.0

K(TURBULENT)
0.7900E-01

N(TURBULENT)
0.2500

LOWER LIMIT RE (TURBULENT)
3000.0

OUTPUT DATA -

R1,INCHES
3.2650

R2,INCHES
3.3150

FLOW LENGTH,INCHES
0.0500

FLOW WIDTH,INCHES
20.6717

AREA,IN2
1.0336

PO,PSIA
65.000

P3,PSIA
15.000

PO/P3
4.333

TO,DEG F
100.000

GAS CONSTANT,LB-FT/LBM-R
53.35221

LOSS COEF.
1.00

MOLECULAR WEIGHT
28.966

CP,BTU/LBM-DEG R
0.240

GAMMA
1.400

VISCOSITY,LB-SEC/IN2
0.2754E-08

SPEED,RPM
6966.1

V,FT/SEC
200.00

CALCULATE
****

POWER

DIMENSIONLESS QUANTITIES

PRESSURE DISTRIBUTIONS

PLOT
****

POWER XC(BAR)

FORCE PRESSURE

TEMPERATURE DENSITY

MACH NUMBER 4FL/D

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*                           *
* * - CHOKING FILM THICKNESS *
* + - TRANSITION REGION     *
* / - TURBULENT FLOW        *
*                           *
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QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM SAMPLE PROBLEM - U. S. CUSTCMARY UNITS

	FILM THICKNESS INCHES	M(DOT) LB/MIN	Q SCFM	KNUDSEN NUMBER	LAMBDA INCHES	STIFFNESS LB/IN	FORCE LB	XC INCHES	FORCE BAR	XC BAR
*	0.51595E-03	0.408	5.342	0.473E-02	0.244E-05	-0.258E+04	31.84	0.198E-01	0.616	0.397
	0.10000E-03	0.418E-02	0.547E-01	0.270E-01	0.270E-05	-30.00	31.23	0.186E-01	0.604	0.373
	0.20000E-03	0.330E-01	0.432	0.134E-01	0.269E-05	-679.0	31.26	0.187E-01	0.605	0.374
	0.30000E-03	0.106	1.386	0.879E-02	0.264E-05	-0.157E+04	31.37	0.189E-01	0.607	0.377
	0.40000E-03	0.226	2.961	0.638E-02	0.255E-05	-0.222E+04	31.56	0.192E-01	0.611	0.385
	0.50000E-03	0.381	4.990	0.491E-02	0.246E-05	-0.254E+04	31.80	0.197E-01	0.615	0.395
	0.60000E-03	0.557	7.286	0.345E-02	0.207E-05	-383.0	31.97	0.203E-01	0.619	0.406
	0.70000E-03	0.745	9.742	0.257E-02	0.180E-05	0.154E+04	31.91	0.207E-01	0.617	0.415
	0.80000E-03	0.939	12.28	0.203E-02	0.162E-05	0.272E+04	31.69	0.211E-01	0.613	0.422
	0.90000E-03	1.136	14.86	0.167E-02	0.150E-05	0.337E+04	31.38	0.214E-01	0.607	0.428
	0.10000E-02	1.335	17.46	0.141E-02	0.141E-05	0.369E+04	31.02	0.217E-01	0.600	0.433
+	0.11000E-02	1.520	19.88	0.123E-02	0.136E-05	0	30.74	0.218E-01	0.595	0.437
+	0.12000E-02	1.680	21.97	0.112E-02	0.134E-05	0	30.61	0.219E-01	0.592	0.438
+	0.13000E-02	1.841	24.09	0.102E-02	0.132E-05	0	30.49	0.220E-01	0.590	0.439
/	0.14000E-02	2.011	26.31	0.928E-03	0.130E-05	0.172E+04	30.33	0.220E-01	0.587	0.441
/	0.15000E-02	2.185	28.58	0.853E-03	0.128E-05	0.166E+04	30.16	0.221E-01	0.584	0.442
/	0.16000E-02	2.359	30.87	0.788E-03	0.126E-05	0.160E+04	30.00	0.222E-01	0.580	0.444
/	0.17000E-02	2.535	33.16	0.733E-03	0.125E-05	0.154E+04	29.84	0.223E-01	0.577	0.445
/	0.18000E-02	2.710	35.46	0.684E-03	0.123E-05	0.149E+04	29.69	0.223E-01	0.575	0.447

	FILM THICKNESS INCHES	FRICTION FACTOR	RE(P)	RE(R)	P(*) PSIA	L(*) INCHES	POWER H.P.	HEAT LOSS BTU/MIN	DEL(T) DEG F	TORQUE LB/FT
*	0.51595E-03	0.384E-01	625.8	322.2	15.00	0.500E-01	0.473E-02	0.201	2.048	0.224E-01
	0.10000E-03	3.782	6.345	59.41	0.793	0.527E-01	0.248E-01	1.054	0.105E+04	0.118
	0.20000E-03	0.479	50.12	119.1	3.131	0.522E-01	0.124E-01	0.526	66.41	0.588E-01
	0.30000E-03	0.149	161.0	180.3	6.696	0.513E-01	0.825E-02	0.350	13.76	0.391E-01
	0.40000E-03	0.695E-01	345.1	244.3	10.73	0.504E-01	0.615E-02	0.261	4.805	0.291E-01
	0.50000E-03	0.411E-01	584.1	311.3	14.46	0.500E-01	0.489E-02	0.207	2.265	0.232E-01
	0.60000E-03	0.280E-01	857.4	380.0			0.404E-02	0.171	1.283	0.191E-01
	0.70000E-03	0.208E-01	0.115E+04	448.9			0.344E-02	0.146	0.816	0.163E-01
	0.80000E-03	0.164E-01	0.146E+04	517.4			0.299E-02	0.127	0.563	0.142E-01
	0.90000E-03	0.135E-01	0.178E+04	585.4			0.264E-02	0.112	0.411	0.125E-01
	0.10000E-02	0.114E-01	0.210E+04	652.8			0.236E-02	0.100	0.313	0.112E-01
+	0.11000E-02	0.105E-01	0.240E+04	719.2						
+	0.12000E-02	0.106E-01	0.265E+04	785.0						
+	0.13000E-02	0.107E-01	0.291E+04	850.7						
/	0.14000E-02	0.105E-01	0.319E+04	916.5						
/	0.15000E-02	0.103E-01	0.347E+04	982.1						
/	0.16000E-02	0.101E-01	0.375E+04	0.105E+04						
/	0.17000E-02	0.991E-02	0.404E+04	0.111E+04						
/	0.18000E-02	0.974E-02	0.433E+04	0.118E+04						

* FILM THICKNESS = 0.51595E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	61.94	0.263	7.433	0.941E-02	303.5	92.33
0.500E-02	59.41	0.275	6.690	0.903E-02	316.1	91.68
0.100E-01	56.74	0.287	5.947	0.864E-02	330.5	90.91
0.150E-01	53.91	0.302	5.203	0.822E-02	347.2	89.96
0.200E-01	50.89	0.320	4.460	0.778E-02	367.1	88.79
0.250E-01	47.62	0.341	3.717	0.730E-02	391.2	87.26
0.300E-01	44.03	0.368	2.973	0.677E-02	421.5	85.21
0.350E-01	39.98	0.404	2.230	0.619E-02	461.6	82.26
0.400E-01	35.24	0.457	1.487	0.550E-02	519.2	77.56
0.450E-01	29.16	0.547	0.743	0.463E-02	616.7	68.35
0.500E-01	15.00	1.000	0	0.270E-02	0.106E+04	6.667

FILM THICKNESS = 0.10000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	64.99	0.134E-01	0.399E+04	0.974E-02	15.51	99.98
0.500E-02	61.84	0.140E-01	0.361E+04	0.926E-02	16.30	99.98
0.100E-01	58.52	0.148E-01	0.323E+04	0.877E-02	17.22	99.98
0.150E-01	55.00	0.158E-01	0.286E+04	0.824E-02	18.32	99.97
0.200E-01	51.23	0.170E-01	0.248E+04	0.768E-02	19.67	99.97
0.250E-01	47.17	0.184E-01	0.210E+04	0.707E-02	21.36	99.96
0.300E-01	42.72	0.203E-01	0.172E+04	0.640E-02	23.59	99.95
0.350E-01	37.76	0.230E-01	0.134E+04	0.566E-02	26.69	99.94
0.400E-01	32.03	0.271E-01	964.1	0.480E-02	31.46	99.92
0.450E-01	25.01	0.347E-01	585.9	0.375E-02	40.28	99.86
0.500E-01	15.00	0.579E-01	207.7	0.225E-02	67.14	99.62

FILM THICKNESS = 0.20000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	64.87	0.529E-01	250.1	0.972E-02	61.29	99.69
0.500E-02	61.75	0.555E-01	226.2	0.926E-02	64.39	99.65
0.100E-01	58.46	0.586E-01	202.2	0.876E-02	68.01	99.62
0.150E-01	54.96	0.624E-01	178.3	0.824E-02	72.33	99.56
0.200E-01	51.23	0.669E-01	154.4	0.768E-02	77.58	99.50
0.250E-01	47.21	0.726E-01	130.4	0.708E-02	84.19	99.41
0.300E-01	42.79	0.801E-01	106.5	0.642E-02	92.85	99.28
0.350E-01	37.86	0.905E-01	82.53	0.568E-02	104.9	99.08
0.400E-01	32.17	0.106	58.59	0.483E-02	123.4	98.73
0.450E-01	25.17	0.136	34.64	0.378E-02	157.5	97.94
0.500E-01	15.00	0.227	10.70	0.227E-02	262.5	94.26

FILM THICKNESS = 0.30000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	64.41	0.114	50.94	0.967E-02	131.8	98.56
0.500E-02	61.39	0.119	45.97	0.922E-02	138.2	98.41
0.100E-01	58.21	0.126	41.00	0.875E-02	145.7	98.23
0.150E-01	54.83	0.134	36.04	0.824E-02	154.7	98.01
0.200E-01	51.22	0.143	31.07	0.770E-02	165.5	97.72
0.250E-01	47.32	0.155	26.10	0.712E-02	179.0	97.33
0.300E-01	43.04	0.170	21.13	0.648E-02	196.6	96.78
0.350E-01	38.25	0.191	16.17	0.577E-02	220.8	95.94
0.400E-01	32.70	0.223	11.20	0.495E-02	257.7	94.47
0.450E-01	25.79	0.282	6.230	0.392E-02	324.8	91.22
0.500E-01	15.00	0.478	1.263	0.235E-02	542.5	75.51

FILM THICKNESS = 0.40000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	63.47	0.184	17.52	0.957E-02	213.3	96.21
0.500E-02	60.65	0.193	15.78	0.915E-02	223.1	95.86
0.100E-01	57.67	0.203	14.05	0.871E-02	234.5	95.43
0.150E-01	54.51	0.215	12.31	0.824E-02	247.8	94.89
0.200E-01	51.13	0.229	10.57	0.774E-02	263.8	94.21
0.250E-01	47.48	0.246	8.830	0.720E-02	283.7	93.30
0.300E-01	43.47	0.268	7.091	0.661E-02	309.1	92.05
0.350E-01	38.97	0.299	5.352	0.594E-02	343.7	90.17
0.400E-01	33.71	0.344	3.614	0.517E-02	395.0	87.02
0.450E-01	27.05	0.427	1.875	0.420E-02	486.2	80.33
0.500E-01	15.00	0.743	0.136	0.250E-02	818.3	44.27

FILM THICKNESS = 0.50000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	62.17	0.253	8.218	0.943E-02	291.9	92.91
0.500E-02	59.59	0.264	7.397	0.905E-02	304.1	92.30
0.100E-01	56.88	0.276	6.575	0.865E-02	318.2	91.57
0.150E-01	54.00	0.291	5.753	0.823E-02	334.6	90.68
0.200E-01	50.93	0.308	4.932	0.777E-02	354.1	89.57
0.250E-01	47.60	0.329	4.110	0.729E-02	377.8	88.12
0.300E-01	43.95	0.356	3.288	0.675E-02	407.8	86.16
0.350E-01	39.84	0.392	2.466	0.615E-02	447.5	83.33
0.400E-01	35.02	0.444	1.645	0.545E-02	504.8	78.79
0.450E-01	28.84	0.534	0.823	0.457E-02	602.7	69.77
0.500E-01	15.00	0.969	0.121E-02	0.267E-02	0.103E+04	11.46

FILM THICKNESS = 0.60000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	60.69	0.314	4.666	0.927E-02	361.2	89.14
0.500E-02	58.38	0.327	4.199	0.893E-02	375.0	88.30
0.100E-01	55.94	0.341	3.732	0.857E-02	390.6	87.30
0.150E-01	53.35	0.3[illegible]7	3.266	0.820E-02	408.7	86.10
0.200E-01	50.58	0.376	2.799	0.779E-02	429.9	84.62
0.250E-01	47.59	0.399	2.333	0.736E-02	455.3	82.75
0.300E-01	44.31	0.427	1.866	0.688E-02	486.9	80.27
0.350E-01	40.61	0.465	1.400	0.635E-02	527.8	76.82
0.400E-01	36.26	0.518	0.933	0.572E-02	585.2	71.50
0.450E-01	30.68	0.606	0.467	0.493E-02	678.8	61.65
0.500E-01	17.59	1.000	0	0.316E-02	0.106E+04	6.667

FILM THICKNESS = 0.70000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	59.19	0.368	2.975	0.911E-02	421.5	85.22
0.500E-02	57.10	0.381	2.677	0.880E-02	436.1	84.17
0.100E-01	54.90	0.396	2.380	0.848E-02	452.5	82.96
0.150E-01	52.57	0.413	2.082	0.814E-02	471.3	81.51
0.200E-01	50.08	0.433	1.785	0.778E-02	493.2	79.76
0.250E-01	47.38	0.457	1.487	0.739E-02	519.2	77.57
0.300E-01	44.41	0.486	1.190	0.697E-02	550.9	74.74
0.350E-01	41.07	0.524	0.892	0.649E-02	591.4	70.89
0.400E-01	37.15	0.576	0.595	0.593E-02	646.9	65.17
0.450E-01	32.09	0.660	0.297	0.523E-02	734.5	55.10
0.500E-01	20.16	1.000	0	0.362E-02	0.106E+04	6.667

FILM THICKNESS = 0.80000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	57.74	0.415	2.053	0.895E-02	473.3	81.36
0.500E-02	55.85	0.429	1.848	0.867E-02	488.3	80.16
0.100E-01	53.85	0.444	1.642	0.839E-02	505.0	78.77
0.150E-01	51.74	0.461	1.437	0.808E-02	524.0	77.14
0.200E-01	49.48	0.481	1.232	0.776E-02	546.0	75.19
0.250E-01	47.04	0.505	1.027	0.741E-02	571.8	72.79
0.300E-01	44.35	0.534	0.821	0.702E-02	603.0	69.74
0.350E-01	41.32	0.571	0.616	0.659E-02	642.3	65.67
0.400E-01	37.75	0.622	0.411	0.609E-02	695.1	59.79
0.450E-01	33.15	0.701	0.205	0.545E-02	776.5	49.83
0.500E-01	22.24	1.000	0	0.400E-02	0.106E+04	6.667

FILM THICKNESS = 0.90000E-03 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	56.37	0.456	1.500	0.880E-02	517.9	77.67
0.500E-02	54.65	0.469	1.350	0.855E-02	533.0	76.36
0.100E-01	52.84	0.485	1.200	0.829E-02	549.7	74.85
0.150E-01	50.91	0.502	1.050	0.801E-02	568.6	73.09
0.200E-01	48.86	0.522	0.900	0.772E-02	590.2	71.01
0.250E-01	46.63	0.546	0.750	0.740E-02	615.5	68.47
0.300E-01	44.17	0.575	0.600	0.705E-02	645.8	65.29
0.350E-01	41.41	0.611	0.450	0.667E-02	683.5	61.12
0.400E-01	38.15	0.659	0.300	0.621E-02	733.5	55.23
0.450E-01	33.93	0.734	0.150	0.563E-02	809.0	45.53
0.500E-01	23.93	1.000	0	0.430E-02	0.106E+04	6.667

FILM THICKNESS = 0.10000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	55.12	0.491	1.143	0.865E-02	556.5	74.22
0.500E-02	53.54	0.505	1.029	0.843E-02	571.4	72.82
0.100E-01	51.88	0.520	0.915	0.819E-02	588.0	71.23
0.150E-01	50.12	0.538	0.800	0.794E-02	606.5	69.38
0.200E-01	48.23	0.558	0.686	0.767E-02	627.7	67.21
0.250E-01	46.18	0.581	0.572	0.739E-02	652.2	64.60
0.300E-01	43.93	0.609	0.457	0.707E-02	681.4	61.36
0.350E-01	41.39	0.643	0.343	0.671E-02	717.4	57.17
0.400E-01	38.40	0.690	0.229	0.630E-02	764.6	51.34
0.450E-01	34.53	0.760	0.114	0.577E-02	834.9	41.99
0.500E-01	25.30	1.000	0	0.455E-02	0.106E+04	6.667

FILM THICKNESS = 0.11000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	54.23	0.515	0.950	0.855E-02	582.7	71.75
0.500E-02	52.75	0.529	0.855	0.834E-02	597.4	70.30
0.100E-01	51.19	0.544	0.760	0.812E-02	613.7	68.66
0.150E-01	49.53	0.562	0.665	0.789E-02	631.9	66.77
0.200E-01	47.76	0.581	0.570	0.764E-02	652.6	64.56
0.250E-01	45.84	0.604	0.475	0.737E-02	676.5	61.91
0.300E-01	43.73	0.631	0.380	0.707E-02	704.8	58.66
0.350E-01	41.34	0.665	0.285	0.674E-02	739.5	54.49
0.400E-01	38.52	0.710	0.190	0.635E-02	784.7	48.75
0.450E-01	34.88	0.777	0.950E-01	0.586E-02	851.3	39.69
0.500E-01	26.18	1.000	0	0.471E-02	0.106E+04	6.667

FILM THICKNESS = 0.12000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	53.86	0.525	0.881	0.851E-02	593.3	70.71
0.500E-02	52.42	0.539	0.793	0.831E-02	607.9	69.25
0.100E-01	50.90	0.554	0.705	0.809E-02	624.1	67.59
0.150E-01	49.29	0.571	0.616	0.787E-02	642.1	65.68
0.200E-01	47.56	0.591	0.528	0.762E-02	662.6	63.46
0.250E-01	45.69	0.613	0.440	0.736E-02	686.2	60.81
0.300E-01	43.63	0.640	0.352	0.707E-02	714.1	57.56
0.350E-01	41.31	0.674	0.264	0.675E-02	748.3	53.40
0.400E-01	38.56	0.718	0.176	0.637E-02	792.7	47.71
0.450E-01	35.01	0.783	0.881E-01	0.589E-02	857.8	38.77
0.500E-01	26.53	1.000	0	0.477E-02	0.106E+04	6.667

FILM THICKNESS = 0.13000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	53.51	0.535	0.820	0.847E-02	603.1	69.73
0.500E-02	52.11	0.548	0.738	0.827E-02	617.6	68.25
0.100E-01	50.63	0.563	0.656	0.807E-02	633.7	66.58
0.150E-01	49.05	0.580	0.574	0.784E-02	651.6	64.66
0.200E-01	47.37	0.600	0.492	0.761E-02	671.9	62.43
0.250E-01	45.55	0.622	0.410	0.735E-02	695.2	59.78
0.300E-01	43.54	0.649	0.328	0.707E-02	722.7	56.53
0.350E-01	41.27	0.682	0.246	0.676E-02	756.4	52.39
0.400E-01	38.59	0.725	0.164	0.639E-02	800.0	46.74
0.450E-01	35.12	0.790	0.820E-01	0.592E-02	863.6	37.93
0.500E-01	26.85	1.000	0	0.483E-02	0.106E+04	6.667

FILM THICKNESS = 0.14000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	53.07	0.546	0.751	0.842E-02	615.3	68.49
0.500E-02	51.71	0.560	0.676	0.823E-02	629.7	67.00
0.100E-01	50.28	0.575	0.601	0.803E-02	645.6	65.31
0.150E-01	48.76	0.591	0.526	0.782E-02	663.3	63.38
0.200E-01	47.13	0.611	0.451	0.759E-02	683.3	61.14
0.250E-01	45.36	0.633	0.375	0.734E-02	706.3	58.48
0.300E-01	43.42	0.659	0.300	0.707E-02	733.3	55.24
0.350E-01	41.22	0.691	0.225	0.676E-02	766.3	51.13
0.400E-01	38.62	0.734	0.150	0.641E-02	808.9	45.55
0.450E-01	35.26	0.797	0.751E-01	0.595E-02	870.8	36.89
0.500E-01	27.23	1.000	0	0.490E-02	0.106E+04	6.667

FILM THICKNESS = 0.15000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	52.63	0.558	0.686	0.837E-02	627.7	67.21
0.500E-02	51.31	0.571	0.618	0.819E-02	641.9	65.71
0.100E-01	49.93	0.586	0.549	0.799E-02	657.6	64.01
0.150E-01	48.45	0.603	0.480	0.779E-02	675.1	62.07
0.200E-01	46.88	0.622	0.412	0.757E-02	694.8	59.83
0.250E-01	45.17	0.643	0.343	0.733E-02	717.4	57.17
0.300E-01	43.29	0.669	0.274	0.707E-02	743.9	53.94
0.350E-01	41.16	0.701	0.206	0.677E-02	776.2	49.86
0.400E-01	38.64	0.743	0.137	0.643E-02	817.7	44.35
0.450E-01	35.39	0.804	0.686E-01	0.599E-02	877.9	35.86
0.500E-01	27.61	1.000	0	0.496E-02	0.106E+04	6.667

FILM THICKNESS = 0.16000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	52.21	0.568	0.631	0.833E-02	639.1	66.01
0.500E-02	50.93	0.582	0.568	0.815E-02	653.1	64.50
0.100E-01	49.59	0.597	0.505	0.796E-02	668.7	62.79
0.150E-01	48.17	0.613	0.442	0.776E-02	685.9	60.85
0.200E-01	46.64	0.632	0.378	0.754E-02	705.3	58.60
0.250E-01	44.98	0.653	0.315	0.731E-02	727.5	55.95
0.300E-01	43.16	0.679	0.252	0.706E-02	753.6	52.74
0.350E-01	41.09	0.710	0.189	0.678E-02	785.2	48.69
0.400E-01	38.66	0.751	0.126	0.644E-02	825.7	43.26
0.450E-01	35.50	0.811	0.631E-01	0.602E-02	884.3	34.92
0.500E-01	27.95	1.000	0	0.502E-02	0.106E+04	6.667

FILM THICKNESS = 0.17000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	51.82	0.578	0.583	0.828E-02	649.6	64.88
0.500E-02	50.58	0.592	0.525	0.811E-02	663.6	63.35
0.100E-01	49.28	0.606	0.466	0.792E-02	678.9	61.64
0.150E-01	47.89	0.623	0.408	0.773E-02	695.9	59.70
0.200E-01	46.41	0.641	0.350	0.752E-02	715.0	57.45
0.250E-01	44.80	0.663	0.291	0.730E-02	736.9	54.81
0.300E-01	43.03	0.688	0.233	0.706E-02	762.5	51.62
0.350E-01	41.03	0.718	0.175	0.678E-02	793.4	47.61
0.400E-01	38.66	0.758	0.117	0.646E-02	833.1	42.24
0.450E-01	35.60	0.817	0.583E-01	0.604E-02	890.1	34.06
0.500E-01	28.26	1.000	0	0.508E-02	0.106E+04	6.667

FILM THICKNESS = 0.18000E-02 INCHES

X INCHES	P PSIA	MACH NUMBER	4FL/D	DENSITY LB-SEC2/FT4	V FT/SEC	T DEG F
0	51.45	0.588	0.541	0.824E-02	659.5	63.80
0.500E-02	50.24	0.601	0.487	0.807E-02	673.3	62.27
0.100E-01	48.98	0.615	0.433	0.789E-02	688.4	60.56
0.150E-01	47.63	0.632	0.379	0.771E-02	705.2	58.61
0.200E-01	46.19	0.650	0.325	0.750E-02	724.0	56.37
0.250E-01	44.63	0.671	0.271	0.729E-02	745.6	53.74
0.300E-01	42.91	0.696	0.216	0.705E-02	770.7	50.57
0.350E-01	40.96	0.726	0.162	0.678E-02	801.1	46.60
0.400E-01	38.66	0.765	0.108	0.647E-02	839.8	41.30
0.450E-01	35.68	0.822	0.541E-01	0.607E-02	895.5	33.27
0.500E-01	28.54	1.000	0	0.513E-02	0.106E+04	6.667

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5. Nielsen, Kaj L.: Methods in Numerical Analysis. Macmillan Co., 1956.

TABLE I. - PARAMETERS CALCULATED BY QUASC

Parameter	Formula[a]	Units	
		SI	U. S.
Gas constant	$\mathcal{R} = \dfrac{\text{Universal gas constant}}{\text{Molecular weight}}$	J/kg-K	$\dfrac{\text{lbf-in.}}{\text{lbm-}^{\circ}\text{R}}$
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 leakage flow	$Re(p) = \rho u2h/\mu$	--------	----------
Reynolds number due to rotational flow	[b]$Re(r) = \bar{\rho}Vh/\bar{\mu}$	--------	----------
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)	$\mu_{air} = \dfrac{c_2 T^{1.5}}{T + c_3}$	$N\text{-sec}/m^2$	lbf-sec/in.^{2}
Power	$\bar{\mu}AV^2/h$	W	hp
Apparent temperature rise due to power dissipation	$T = \dfrac{c_4 \times \text{Power}}{\dot{M}c_p}$	K	$^{\circ}R$
Shear heat	$H = c_5 \times \text{Power}$	W	Btu/min
Torque	Power/Speed	N-m	ft-lb
Sealing dam force	$F = W\displaystyle\int_0^{\Delta R} (P - P_3)dx$	N	lbf
Center of pressure	$x_c = \dfrac{W}{F}\displaystyle\int_0^{\Delta R} (P - P_3)\ x\ dx$	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/SDATA/

Variable name	Description	Units	
		SI	U. S.
R1IN	Inner radius of seal	m	in.
R2IN	Outer radius of seal	m	in.
RDIFIN	Flow length	m	in.
WIDTH	Mean flow width	m	in.
MOLWT	Molecular weight		
CP	Specific heat	J/(kg)(K)	Btu/(lbm)(^{o}R)
MU	Reservoir viscosity. The program will calculate MU 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. (10))	---	---
CONLAM	Constant in friction factor - Reynolds number relation for laminar flow	---	---
XTURB	Exponent in friction factor - Reynolds number relation for turbulent 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. It 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, and $4\bar{f}(L - x)/D$ 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 $4\bar{f}(L - x)/D$ against x.	---	---
SKPH	Logical variable. If it is set to .TRUE., no film thickness data will be read.	---	---
NOSI	Logical variable. If it is set to .TRUE., input, internal calculations, and output will be in U.S units. If it is set to .FALSE., input, internal calculations, and output will be in SI units.	---	---

TABLE III. - VARIABLES IN NAMELIST/PDATA/

Variable name	Description	Units	
		SI	U. S.
POIN	Sealed gas pressure (upstream reservoir pressure), P_0	N/m^2	$lbf/in.^2$
P3IN	Ambient pressure (downstream reservoir pressure), P_3	N/m^2	$lbf/in.^2$
PRIN	Sealed gas/ambient pressure ratio, P_0/P_3	---	---
TOIN	Sealed gas temperature (upstream reservoir temperature), T_0	K	^{o}F
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 and new SDATA are expected. INCODE = 2 means new film thickness data are expected. INCODE = 3 means new PDATA are expected.	---	---

TABLE IV. - DATA SHEET FOR SAMPLE PROBLEM

Card column												
1-6	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    -   INTERNATIONAL UNITS
 $SDATA R1IN= .082931, R2IN= .084201, RDIFIN=0., WIDTH=0., MOLWT=28.966,
 CP=1.0047788E3, GAMMA=1.4, MU=0., SPEED=0., CAPV=60.96, XLAM=1., XTURB=0.25,
 CONLAM=24., CONTRB=.079, RELAM=2300., RETURB=3000., PWRSKP=F, PRSSKP=F,
 NRMSKP=F, PLTSKP=8*F, NOSI=F, SKPH=F $
 18
.00000254    .00000508    .00000762    .00001016    .00001270    .00001524
.00001778    .00002032    .00002286    .00002540    .00002794    .00003048
.00003302    .00003556    .00003810    .00004064    .00004318    .00004572
 $PDATA POIN=448158.57, P3IN=103421.21, PRIN=0., TOIN=310.92778, LOSS=1.,
 INCODE=1 $
     SAMPLE PROBLEM    -   U. S. CUSTOMARY UNITS
 $SDATA R1IN=3.265, R2IN=3.315, RDIFIN=0., WIDTH=0., MOLWT=28.966, CP=.24,
 GAMMA=1.4, MU=0., SPEED=0., CAPV=200., XLAM=1., XTURB=0.25, CONLAM=24.,
 CONTRB=.079, RELAM=2300., RETURB=3000., PWRSKP=F, PRSSKP=F, NRMSKP=F,
 PLTSKP=8*F, NOSI=T, SKPH=F $
 18
.0001        .0002        .0003        .0004        .0005        .0006
.0007        .0008        .0009        .0010        .0011        .0012
.0013        .0014        .0015        .0016        .0017        .0018
 $PDATA POIN=65., P3IN=15., PRIN=0., TOIN=100., LOSS=1., INCODE=1 $
```

TABLE V. - STEPS IN SOLUTION OF EQUATION (C3) BY METHOD OF ITERATION

Guessed value of M	G(M)	Are M and G(M) equal?
0.1	0.3841	No
.3841	.4926	No
.4926	.5078	No
.5078	.5087	No
.5087	.5087	Yes

TABLE VI. - PARAMETERS IN COMMON BLOCK /CONSTS/

Word number	Symbol	Description
1	γ	Ratio of specific heats
2	ΔR	Flow length
3	n_l	Exponent in friction factor - Reynolds number relation for laminar flow
4	k_l	Constant in friction factor - Reynolds number relation for laminar flow
5	n_t	Exponent in friction factor - Reynolds number relation for turbulent flow
6	k_t	Constant in friction factor - Reynolds number relation for turbulent flow
7	T_0	Sealed gas reservoir temperature
8	P_0	Sealed gas reservoir pressure
9	P_3	Ambient pressure
10	P_{tol}	Pressure tolerance to stop iteration on exit pressure for subcritical flow
11	$\mathcal{R}$	Gas constant
12	C_L	Entrance velocity loss coefficient
13	$(Re)_l$	Upper limit on Re for laminar flow
14	$(Re)_t$	Lower limit on Re for turbulent flow
15	μ_0	Sealed gas reservoir viscosity
16	T^*	Temperature at point of choking

TABLE VII. - PARAMETERS IN COMMON BLOCK /ARRAYS/

Array number	Symbol	Array dimension	Description
1	x	(101)	Distance across face of seal
2	P	(20, 101)	Pressure
3	M	(20, 11)	Mach number
4	u	(20, 11)	Leakage flow velocity (x-direction)
5	T	(20, 11)	Temperature
6	ρ	(20, 11)	Density
7	B	(20, 11)	Friction parameter, $B = 4\bar{f}(L - x)/D$
8	h	(20)	Film thickness (first element is h^*)
9	$\bar{x}_c$	(20)	Dimensionless center of pressure
10	L	(20)	Distance from entrance to point of choking
11	P^*	(20)	Choking pressure
12	Re	(20)	Reynolds number
13	$\bar{f}$	(20)	Mean friction factor
14	---	(20)	Power
15	F	(20)	Force

TABLE VIII. - PARAMETERS IN COMMON BLOCK /CONVRT/

Word number in array CONV	Variable to which constant applies	Word number in array CONV	Variable to which constant applies
1	Temperature	7	Reynolds number
2	Sutherland's law	8	Power
3	Sutherland's law	9	Temperature difference
4	Speed	10	Torque
5	Mass flow rate	11	Velocity
6	Standard volume flow	12	Density

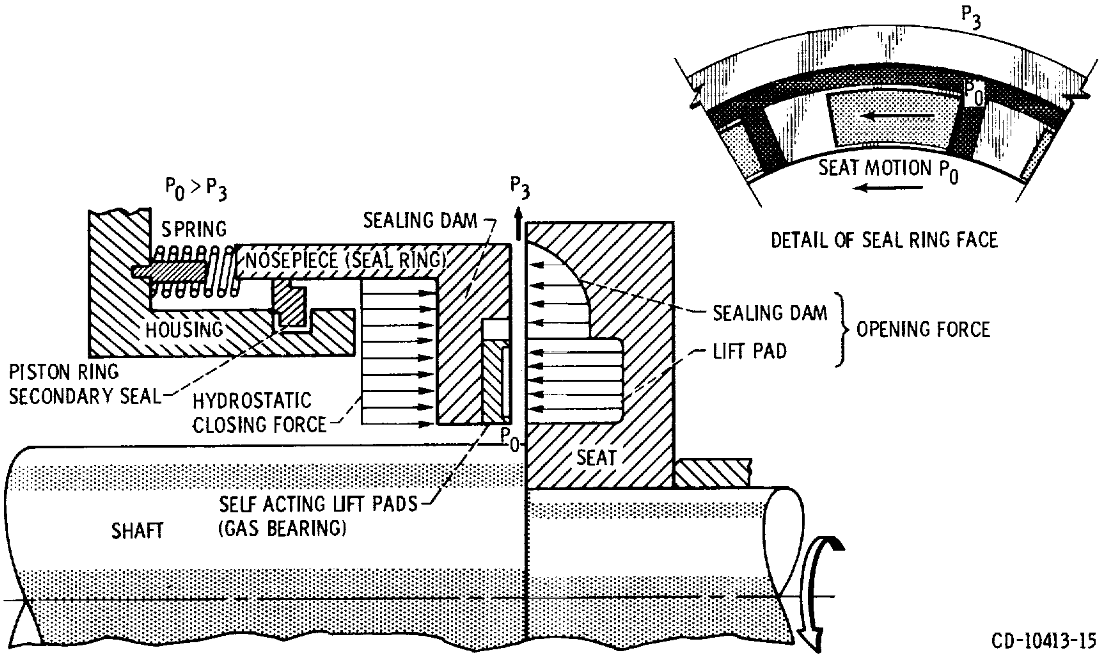

Figure 1. - Pressure-balanced face seal with a gas bearing added for axial film stiffness.

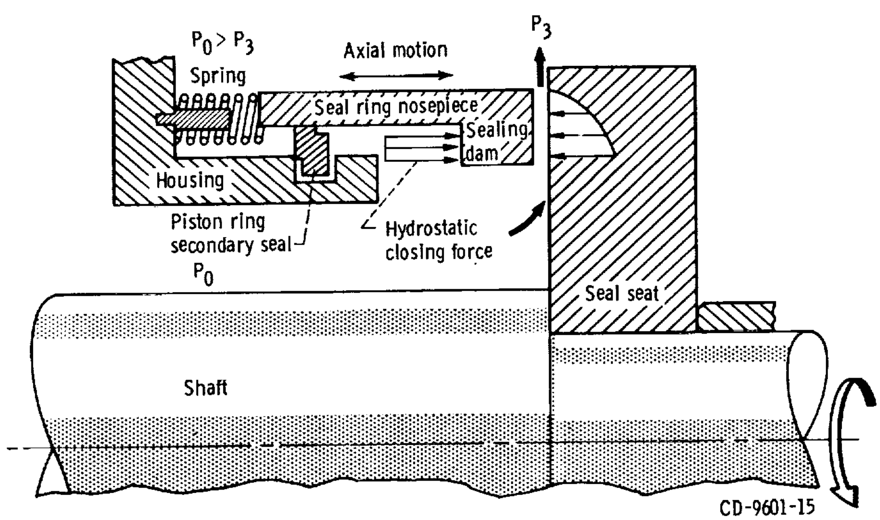

Figure 2. - Pressure-balanced face seal with no axial film stiffness.

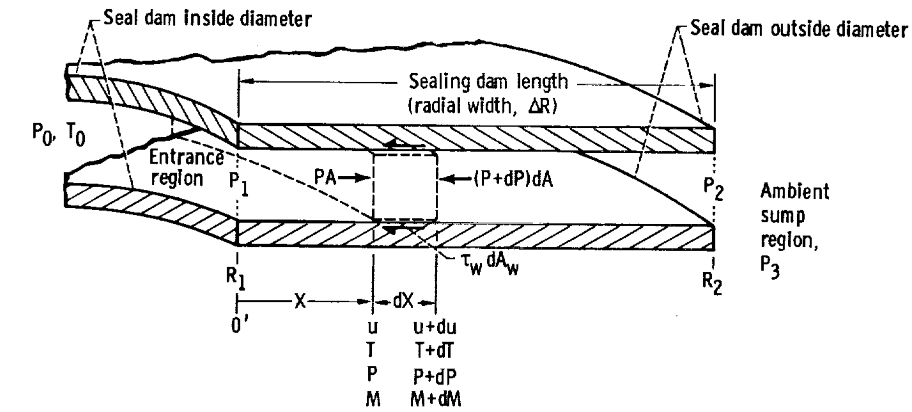

Figure 3. - Model and notation of sealing faces, including control volume for quasi-one-dimensional flow.

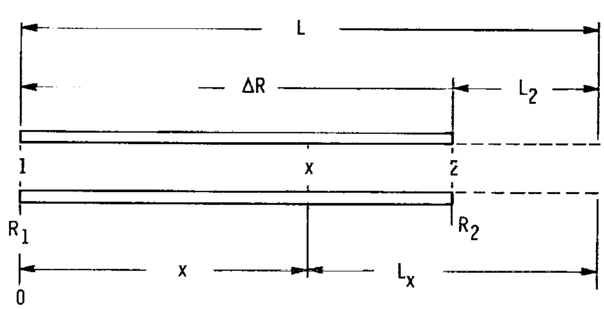

Figure 4. - Lengths and stations used in the analysis. (Subsonic case is shown.)

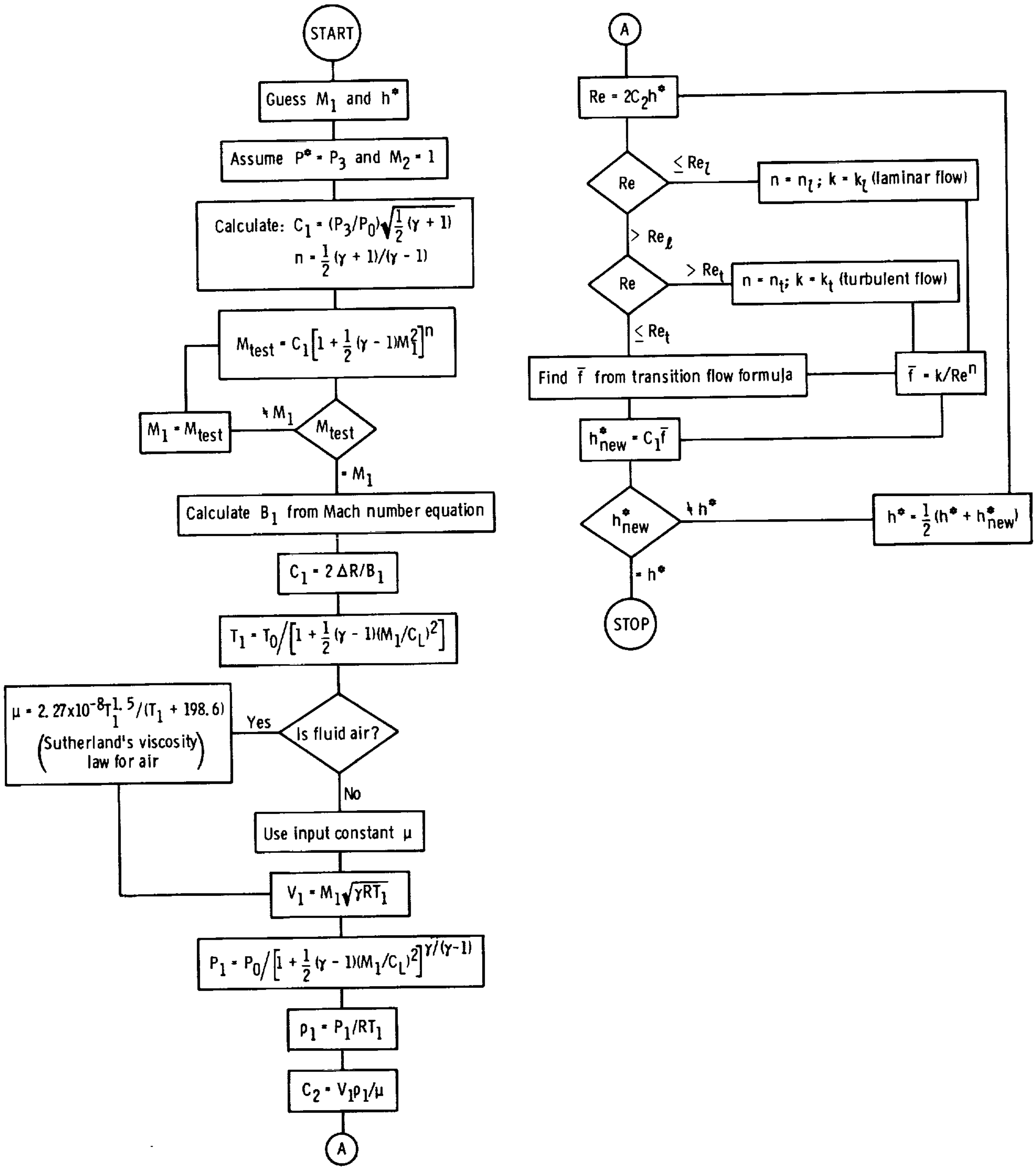

Figure 5. - Block diagram of solution scheme for finding choking film thickness.

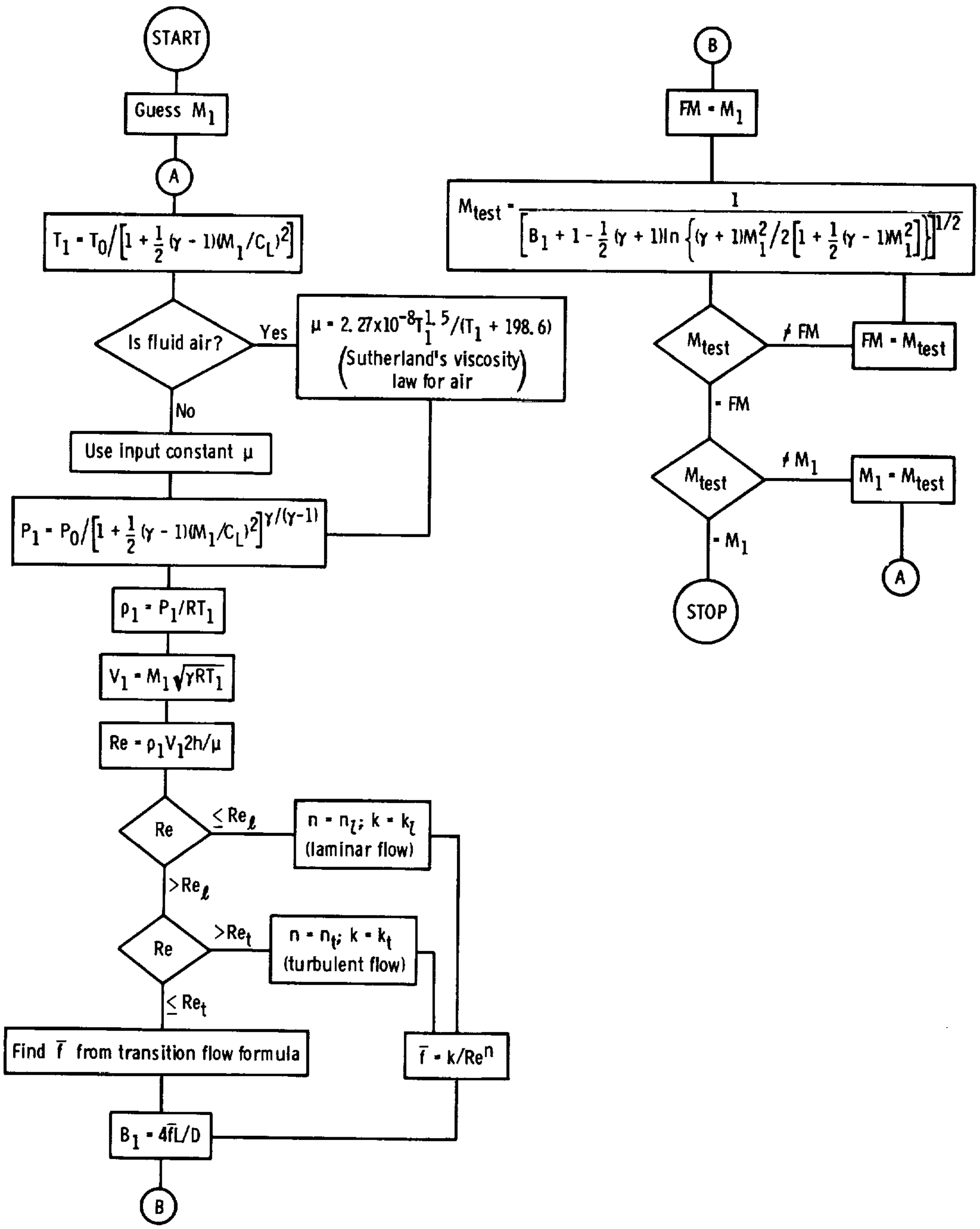

Figure 6. - Block diagram of solution scheme for choked flow.

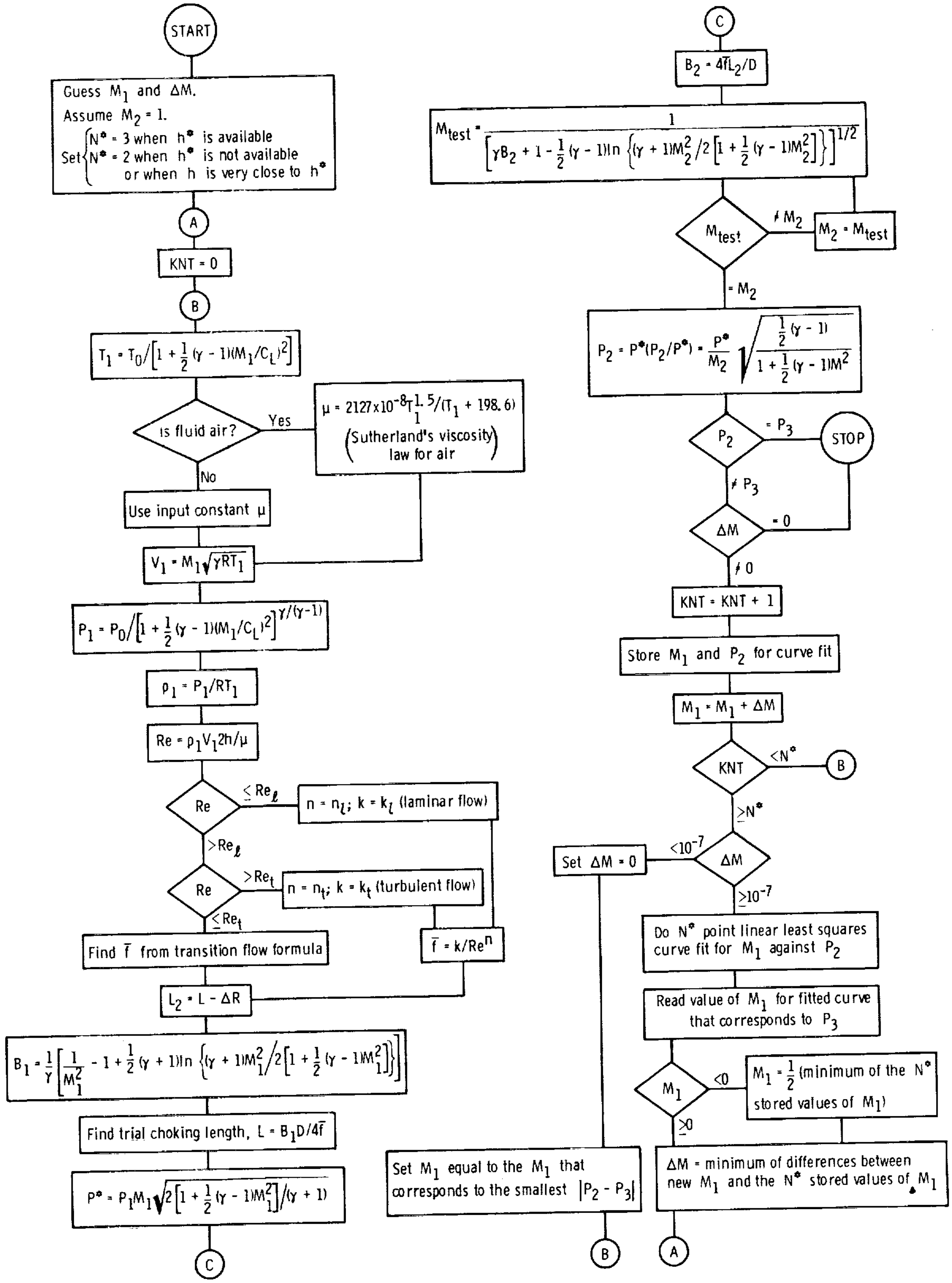

Figure 7. - Block diagram of solution scheme for subsonic flow.

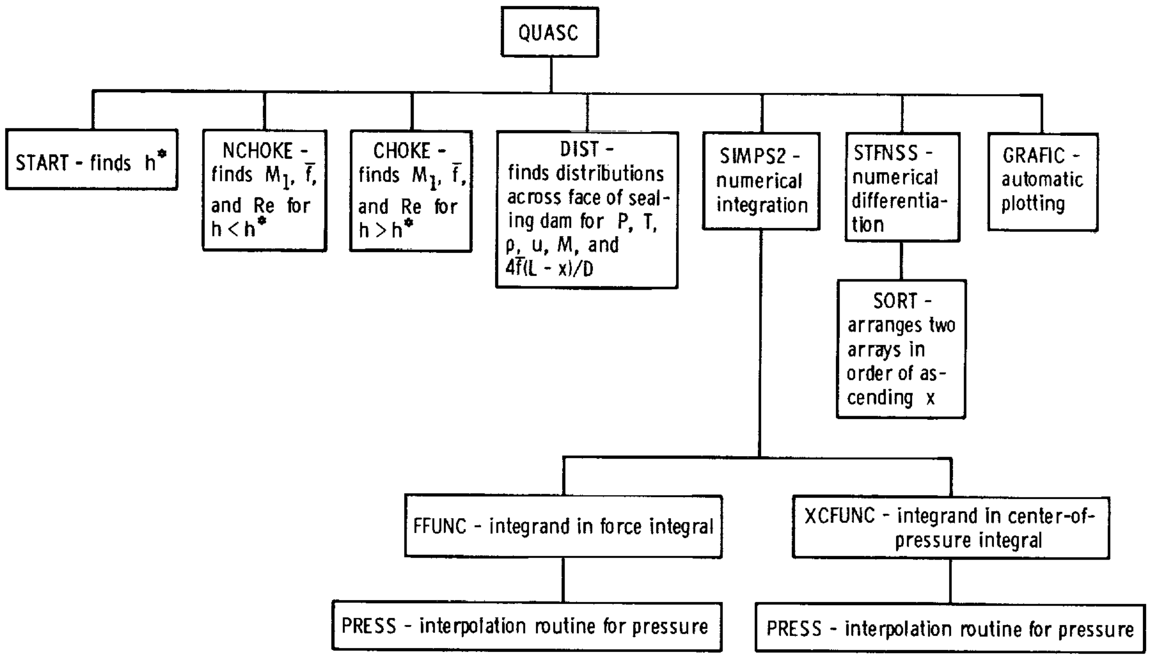

Figure 8. - Diagram of subroutine calls.

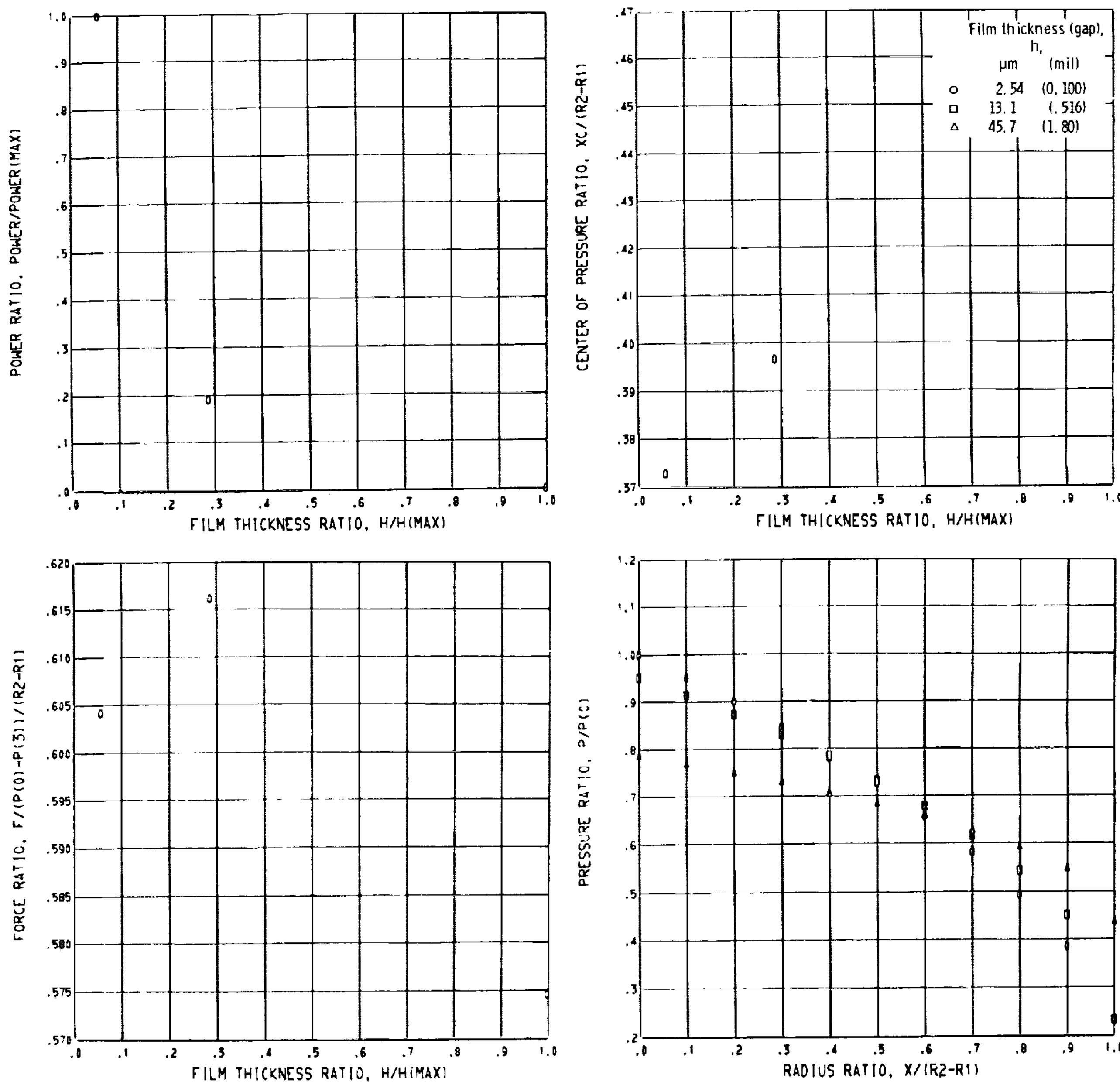

Figure 9. - Sample problem output plots.

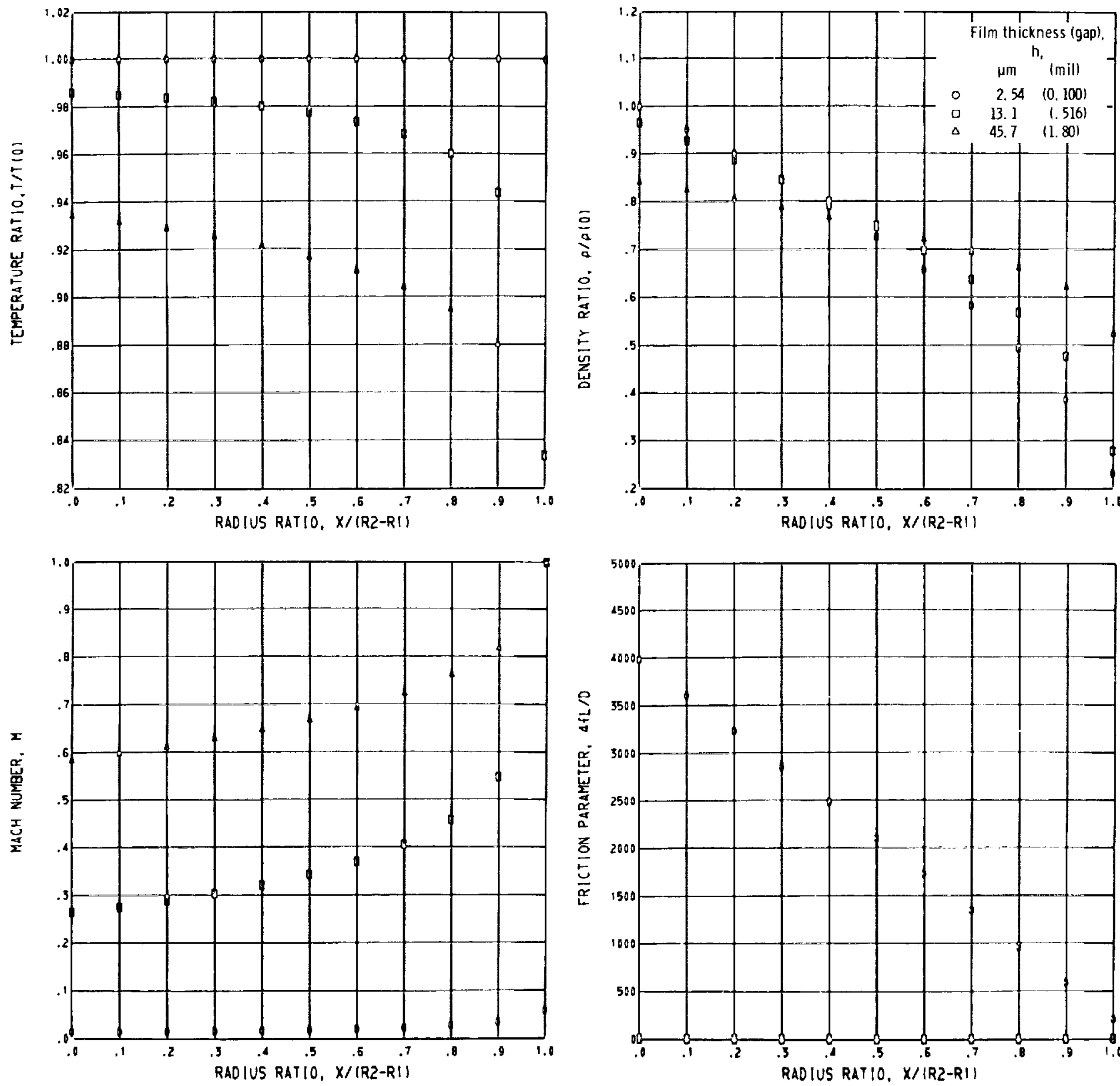

Figure 9. - Concluded.

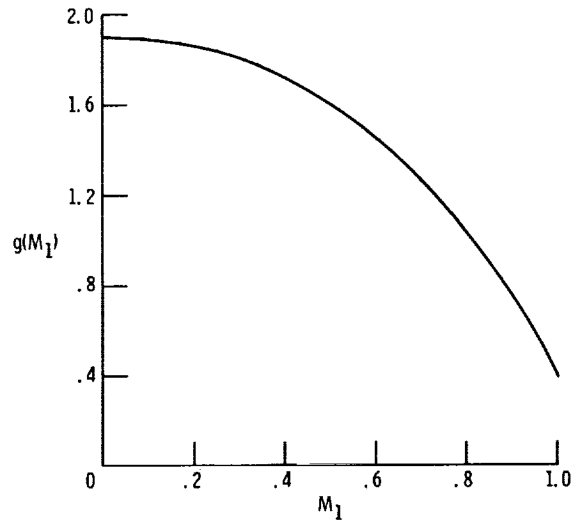

Figure 10. - Typical variation of Mach number function $g(M_1)$ with Mach number for a low pressure ratio, $P_0/P_3 = 3.0$. Specific heat ratio γ, 1.4; entrance velocity loss coefficient C_L, 0.8.

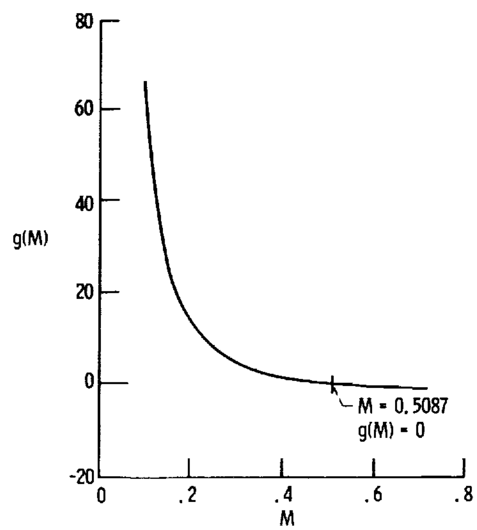

Figure 11. - Typical variation of Mach number function g(M) with M for which a solution of equation (C3) is possible.