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

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**Abstract**

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

**Key Words (Suggested by Author(s))**
- Computer program
- Sealing dam
- Lubrication
- Compressible flow
- Seal
- Narrow slots
- Face seal

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SUMMARY

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

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

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

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

INTRODUCTION

Shaft seals in advanced rotating machinery, such as in advanced aircraft turbine engines, will operate at higher speeds, temperatures, and pressures than shaft seals in current use. Because of these severe operating conditions, a positive face separation (no rubbing contact) is required for long life and reliability (ref. 1). However, seal-face deformation is very likely to occur.
These deformations may be caused by various distortions (thermal, centrifugal, pressure, etc.). Seal-face distortions become more pronounced under severe operating conditions and are usually detrimental to seal performance. Hence, prediction of these face deformation effects on gas-film-seal performance is of paramount importance. This report presents an analysis and computer program to enable prediction of gas-film-face-seal performance when face deformations and/or radial area change is significant. The analysis is especially useful for choked flow conditions.

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

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

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

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

QUASI-ONE-DIMENSIONAL FLOW ANALYSIS

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

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

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

Seal Leakage Passage Flow

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

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

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

Conservation of mass:

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

Conservation of energy:

$$\frac{dT}{T} + \frac{\gamma - 1}{2} M^2 \frac{du^2}{u^2} = 0 \quad (2)$$
Equation of state:

\[ \frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dT}{T} \]  \hspace{1cm} (3)

Conservation of momentum (for a small area change):

\[-A \, dP - \tau_w \, dA_w = \dot{M} \, du \] \hspace{1cm} (4)

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

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

\[ D = \frac{4A}{\phi_w} = 2h \] for radial flow between parallel disks and plates

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

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

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

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

\[ \frac{du}{u} = \frac{-1}{1 - M^2} \frac{dA}{A} + \frac{\gamma M^2}{2(1 - M^2)} \frac{4f \, dx}{D} \] \hspace{1cm} (6)
Solving equation (5) for \( \frac{4f}{dx} \) and substituting that into equations (6) to (9) give

\[
\frac{dT}{T} = \frac{dA}{A} - \frac{\gamma(-1)M^2}{2(1 - M^2)} \frac{4f}{dx}
\]

(7)

\[
\frac{dP}{P} = \frac{\gamma M^2}{1 - M^2} \frac{dA}{A} - \frac{\gamma M^2}{2(1 - M^2)} \frac{4f}{dx}
\]

(8)

\[
\frac{dP}{P} = \frac{\gamma M^2}{1 - M^2} \frac{dA}{A} - \frac{\gamma M^2}{2(1 - M^2)} \frac{4f}{dx}
\]

(9)

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

\[
\frac{du}{u} = \frac{dM^2}{2M^2 \left(1 + \frac{\gamma - 1}{2} M^2\right)}
\]

(10)

\[
\frac{dT}{T} = \frac{\gamma - 1}{2} \frac{dM^2}{1 + \frac{\gamma - 1}{2} M^2}
\]

(11)

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

(12)

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

(13)

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

\[
\frac{u^*}{u} = \frac{1}{M} \sqrt{\frac{1 + \frac{\gamma - 1}{2} M^2}{\frac{1}{2} (\gamma + 1)}}
\]

(14)
Hence, once the Mach number distribution is known, the physical quantities of interest can be found.

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

\[
A = 2\pi rh \quad \text{for the coaxial ring geometry}
\]
\[
A = Wh \quad \text{for the rectangular plate geometry}
\]

\[
r = R_1 \pm x
\]
\[
h = h_1 + x \sin \alpha
\]

Equation (5) can be written as

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

where

\[
T^* = \frac{T}{T_0} = \frac{1 + \frac{\gamma - 1}{2} M^2}{\frac{1}{2} (\gamma + 1)}
\]

\[
\rho^* = \frac{AM}{A^*} \sqrt{\frac{1}{1 + \frac{\gamma - 1}{2} M^2} \frac{1}{(\gamma + 1)}}
\]

\[
\frac{P^*}{P} = \frac{AM}{A^*} \sqrt{\frac{1}{1 + \frac{\gamma - 1}{2} M^2} \frac{1}{(\gamma + 1)}}
\]
\[
F(x) = \begin{cases} 
    x & \text{for flow with no radial expansion} \\
    R_1 + x & \text{for radial outward flow} \\
    R_2 - x & \text{for radial inward flow}
\end{cases}
\]

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

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

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

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

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

\[
M = \frac{u}{c} = \frac{u}{\sqrt{\gamma R T}} \tag{24}
\]

**Entrance Flow**

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

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

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

(26)

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

SOLUTION OF EQUATIONS

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

\[
\frac{P}{\rho} = \mathcal{R}T
\]  

(27)

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

- **\( P_0 \)**: sealed-gas pressure (upstream reservoir pressure)
- **\( P_3 \)**: ambient pressure (downstream reservoir pressure)
- **\( T_0 \)**: sealed-gas temperature (upstream reservoir temperature, also the stagnation temperature)
- **\( C_L \)**: entrance velocity loss coefficient
- **\( \Delta R \)**: distance across face of sealing dam
- **\( h(x) \)**: film thickness distribution
- **\( k, n \)**: constants in friction factor–Reynolds number relation

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

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

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

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

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

**COMPUTER PROGRAM**

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

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

In general, AREAX performs the following operations in analyzing the flow across a seal: It reads the input data and checks that these data are consistent. For instance, there are three input variables which can determine the flow length. Since only two are necessary, the third must be made consistent with the other two. When the input data have been read, AREAX analyzes the flow for each combination of film thickness and tilt angle.
The program first solves the Mach number equation and determines the Mach number distribution across the seal face. AREAX then determines the distributions across the seal face of pressure; temperature; density; velocity; mean friction factor; Reynolds number; mass and volume flow rates; Knudsen number; seal opening force; center of pressure; and where appropriate, rotational Reynolds number, variables associated with power dissipation, and axial film stiffness.

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

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

The formulas for the parameters calculated by AREAX are listed in Table 1. When the flow is in either the transitional or turbulent flow regime, the power loss due to rotation is not calculated. Also, there is no Reynolds number criterion for determining turbulence due to rotation. A complete list of the variable names used by the program is given in the program listing in appendix C. Flow charts of AREAX and the subprograms are also in appendix C.

Input Data

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

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

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

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

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

/   choked flow
+   flow in laminar-turbulent transitional regime
T   flow in turbulent regime

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

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

SAMPLE PROBLEM

An example of the use of the computer program is given here with the following conditions: Air at 45 N/cm² abs (65.0 psia) is to be sealed from ambient air at 10.3 N/cm² abs (15.0 psia) by a coaxial ring seal operating in the externally pressurized mode. The mean temperature of the pressurized air is 311 K (100° F). The sealing dam outside diameter is 16.84 centimeters (6.630 in.), and the inside diameter is
16.58 centimeters (6.530 in.). The seal faces are separated by a negative linear tilt of 1 milliradian. (The smallest gap is located at the outer radius.) The design surface speed is 61 meters per second (200 ft/sec).

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

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

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

REGION OF VALIDITY AND USAGE AND PROGRAM EFFICIENCY

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

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

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

(28)

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

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

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

(29)

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

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

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

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

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

CONCLUDING REMARKS

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

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 7, 1973,
APPENDIX A

SYMBOLS

A area
\( C_L \) entrance velocity loss coefficient
\( c \) speed of sound
\( c_p \) specific heat at constant pressure
\( D \) hydraulic diameter (\( D = 2h \) for coaxial rings and narrow slots)
\( F \) seal opening force
\( \bar{F} \) dimensionless seal-opening-force pressure profile factor
\( \bar{f} \) mean Fanning friction factor
\( H \) shear heat
\( h \) film thickness (gap)
\( Kn \) mean Knudsen number, \( \lambda/h_m \)
\( k \) numerical constant in friction factor - Reynolds number relation
\( M \) Mach number, \( u/\sqrt{\gamma R T} \)
\( M \) mass flow
\( m \) molecular weight of gas
\( n \) exponent in friction factor - Reynolds number relation
\( P \) pressure
\( P_w \) wetted perimeter
\( Q \) volume leakage flow rate
\( R_1 \) inner radius
\( R_2 \) outer radius
\( \Delta R \) sealing dam radial width (physical flow length), \( R_2 - R_1 \)
\( \gamma \) gas constant (universal gas constant/molecular weight)
\( \gamma_u \) universal gas constant
\( Re \) Reynolds number
\( Re(p) \) Reynolds number of leakage flow
Re(r)  Reynolds number of rotational flow
r     radius
S     axial film stiffness
T     temperature
u     leakage flow mean velocity (x-direction)
V     mean rotational velocity
W     flow width
x     flow direction coordinate
x_c   center of pressure
\bar{x}_c dimensionless center of pressure
\alpha relative inclination angle of surface (positive \alpha designates h_2 > h_1)
\gamma specific-heat ratio
\lambda mean free path of gas molecules
\mu  absolute (dynamic) viscosity
\rho  density
\tau shear stress

Subscripts:

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

Superscript:

* critical flow condition
APPENDIX B

DETAILED DESCRIPTION OF PROGRAM

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

Main Program AREAX

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

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

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

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

The arrays in COMMON block /TRAYS/ (table IX) contain the parameters used in the solution of the Mach number equation for the film thickness under consideration.
COMMON blocks /CTITLE/ and /PRNT/ contain the title, which identifies the data, and the labels for identifying which parameters are calculated. COMMON block /LOGICL/ contains logical variables.

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

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

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

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

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

Subprogram NCFLOW

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

Subprogram DISTS

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

Subprogram PRESS

Function subprogram PRESS uses a three-point Lagrange interpolation to determine the Mach number and film thickness at distance $x$ across the seal face. Then pressure is calculated from equation (17).
Subprogram RK1

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

Subprogram SIMPS1

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

Subprogram STFNSS

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

Subprogram FRFUNC

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

Subprograms FFUNC and XCFUNC

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

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

Subprogram GRAFIC

Subprogram GRAFIC makes the following plots:
1. Power against mean film thickness
2. Center of pressure against mean film thickness
3. Force against mean film thickness
4. Pressure against \(x\)
5. Temperature against \(x\)
6. Density against \(x\)
7. Mach number against \(x\)
8. Reynolds number against \(x\)
9. Mean friction factor against \(x\)

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

Subprogram BLOCK

Subprogram BLOCK is a block data subprogram to load constants into labeled COMMON.
Define logical, real, and double precision variables, labeled COMMON storage, and NAMELIST lists

Read data identification

Read flow length data

Check that flow length data are consistent

Are flow length data consistent?

No

Write an error message

Yes

Read film thickness data

Read reservoir data, including INCODE

Check that reservoir data are consistent

Are reservoir data consistent?

No

Write an error message

Yes

Read film thickness and reservoir data, including INCODE

INCODE = 1

INCODE = 3 or 4

INCODE = 2

INCODE = 3

INCODE = 4

INCODE = 2
140 Write data identification

Write flow length and reservoir data

Calculate program constants

Examine plotting array and set up array of labels to be printed

Write consistent input data and array of labels

200

\( J = 1 \)

\( J \leq J\text{DONE} \)

210

Read solution of Mach number equation from previous running of program

Calculate film thickness and critical area \( A^* \)

Call subroutine NCFLOW to determine solution of Mach number equation

240

Call subroutine DISTS to determine profiles of pressure, temperature, density, Mach number, velocity, Reynolds number, and mean friction factor

Calculate mass flow rate, volume flow rate, Knudsen number, mean free path of gas molecules, and rotational Reynolds number

Skip calculations based on power dissipation? No

Calculate power, shear heat, temperature, and torque

Yes

Calculate sealing dam force and center of pressure

270

\( J = J + 1 \)

\( J \neq NJ \)

275
Call subroutine STFNSS to determine axial film stiffness.

Write output data.

Call subroutine GRIFIC to make plots.

INCODE = 1

INCODE = 2

INCODE = 3

INCODE = 4

INCODE = 130

INCODE = 100

INCODE = 110

INCODE = 120
Comment: Use method of iteration to solve Mach number equation when flow is subsonic (i.e., when \( M_2 < 1, \Delta R, P_2 = P_3 \)) and when flow is choked (i.e., when \( M_2 = 1, \Delta R, P_2 > P_3 \)).

1. Enter
2. Guess a value for entrance Mach number \( M_1 \)
3. Call subroutine RK1 to solve Mach number equation
4. Change guess for \( M_1 \) by setting \( M_1 = M_1 \frac{X^*}{\Delta R} \)
5. Calculate exit Mach number
6. Calculate exit pressure \( P_2 \)
7. If \( x^* \geq \Delta R \) then No, else Yes
8. If \( P_2 \geq P_3 \) then Yes, else No
9. If \( P_2 = P_3 \) then Yes, else No
10. Have two points been found such that \( P_2 < P_3 \) for one and \( P_2 > P_3 \) for the other?
   a. If Yes, then Do straight-line curve fit on the two stored points
   b. If No, then Store \( M_1 \) and \( P_2 \) for curve fitting
11. Read \( M_1 \) from fitted curve that corresponds to \( P_2 = P_3 \)
12. Punch Mach number distribution on cards
13. Return
DISTS

Enter

1 = 2

Calculate temperature, pressure, density, and velocity

1 + 11

Return

PRESS

Enter

Search X-array for value of X closest to XX

X(I) = XX?

Yes → Set PRESS equal P(I)

No

Return
RKI

Comment: Runge-Kutta solution of Mach number equation

Enter

Define double-precision constants and arithmetic function for \( \frac{dM^2}{dx} \)

\( Y_0 \) = trial value for square of entrance Mach number

Set initial values of \( N_1 \) and \( N_2 \)

\( 100 \)

Set \( Y(1) = Y_0 \)

\( \Delta x \) = fraction of \( \Delta R \)

\( 200 \)

\( I = N_1 \)

Calculate \( K_1, K_2, K_3, K_4 \) - \( \frac{dM^2}{dx} \) for Runge-Kutta solution of differential equation

\( \Delta Y = \frac{[K_1 + 2(K_2 + K_3) + K_4]}{6} \)

\( Y(I) = Y(I - 1) + \Delta Y \)

\( Y(I) \)

\( \leq 1 \)

\( Y(I) \)

\( > 1 \)

\( \leq 1 \)

\( X(I) \)

\( \Delta R \)

\( I = I + 1 \)

\( I = N_2 \)

\( N_1 = N_2 + 1 \)

\( N_2 = N_1 + 9 \)

Return

Reduce step size

320

600

315

310

320

28
SIMPS1

Enter

Integrate entire interval

Set N = 1, FRAC = 2 * T

1

FRAC = \( \frac{1}{2} \) FRAC

2

Test = FRAC * ANS

K = N

I = 1

NTTEST

<NE(I)

7

I = I + 1

\# K

Evaluate integral from V(I) to VN

<200

\( \geq 200 \)

KER = KER + 1

N

Accumulate test answer

No

Is integral accurate?

Yes

Accumulate final answer

Return
Error condition: set derivatives to zero

IND = 1

Search XX array for laminar, nonchoked flow

IND = 2

Search XX array for laminar, choked flow

IND = 3

Search XX array for turbulent, nonchoked flow

IND = 4

Search XX array for turbulent, choked flow

Arrange selected values of XX in ascending order

IND = IND + 1

Form sums and products for Lagrange numerical differentiation

Form derivative

Rearrange derivatives in original order of XX

Return
**FFUNC**

Enter

FFUNC = Pressure at X - P3

Return

**XCFUNC**

Enter

XCFUNC = (Pressure at X - P3) x X

Return

**SORTXY**

Enter

I = 1

J = I + 1

(X(J) < X(I)) ?

Yes

Interchange X(I) and X(J)

Interchange Y(I) and Y(J)

J = J + 1

I = I + 1

No

J = J + 1

I = I + 1

Return
Comment: Force and center of pressure already dimensionless

Define plot titles and labels

Search H array for maximum film thickness h and POWER array for maximum power

Normalize h

Skip plot of h against power?

Yes

210

No

Normalize power

Skip plot of h against force?

Yes

220

No

Plot h against force

Skip plot of h against center of pressure?

Yes

300

No

Plot h against center of pressure

Normalize flow direction coordinate x

Skip plot of h against power?

Yes

310

No

Plot x against pressure
QUASI-CNE DIMENSIONAL COMPRESSIBLE FLOW WITH FRICTION AND AREA
CHANGE. AREA CHANGE MAY BE DUE TO RADIAL EXPANSION AND/OR
RELATIVE TILING OF THE SEALING SURFACES.

INPUT VARIABLES
***************

TITLE - ALPHANUMERIC IDENTIFICATION OF THE DATA

NSI - NUMERICAL SIGNAL WHICH INDICATES WHICH SYSTEM OF UNITS IS
USED FOR INPUT, OUTPUT, AND INTERNAL CALCULATIONS
(NSI = 1 MEANS SI UNITS - NSI = 2 MEANS US UNITS)

RINNER - INNER RADIUS OF CIRCULAR SEAL
ROUTER - OUTER RADIUS OF CIRCULAR SEAL

RDIFIN - DISTANCE ACROSS SEAL

WIDTH - FLOW WIDTH FOR SEALS WITH NO RADIAL EXPANSION

MOLWT - MOLECULAR WEIGHT

CP - SPECIFIC HEAT OF GAS

MUIN - RESERVOIR VISCOSITY FOR GAS OTHER THAN AIR

GAMMA - RATIO OF SPECIFIC HEATS

SPEED - ROTATIONAL VELOCITY

CAPV - SURFACE SPEED

XLAM - EXPONENT IN FORMULA FOR VARIATION OF FRICTION FACTOR
WITH REYNOLDS NUMBER FOR LAMINAR FLOW

XTURB - EXPONENT IN FORMULA FOR VARIATION OF FRICTION FACTOR
WITH REYNOLDS NUMBER FOR TURBULENT FLOW

CONLAM - CONSTANT IN FORMULA FOR VARIATION OF FRICTION FACTOR
WITH REYNOLDS NUMBER FOR LAMINAR FLOW

CONTRB - CONSTANT IN FORMULA FOR VARIATION OF FRICTION FACTOR
WITH REYNOLDS NUMBER FOR TURBULENT FLOW

RELAM - UPPER LIMIT OF REYNOLDS NUMBER FOR LAMINAR FLOW

RETURB - LOWER LIMIT OF REYNOLDS NUMBER FOR TURBULENT FLOW

PWRSKP - LOGICAL VARIABLE - IF TRUE, SKIP CALCULATIONS

INVOLVING POWER

PRSSKP - LOGICAL VARIABLE - IF TRUE, SKIP PRINTOUT OF
DISTRIBUTIONS OF PRESSURE, TEMPERATURE, DENSITY,
MACH NUMBER, VELOCITY, AND FRICTION PARAMETER
ACROSS THE FACE OF THE SEAL

NRMSKP - LOGICAL VARIABLE - IF TRUE, SKIP NORMALIZATION OF
FORCE AND CENTER OF PRESSURE

PLTSKP - LOGICAL ARRAY - IF ANY ELEMENT IS TRUE, SKIP THE
PLOT OF THE CORRESPONDING VARIABLE

PLTSKP(1) - POWER VS CHARACTERISTIC FILM THICKNESS
PLTSKP(2) - CENTER OF PRESSURE VS CHARACTERISTIC
              FILM THICKNESS
PLTSKP(3) - FORCE VS CHARACTERISTIC FILM THICKNESS
PLTSKP(4) - PRESSURE VS X
PLTSKP(5) - TEMPERATURE VS X
PLTSKP(6) - DENSITY VS X
PLTSKP(7) - MACH NUMBER VS X
C

PLTSKP(8) - REYNOLDS NUMBER VS X
PLTSKP(9) - MEAN FRICTION FACTOR VS X

C

HMEAN - MEAN FILM THICKNESS
ALPHA - TILT ANGLE
NJ - NUMBER OF FILM THICKNESS
JDONE - NUMBER OF CASES COMPLETED IN PREVIOUS RUNNING OF THE PROGRAM

C

PIN - PRESSURE AT INNER RADIUS OF CIRCULAR SEAL CR PRESSURE AT ENTRANCE OF SEAL WITH NO RADIAL EXPANSION
P2IN - PRESSURE AT OUTER RADIUS OF CIRCULAR SEAL CR PRESSURE AT EXIT OF SEAL WITH NO RADIAL EXPANSION
PRIN - PO/P3
TOIN - SEALED GAS TEMPERATURE
LOSS - ENTRANCE VELOCITY LOSS COEFFICIENT

C

INCODE = INPUT CODE
INCODE=1, PROGRAM TRANSFERS TO READ NEW TITLE CARD
INCODE=2, PROGRAM TRANSFERS TO READ NEW SEAL DATA
INCODE=3, PROGRAM TRANSFERS TO READ NEW FILM THICKNESS DATA
INCODE=4, PROGRAM TRANSFERS TO READ NEW RESERVOIR DATA

C

OUTPUT VARIABLES

X - DISTANCE ACROSS SEAL FACE
W - FILM THICKNESS THAT CORRESPONDS TO X

PARAMETERS THAT VARY ONLY WITH FILM THICKNESS

MDF - MASS FLOW RATE
Q - VOLUME FLOW RATE
KN - KNUDSEN NUMBER
LAMDA - MEAN FREE PATH OF GAS MOLECULES
RER - ROTATIONAL FLOW REYNOLDS NUMBER
POWER - POWER DISSIPATED DUE TO VISCOUS SHEARING
DELT - APPARENT TEMPERATURE RISE DUE TO VISCOUS SHEARING
HSHEAR - SHEAR HEAT
TORQUE - TORQUE
FORCE - SEALING DAM FORCE
FBAR - NORMALIZED SEALING DAM FORCE
XC - CENTER OF PRESSURE
XCBAR - NORMALIZED CENTER OF PRESSURE
STIFF - AXIAL FILM STIFFNESS
H1 - FILM THICKNESS AT INNER RADIUS OF SEAL
H2 - FILM THICKNESS AT OUTER RADIUS OF SEAL

PARAMETERS THAT VARY WITH FLOW LENGTH AND FILM THICKNESS

P - PRESSURE
MACH - MACH NUMBER
U - RADIAL VELOCITY

C

************+******
X - DISTANCE ACROSS SEAL FACE
H - FILM THICKNESS THAT CORRESPONDS TO X

PARAMETERS THAT VARY ONLY WITH FILM THICKNESS

82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
T - TEMPERATURE
RHO - DENSITY
REP - PRESSURE FLOW REYNOLDS NUMBER
FRICT - FRICTION FACTOR

PROGRAM VARIABLES - SOME OF THESE ARE OUTPUT, ALSO

RC - RADIUS OF SEAL AT INLET (RO = R1 FOR INTERNALLY
PRESSURIZED CIRCULAR SEALS, RO = R2 FOR EXTERNALLY
PRESSURIZED CIRCULAR SEALS, AND RO = 0 FOR SEALS WITH NO
RADIAL EXPANSION)
R GAS - GAS CONSTANT
FAREA - SURFACE AREA
MU - RESERVOIR VISCOSITY
TO - SEALED GAS TEMPERATURE
PTOL - TOLERANCE FOR CUT-OFF ON PRESSURE ITERATION
H MIN - MINIMUM FILM THICKNESS
CNVT - ARRAY OF CONSTANTS NEEDED IN THE CALCULATIONS
(CNVT(I,1) ARE CONSTANTS IN SI UNITS)
(CNVT(I,2) ARE CONSTANTS IN US UNITS)

PARAMETERS CALCULATED AT POINT OF CHOKEING

XSTAR - DISTANCE FROM ENTRANCE TO POINT OF CHOKEING
PS T R - PRESSURE
ASTAR - CROSS-SECTIONAL AREA
TSTAR - TEMPERATURE

REAL MACH, MOLWT, LOSS, KN, LAMDA, MU, IN, MU, MDM T
DOUBLE PRECISION XX, FM, HH
LOGICAL PWRSKP, PRSSKP, NRMSKP, PLTSKP
EXTERNAL FUNC, XC FUNC
DIMENSION CALC(8,4), MDM T(20), O(20), KN(20), LAM DA(20), RER(20),
1 XC(20), DELT(20), HMEAR(20), TORQUE(20), HMIN(20),
1 COMMON /ARRAYS/X(11), P(11,20), MACH(11,20), U(11,20), T(11,20),
1 RHO(11,20), REP(11,20), FRIC T(11,20), H(11,20), XBAR(20),
2 POWER(20), FORCE(20), STIFF(20), FBAR(20), H1(20), H2(20),
1 ALPHA(20), HMEAN(20), XSTAR(20), PS T AR(20), ASTAR(20),
1 COMMON /CON S/T GAMMA, RDIF, R0, SIGN, X LAM, XTUR B, CNLAM, CONTR B, RELAM,
1 RETURB, TO, PO, P3, PTOL, R GAS, LOSS, MU, PI, RUN IV(2), CNVT(11,2), NS I
1 COMMON /TRAYS/N, XX(201), FM(201), HH(201), J, TSTAR
1 COMMON /CTI TLE /TITLE(12)
1 COMMON /PRNT/C1(4), C2(4), C3(4), C4(4), C5(4), C6(4), C7(4), C8(4), BLA AK
1 COMMON /LOGIC/PWRSKP, PRSSKP, NRMSKP, PLTSKP(9)
1 NAMELIST/SEAL/RINNER, ROUTER, RDIFIN, WIDTH, MOLWT, CP, MU, IN, GAMMA, CAPV,
1 SPEED, XLAM, XTURB, CNLAM, CONTR B, RELAM, RETURB, PWRSKP, PRSSKP,
2 KRM SKP, PLT SKP, NSI
1 NAMELIST/H DATA/ HMEAN, ALPHA, NJ, JDONE
1 NAMELIST/RES DAT/P3IN, P2 IN, PRIN, TCI N, LOSS, INCODE
1 COMMON /LOGIC/P, NS I
1 COMMON/TRAY/N, XX(201), FM(201), HH(201), J, TSTAR
1 COMMON /CTITLE /TITLE(12)
1 COMMON/PRNT/C1(4), C2(4), C3(4), C4(4), C5(4), C6(4), C7(4), C8(4), BLA AK
1 COMMON/LOGIC/PWRSKP, PRSSKP, NRMSKP, PLTSKP(9)
1 NAMELIST/SEAL/RINNER, ROUTER, RDIFIN, WIDTH, MOLWT, CP, MU, IN, GAMMA, CAPV,
1 SPEED, XLAM, XTURB, CNLAM, CONTR B, RELAM, RETURB, PWRSKP, PRSSKP,
2 KRM SKP, PLT SKP, NSI
1 NAMELIST/H DATA/ HMEAN, ALPHA, NJ, JDONE
1 NAMELIST/RES DAT/P3IN, P2 IN, PRIN, TCI N, LOSS, INCODE

READ TITLE CARD AND SEAL DATA

100 READ(5,1) TITLE
110 READ(5,SEAL)
C CHECK CONSISTENCY OF FLOW LENGTH PARAMETERS

IF (RINNER.EQ.0.0) GO TO 111
IF (RROLLER.EQ.0.0) GO TO 112
R1 = RINNER
R2 = RROLLER
RDIF = R2-R1
GO TO 116

111 IF (ROLLER.EQ.0.0) GO TO 113
IF (RDIFIN.EQ.0.0) GO TO 114
RDIF = RDIFIN
R2 = RROLLER
R1 = R2-RDIF
GO TO 116

112 IF (RDIFIN.EQ.0.0) GO TO 114
RDIF = RDIFIN
R1 = RINNER
R2 = R1-RDIF
GO TO 116

113 IF (RDIFIN.EQ.0.0) GO TO 114
RDIF = RDIFIN
R1 = 0.0
R2 = 0.0
IF (WIDTH.EQ.0.0) GO TO 116

C ERROR IN FLOW LENGTH DATA

114 WRITE (6,10) TITLE,RINNER,ROLLER,RDIFIN,WIDTH
115 READ (5,RESDAT)
GO TO (100,110,115,115),INCODE

C FLOW LENGTH DATA CONSISTANT
C CHECK CONSISTENCY OF PLOT CONTROL PARAMETERS

116 IF (NRMSKP) PLSKP(3)=.TRUE.
IF (.NOT.PRSSKP) GO TO 118
DO 117 I=4,10
117 PLSKP(I) = .TRUE.
DO 118 I=11,11
119 X(I) = FLOAT(I-1)*RDIF/10.0
C READ FILM THICKNESS DATA

120 READ(5,FDATA)
C READ RESERVOIR DATA AND CHECK CONSISTENCY OF PRESSURE DATA

130 READ(5,RESDAT)
IF (P1IN.EQ.0.0) GO TO 134
IF (P2IN.EQ.0.0) GO TO 132
P1 = P1IN
P2 = P2IN
PR = P1/P2
GO TO 140

C
132 IF (PRIN.EQ.0.0) GO TO 133
PR = PRIN
P1 = P1IN
P2 = P1/PR
GO TO 140

C
133 P1 = P1IN
P2 = P2IN
PR = C.
GO TO 140

C
134 IF (P2IN .NE. 0.0) GO TO 131
C
C ERROR IN PRESSURE DATA
C
135 WRITE(6,12) TITLE
GO TO (100,110,120,130),INCODE
C
C PRESSURE DATA CONSISTANT
C
140 PO = AMAX1(P1,P2)
P3 = APMIN(P1,P2)
C
C WRITE INPUT DATA
C
WRITE (6,20) TITLE
IF (NSI.EQ.1) WRITE (6,22) RINNER,P1IN,MOLWT,ROUTER,P2IN,CP,
1 CONLAM,RDFIN,PRIN,GAMMA,XLAM,WIDHT,TOI,N,MIN,RELAM,LCSS,
2 SPEED,CONTRB,CAPV,XTURB,RETURB
IF (NSI.EQ.2) WRITE (6,24) RINNER,P1IN,MOLWT,ROUTER,P2IN,CP,
1 CONLAM,RDFIN,PRIN,GAMMA,XLAM,WIDHT,TOI,N,MIN,RELAM,LCSS,
2 SPEED,CONTRB,CAPV,XTURB,RETURB
C
C CALCULATE PROGRAM CONSTANTS
C
RGAS = RUNIV(NSI)/MOLWT
SIGN = 1.0
IF (WIDTH .NE. 0.0) GO TO 141
WIDTH = PI*(R1*R2)
FAREA = PI*(R2**2-R1**2)
IF (P2.GT.P1) SIGN = -1.0
RO = R1
IF (P2.GT.P1) RO=R2
GO TO 142

141 RO = C.C
FAREA = WIDTH*RDFI
CAPV = 0.0
SPEED = 0.0

142 TO = TOIN
IF (NSI.EQ.2) TO=TOIN+460.
MU = MLIN
IF (GAMMA .EQ. 1.4) MU=CNVT(1,NSI)*TO**1.5/(TO+CNVT(2,NSI))
N = ALOG10(P3)
PTOL = 5.*10.**(N-4)

IF (SPEED.EQ.0.0) GO TO 143

CAPV = PI*SPEED*(R1*R2)/CNVT(3,NSI)
GO TO 145

143 IF (CAPV.EQ.0.0) GO TO 144

SPEED = CNVT(3,NSI)*CAPV/PI/(R1+R2)
GO TO 145

144 PWRSKP = .TRUE.
CP = 0.0
145 IF (PWRSKP) PLTSKP(1)=.TRUE.

C CALCULATE ENTRANCE, EXIT, AND MINIMUM FILM THICKNESSES - ALSO
C CALCULATE RADIAL DISTRIBUTION OF FILM THICKNESS

DO 147 J=1,NJ
H1(J) = HMEAN(J)-.50*RDIF*SIN(ALPHA(J))
H2(J) = 2.0*HMEAN(J)-H1(J)
MIN(J) = AMIN1(H1(J),H2(J))
DO 146 I=1,11

146 H1(I,J) = H1(J)+(RO-R1+X(I)*SIGN)*SIN(ALPHA(J))
147 CONTINUE
C SET UP ARRAY OF LABELS

DO 150 I=1,8
DO 150 J=1,4
CALC(I,J) = BLANK
DO 150 I=1,8
GO TO (151,152,153,154,155,156,157,158),I

151 IF (PWRSKP) GO TO 160
DO 151 J=1,4
1151 CALC(I,J) = C1(I)
GO TO 160
152 IF (NRMSKP) GO TO 160
DO 152 J=1,4
1152 CALC(I,J) = C2(I)
GO TO 160
153 IF (PRSSKP) GO TO 160
DO 153 J=1,4
1153 CALC(I,J) = C3(I)
GO TO 160
154 IF (PLTSKP(1)) GO TO 1154
CALC(I,1) = C4(1)
CALC(I,2) = C4(2)
1154 IF (PLTSKP(2)) GO TO 160
CALC(I,3) = C4(3)
CALC(I,4) = C4(4)
GO TO 160
155 IF (PLTSKP(3)) GO TO 1155
CALC(I,1) = C5(1)
CALC(I,2) = C5(2)
1155 IF (PLTSKP(4)) GO TO 160
CALC(I,3) = C5(3)
CALC(I,4) = C5(4)
GO TO 160
156 IF (PLTSKP(5)) GO TO 1156
CALC(1,1) = C6(1)
CALC(1,2) = C6(2)
1156 IF (PLTSKP(6)) GO TO 160
CALC(1,3) = C6(3)
CALC(1,4) = C6(4)
GO TO 160
1157 IF (PLTSKP(7)) GO TO 1157
CALC(1,1) = C7(1)
CALC(1,2) = C7(2)
1157 IF (PLTSKP(8)) GO TO 160
CALC(1,3) = C7(3)
CALC(1,4) = C7(4)
GO TO 160
158 IF (PLTSKP(9)) GO TO 160
CALC(1,1) = C8(1)
CALC(1,2) = C8(2)
160 CONTINUE
C
WRITE CHECKED INPUT DATA
C
IF (NS1.EQ.1) WRITE (6,21) R1,PO,MOLW,T,(CALC(1,I),I=1,4),R2,P3,
1 CP,(CALC(2,I),I=1,4),RDIF,PR,GAMMA,(CALC(3,I),I=1,4),WIDTH,
2 TO,MRU,(CALC(4,I),I=1,4),RGAS,SPEED,(CALC(5,I),I=1,4),LOSS,
3 CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4),(CALC(8,I),I=1,4)
IF (NS1.EQ.2) WRITE (6,23) R1,PO,MOLW,(CALC(1,I),I=1,4),R2,P3,
1 CP,(CALC(2,I),I=1,4),RDIF,PR,GAMMA,(CALC(3,I),I=1,4),WIDTH,
2 TO,MRU,(CALC(4,I),I=1,4),RGAS,SPEED,(CALC(5,I),I=1,4),LOSS,
3 CAPV,(CALC(6,I),I=1,4),(CALC(7,I),I=1,4),(CALC(8,I),I=1,4)
WRITE (6,19)
C
BEGIN MAIN CALCULATION
C
200 DO 27C J=1,NJ
C
CHECK FOR RESTARTING WHEN SOME CASES ARE FINISHED BY PREVIOUS
RUNNING OF THE PROGRAM. IF JDONE Is GREATER THAN ZERO, READ X AND
MACH NUMBER DISTRIBUTIONS CALCULATED BY PREVIOUS RUNNING OF THE
PROGRAM. CALCULATE H DISTRIBUTION AND A*. DIMENSIONALIZE X, X*,
P*, AND T*.
C
IF (J,JT,JDONE) GO TO 21C
READ (5,2) JJ,N,PSTAR(JJ),XSTAR(JJ),TSTAR
IF (J,JT,JG) GO TO 201
WRITE (6,15)
STOP
C
201 READ (5,3) (XX(I),I=1,N)
READ (5,3) (FM(I),I=1,N)
DO 202 I=1,N
XX(I) = XX(I)*RDIF
HH(I) = H1(J)+(RO-R1*XX(I)*SIGN)*SIN(ALPHA(J))
202 CONTINUE
PSTAR(J) = PSTAR(J)*PC
XSTAR(J) = XSTAR(J)*RDIF
TSTAR = TSTAR*TO
ASTAR(J) = HH(N)
C
WRITE (6,19)
C
END
IF (RO .NE. 0.0) ASTAR(J) = 2.0*PI*(RO*X(N)*SIGN)*HH(N)
GO TO 240

C CALL SUBROUTINES TO DETERMINE SOLUTION OF MACH NUMBER EQUATION AND
DISTRIBUTIONS OF PARAMETERS THAT VARY WITH X

C 210 CALL NCFLOW
C 240 CALL CISTS
C
C CALCULATE PARAMETERS THAT VARY ONLY WITH FILM THICKNESS

245 MDOT(J) = WIDTH*H(6,J)*RHO(6,J)*U(6,J)*CNVT(4,NSI)
Q(J) = CNVT(5,NSI)*MDOT(J)
KN(J) = 2.96*MACH(6,J)/REP(6,J)
LAMCA(J) = KN(J)*HMEAN(J)
FMU = ML
IF (GAMMA .EQ. 1.4) FMU = CNVT(1,NSI)*T(6,J)**1.5/(T(6,J)*CNVT(2,NSI))
RE(J) = RHO(6,J)*CAPV/HMEAN(J)/FMU/CNVT(6,NSI)
TF(PWR,SKP) GO TO 260

C CALCULATE POWER, SHEAR HEAT, TORQUE, AND TEMPERATURE RISE DUE
C TO POWER DISSIPATION

250 POWER(J) = 0.
IF (REP(6,J) .LE. RELAM) POWER(J) = FMU*FAREA*CAPV**2/HMEAN(J)/
1 CNVT(7,NSI)
HSHEAR(J) = CNVT(8,NSI)*POWER(J)
DELT(J) = HSHEAR(J)/ABS(MDOT(J))/CP
TORQUE(J) = POWER(J)*CNVT(9,NSI)/SPEED

C CALCULATE FORCE AND CENTER OF PRESSURE

C 260 K=0
K=K+1
FORCE(J) = SIMPS1(0.,RDIF,FFUNC,K)*WIDTH
XC(J) = SIMPS1(0.,RDIF,XCFUNC,KK)*WIDTH/FORCE(J)

C 265 IF (K .NE. 0) WRITE (6,13)
IF (K .NE. 0) WRITE (6,14)
IF (NRMSKP) GO TO 270
FBAR(J) = FORCE(J)/RDIF/(PD-P3)/WIDTH
XBAR(J) = XC(J)/RDIF

270 CONTINUE
C 275 CALL STFNSS

C WRITE OUTPUT DATA AND PLOT THEM (SUBROUTINE GRAFIC)
C
C 280 IF (NSI .EQ. 1) WRITE (6,25)
C 281 IF (NSI .EQ. 2) WRITE (6,26)
C 285 DO 710 J=1,NJ
C 286 WRITE (6,43) HMEAN(J),HMIN(J),ALPHA(J),MDCT(J),C(J),RER(J),
1 STIFF(J),FORC(J),XC(J)
IF (ABS(MACH(11,J)-1.0) .LT. 1.E-5) WRITE (6,45)
IF (REP(6,J) .GT. RELAM) AND REP(6,J) .LT. RETURB) WRITE (6,46)
IF (REP(6,J) .GE. RETURB) WRITE (6,47)

710 CONTINUE
WRITE (6,27) 444
IF (.NOT.NRMSKP) WRITE (6,28) 445
IF (NSI.EQ.1) WRITE (6,29) 446
IF (NSI.EQ.2) WRITE (6,3C) 447
IF (.NOT.NRMSKP) WRITE (6,31) 448
DO 720 J=1,NJ 449
WRITE (6,48) HMEAN(J),HMIN(J),ALPHA(J),KN(J),LAMDA(J), 450
L XSTAR(J),PSTAR(J) 451
IF (.NOT.NRMSKP) WRITE (6,441) 452
IF (NSI.EQ.2) WRITE (6,43) 453
DO 720 J=1,NJ 454
WRITE (6,48) HMEAN(J),HMIN(J),ALPHA(J),PCWTR(J),HSHEAR(J),DELT(J), 455
L TORUE(J) 456
IF (ABS(MACH(1,J)-1.0) .LT. 1.E-5) WRITE (6,45) 457
IF (PEP(6,J) .LT. RETURB) WRITE (6,46) 458
IF (PEP(6,J) .GE. RETURB) WRITE (6,47) 459
720 CONTINUE 460
C IF (PWSKP) GO TO 740 461
WRITE (6,32) 462
IF (NSI.EQ.1) WRITE (6,33) 463
IF (NSI.EQ.2) WRITE (6,34) 464
DO 730 J=1,NJ 465
WRITE (6,43) HMEAN(J),HMIN(J),ALPHA(J),PCWTR(J),HSHEAR(J),DELT(J), 466
L TORUE(J) 467
IF (ABS(MACH(1,J)-1.0) .LT. 1.E-5) WRITE (6,45) 468
IF (PEP(6,J) .LT. RETURB) WRITE (6,46) 469
IF (PEP(6,J) .GE. RETURB) WRITE (6,47) 470
730 CONTINUE 471
C 740 IF (PRSSKP) GO TO 800 472
DO 750 J=1,NJ 473
DO 745 I=1,11 474
IF (NSI.EQ.2) T(I,J) = T(I,J) - 460. 475
745 CONTINUE 476
IF (MOC(J,3).EQ.1) WRITE (6,35) 477
A1 = WICTH*HI(J) 478
A2 = WIDTH*H2(J) 479
IF (RO.NE.0.0) A1=2.0*PI*R1*HI(J) 480
IF (RO.NE.0.0) A2=2.0*PI*R2*H2(J) 481
DADR = ABS(A1-A2)/RADIF 482
DELA = ABS(A1-A2)/MIN1(A1,A2) 483
IF (NSI.EQ.1) WRITE (6,36) HMEAN(J),H1(J),DADR,ALPHA(J), 484
L H2(J),DELA 485
IF (NSI.EQ.2) WRITE (6,37) HMEAN(J),H1(J),DADR,ALPHA(J), 486
L H2(J),DELA 487
IF (ABS(MACH(1,J)-1.0) .GT. 1.E-5) WRITE (6,38) 488
IF (ABS(P(1,J)-P3) .GT. PTOL) WRITE (6,39) 489
WRITE (6,40) 490
IF (NSI.EQ.1) WRITE (6,41) 491
IF (NSI.EQ.2) WRITE (6,42) 492
WRITE (6,43) (X(I),H(I,J),MACH(I,J),U(I,J),RHO(I,J),P(I,J), 493
L T(I,J),REPI,J,FRICT(I,J),I=1,11) 494
750 CONTINUE 495
C 800 CALL GRAFIC 496
GO TO (100,110,12C,13O), INCODE 497
C C END OF PROGRAM 498
C

END
DETERMINE THE MACH NUMBER DISTRIBUTION SUCH THAT M=1.0 AT X=X*.
FOR CHOKED FLOW, X=RDIF - FOR SUBSONIC FLOW, P2=P3.

PROGRAM VARIABLES

ENTRANCE CONDITIONS

H1 - FILM THICKNESS
A1 - CROSS-SECTIONAL AREA
FM(1) - INITIAL GUESS OF MACH NUMBER
TT1 - TEMPERATURE
P1 - PRESSURE

EXIT CONDITIONS

H2 - FILM THICKNESS
A2 - CROSS-SECTIONAL AREA
P2 - PRESSURE
FM2 - MACH NUMBER

CONDITIONS AT CHOKEING

XSTAR - FLOW LENGTH
HSTER - FILM THICKNESS
ASTER - CROSS-SECTIONAL AREA
PSTER - PRESSURE
TSTAR - TEMPERATURE

PROGRAM VARIABLES

DELX - STEP SIZE
N - NUMBER OF POINTS IN SOLUTION OF MACH NUMBER EQUATION

ARITHMETIC FUNCTION FLGRNG DOES A 3 POINT LAGRANGE INTERPOLATION

SUBROUTINE NCFLW
DOUBLE PRECISION X,FM,H,XO,X1,X2,Y0,Y1,Y2,XX(2),PP(2),FM2,P2,
        1  ASTER,PSTER,P1,A1,A2
REAL LOSS,MU
COMMON/ARRAYS/E(231),FM(11,20),E2(1420),H1(20),H2(20),ALPHA(20),
        1  FMEAN(20),XSTAR(20),PSTAR(20),ASTAR(20)
COMMON/ARRAYS/N,X(201),FM(201),H(201),J,TSTAR
COMMON/CONSTANTS/GAMMA,ROIF,RO,SIGN,REF(6),TO,PO,P3,PTCL,RGAS,LOSS,
        1  MU,P1,RUNIV(2),CNVT(11,2),NSI
DIMENSION SX(201),SY(201)
FLGRNG(X,XO,X1,X2,Y0,Y1,Y2) = YC*(X-X1)*(X-X2)/(X0-X1)/(X0-X2)+
        1  YL*(X-X0)/(X-X1)/(X1-X0)+(X-X0)/(X-X1)/(X1-X0)/
        2  (X2-X1)

SET BOUNDARY CONDITIONS - DEFINE CONSTANTS NEEDED IN SOLUTION OF
MACH NUMBER EQUATION
PnLC = c.0
EX = .50
NN = ALOG10(RDIF)
XTOL = RDIF*10.0**(NN-5)
FM(1) = .25DO
IF (J.NE.1) FM(1) = FM(M,J-1)*H(J)/H(J-1)
CON = SIN(ALPHA(J))
X(1) = 0.
H(1) = H(1)
IF (SIGN.LT.0) H(1) = H(1)/H(1)
IF (RO.EQ.0) GO TO 90
A1 = Z.C*PI*RDIF
IF (SIGN.LT.0) A2 = 2.0*PI*(RO-RDIF)*H(1)
GO TO 95
90 A1 = FM(1)
A2 = H(1)*RDIF
95 XX(1) = C.O0
XX(2) = 0.0
PP(1) = 0.0
PP(2) = 0.0

C C GUESS A STARTING VALUE FOR THE ENTRANCE MACH NUMBER - CALL
C SUBROUTINE RK1 TO FIND THE SOLUTION OF THE MACH NUMBER EQUATION
C
100 CALL RK1(CON)
FMOLD = FM(1)
XSTAR(J) = X(N)
IF (XSTAR(J).LT.RDIF) GO TO 145

C C CALCULATE P2
C
120 TT1 = TO/(1.0+.50*(GAMMA-1.0)*(FM(1)/LOSS)**2)
TSTAR = TT1*(1.0+.50*(GAMMA-1.0)*FM(1)**2)/.5/(GAMMA+1.0)
HSTER = P(N)+TSTAR
ASTER = I-STER
IF (RO.EQ.0) ASTER = 2.0*PI*RO*XSTAR(J)*SIGN*HSTER
P1 = PC/1.0+.50*(GAMMA-1.0)*(FM(1)/LOSS)**2)**(GAMMA/(GAMMA-1.0))
PSTER = P1*ASTEM1/FM(1)/ASTER**SQR((1.0+.50*(GAMMA-1.0)*FM(1)**2)/
1.5/(GAMMA+1.0))

C 130 FM2 = 1.00
II = 1
IF (ABS(RDIF-XSTAR(J)).LE.XTOL) GO TO 143
135 DO 140 II=1,N
II = I
IF (RDIF-X(I)) 141,142,140
140 CONTINUE
141 IF (II.LE.2) II=2
IF (II.GE.N) II=N-1
FM2 = FLGRNG(RDIF,X(II-1),X(II),X(II+1),FM(II-1),FM(II),FM(II+1))
GO TO 143
142 FM2 = FM(II)
143 P2 = ASTER*PSTER/A2/FM2*SQR((.50*(GAMMA+1.0)/(1.0+.50*(GAMMA-1.0)
1.*FM2**2))

C C FOR CHECKED FLow, CMIT ITERATION FOR P2=P3
C
IF (ABS(XSTAR(J)-RDIF).LE.XTOL.AND.P2.GE.P3) GO TO 160
IF (ABS(P2-P3).LT.PTOL) GO TO 160
FOR SUSSONIC FLOW, COMPARE P2 AND P3. IF THEY ARE NOT EQUAL, SAVE THE VALUES OF P2 AND M1. WHEN 2 SUCH POINTS HAVE BEEN SAVED, DO A LINEAR INTERPOLATION TO DETERMINE THE M1 THAT CORRESPONDS TO P2=P3.

IF (PSTER.LE.P3) GO TO 146
IF (PSTER.LT.500*P2) EX=EX/2.0
IF (ABS(POLD-P2)*LT.10.0*PTOL) EX=EX/2.0
IF (EX.LT.1.0) EX=EX/2.0

144 POLC = P2
145 FM(1) = FM(1)*(XSTAR(J)/RDIF)**EX
GO TO 153

146 IF (P2.GT.P3) GO TO 150
XX(1) = FM(1)
PP(1) = P2
IF (XX(2).NE.0.0) GO TO 152
IF (SIGN.GT.0.0.OR.ABS(XSTAR(J)-RDIF).LT.XTOL) GO TO 151
FM(1) = FM(1)*RDIF/XSTAR(J)**.25
GO TO 153

150 IF (P2.GT.PP(2)) EX=EX/2.0
XX(2) = FM(1)
PP(2) = P2
IF (XX(1).NE.0.0) GO TO 152
151 FM(1) = FM(1)*(P2/P3)**EX
GO TO 153

152 IF (P2.GT.PP(2)) FM(1) = (P3-PP(2))*(XX(1)-XX(2))/(PP(1)-PP(2))**EX

153 IF (FM(1).LT.1.00) GO TO 100
FM(1) = (0.0*FMOLD+1.00)/3.00
GO TO 100

160 ASTAR(J) = ASTER
PSTAR(J) = PSTER
IND = 1
DO 170 I=1,N
IF (1.EQ.1) GO TO 165
IF (1.EQ.N) GO TO 166
IF (X(I)-SX(IND).LT.1.E-8) GO TO 170
IF (FM(I)-SY(IND).LT.1.E-8) GO TO 170
IND = IND+1
166 SX(IND) = X(I)
SY(IND) = FM(I)

170 CONTINUE
DO 175 I=1,IND
SX(I) = SX(I)/RDIF

175 CONTINUE
PPUNCH = PSTAR(J)/PC
XPUNCH = XSTAR(J)/RDIF
TPUNCH = TSTAR/TO
WRITE (6,10) J,IND,PPUNCH,XPUNCH,TPUNCH
K = 0
NNN = (IND/5)*5
NN = NNN+1
DO 180 I=1,NNN+5
II = I+4
WRITE (6,11) (SX(J),J=1,II),K
K = K+1
180 CONTINUE
II = IND-NNN
IF (II.EQ.1) WRITE (6,12) (SX(J),J=NN,IND),K
IF (II.EQ.2) WRITE (6,13) (SX(J),J=NN,IND),K
IF (II.EQ.3) WRITE (6,14) (SX(J),J=NN,IND),K
IF (II.EQ.4) WRITE (6,15) (SX(J),J=NN,IND),K
K = K+1
DO 185 I=1,NNN,5
II = I+4
WRITE (6,11) (SY(J),J=I,II),K
K = K+1
185 CONTINUE
II = IND-NNN
IF (II.EQ.1) WRITE (6,12) (SY(J),J=NN,IND),K
IF (II.EQ.2) WRITE (6,13) (SY(J),J=NN,IND),K
IF (II.EQ.3) WRITE (6,14) (SY(J),J=NN,IND),K
IF (II.EQ.4) WRITE (6,15) (SY(J),J=NN,IND),K
RETURN
C
10 FORMAT (2H* ,2HJ=,I3,3H N=,I3,5H P* =,E14.7,5H X* =,E14.7,5H T* =,
1 E14.7)
11 FORMAT (2H* ,5E14.7,I10)
12 FORMAT (2H* ,E14.7,I66)
13 FORMAT (2H* ,2E14.7,I52)
14 FORMAT (2H* ,3E14.7,I38)
15 FORMAT (2H* ,4E14.7,I24)
C
END
C
C DISTRIBUTIONS OF PRESSURE, TEMPERATURE, DENSITY, MACH NUMBER,
C VELOCITY, REYNOLDS NUMBER, AND MEAN FRICTION FACTOR
C
C PROGRAM VARIABLES
C ********************
C
K - NUMBER OF POINTS IN SOLUTION OF MACH NUMBER EQUATION
XX - ARRAY OF INDEPENDENT VARIABLE (DISTANCE) IN SOLUTION OF
     MACH NUMBER EQUATION
FM - MACH NUMBER ARRAY FROM SOLUTION OF MACH NUMBER EQUATION
X - ARRAY OF EQUALLY SPACED DISTANCES
MACH - MACH NUMBER AT X
T - TEMPERATURE
U - RADIAL VELOCITY
RH - DENSITY
P - PRESSURE
RE - REYNOLDS NUMBER
FRCT - MEAN FRICTION FACTOR
C
ARITHMETIC FUNCTION FLGNG DOES A 3 POINT LAGRANGE INTERPOLATION
C
SUBROUTINE FLGNG
REAL MACH,LSS,ML,MLX
DOUBLE PRECISION FRFUNC, XX, FM, HH, XC, X1, X2, YC, Y1, Y2
COMMON / ARRAYS / (X(11), P(11, 2C), MACH(11, 20), U(11, 20), T(11, 20),
R(11, 2C), REP(11, 2C), FRCT(11, 20), H(11, 20), XBAR(20),
POW(2C), FORCE(2C), STIFF(20), FBAR(20), EXTRA(80), XSTAR(20),
*STAR(2C), ASTAR(2C)
COMMON / TRAYS / N, XX(201), FM(2C1), HH(2C1), J, TSTAR
COMMON / CONSTs / GAMMA, R0, FF, RC, SIGM, EX(B), P3, PTGL, RGAS, LCSS, MU, PI,
FRIV(2), CNVT(11, 2), N1, I
FLGRNG(X, X0, Y1, X1, X2, Y0, Y1, Y2) = YC*(X-X1)*(X-X2)/(X1-X0)/(X0-X2)+
Y1*(X-X0)*Y2*(X-X1)/(X1-X0)/(X1-X2)+Y2*(X-XC)*(X-X1)/(X2-XC)/
*(X2-X1)
AN = 1.C
KK = 1
DO 16 JC J = 1, 11
DO 12 KC K = KK, N
   IF (X(J)-XX(K)) 121, 122, 123
121 CONTINUE
122 MACH(I, J) = FM(KK)
123 T(I, J) = .5C*(GAMMA+1.C)*SRT(CANV(11, ASI)*GAMMA*RGAS*T(I, J))
U(I, J) = MACH(I, J)*SRT(CANV(11, ASI)*GAMMA*RGAS*T(I, J))
IF (R0.XE.0.) AN = 2.C*PI* (RC+X(I)*SIGN)
P(I, J) = PSTAR(J)*ASTAR(J)/AN/H(I, J)*SRT(1.5)*(GAMMA+1.0)/
   (1.0+50*(GAMMA-1.0)*MACH(I, J)**2)/MACH(I, J)
IF (KK.CT.250) GO TO 135
IF (I.LT.11) GO TO 135
IF (AP=PI(J)-PI3)*LT.PTGL) GC TO 135
KK = 2C
MACH(I, J) = 1.C
GO TO 133
133 RH0(I, J) = P(I, J)*CNVT(1C, ASI)/RGAS/T(I, J)
M1 = M1
IF (GAMMA.EQ.1.4) M1 = CNVT(1C, ASI)*T(I, J)**1.5/T(I, J)+CNVT(2, ASI)
REPI(I, J) = RH0(I, J)*UI(I, J)**2.+G(H(I, J)/MX/CNVT(6, ASI)
FRCT(I, J) = FRFLNC(REP(I, J))
134 CONTINUE

C
PETLPA
END
C
C PRESSURE CALCULATION FOR NUMERICAL INTEGRATIONS
C
C PROGRAM VARIABLES
***************
C X = DISTANCE ACROSS FACE OF SEAL
C XX = STORED X DISTRIBUTION FROM 0 TO X*
C FM = MACH NUMBER DISTRIBUTION WITH XX
C FF = FILM THICKNESS DISTRIBUTION WITH XX
C
C FMM = MACH NUMBER AT X
C FF = FILM THICKNESS AT X
C AN = AREA AT X
C PRESS = PRESSURE AT X
C
C ARITHMETIC FUNCTION FLGRNG DOES A 3 POINT LAGRANGE INTERPOLATION
C
FUNCTION PRESS(X)
DOUBLE PRECISION XX, FM, HH, XC, X1, X2, YC, Y1, Y2
REAL LCSS
COMMON/ARRAYS/EXTRA(1971), PSTAR(20), ASTAR(20)
COMMON/TRAYS/N, XX(2C1), FM(2C1), HH(2C1), J, TSTAR
COMMON/CONSTS/GAMMA, R0IF, RG, SIGND(6), T0, PC, P3, FT, RCAS, LCSS, MU, PI,
1 RUNVVE(2), CNVT(11,2), NSI
FLGRNG(X, XM, X1, X2, YC, Y1, Y2) = YC*(X-X1)*(X-X2)/(X1-X2)/(X1-X2)+
1 Y1*(X-X1)/(X1-X2)/(X1-X2)+Y2*(X-XC)*(X-X1)/(X2-XC)/
2 (X2-X1)
C
AN = 1.0
DO 120 I=1,N
KK = I
IF (X-XX(I)) 122, 121, 120
120 CONTINUE
GO TO 122
121 FM = FM(KK)
H = FF(KK)
GO TO 125
122 IF (KK.LE.2) KK=2
IF (KK .LT. N) KK=N-1
C
120 FMM = FLGRNG(X, XX(KK-1), XX(KK), XX(KK+1), FM(KK-1), FM(KK), FM(KK+1))
H = FL(RNG(X, XX(KK-1), XX(KK), XX(KK+1), HH(KK-1), HH(KK), HH(KK+1))
C
135 IF (RC .LT. 0.0) AN=2.0*PI*(RC+X*SIGN)
PRESS = PSTAR(J)*ASTAR(J)/AN/HC*SQRT(0.50*(GAMMA+1.0)/
1 (1.0+.5C*(GAMMA-1.0)*FMM**2))/FM**
DO UNE PREC l SIC RUNG-E-KUTTA SOLLUTION OF THE MACH NUMBER EQUATION
FOR FLOW WITH AREA CHANGE AND FRICTION

BOUNCY CONDITION IS: Y=1.0 AT X=0. DECREASE STEP SIZE UNTIL A
SATISFACTORY X IS FOUND.

WORKING VARIABLES ARE IN DOUBLE PRECISION

PROGRAM VARIABLES
***************

X - DISTANCE FROM INLET
Y - FIlM THICKNESS
R - SOLUTION OF MACH NUMBER EQUATION
T - RADIALS THAT CORRESPONDS TO X
T - LOCAL TEMPERATURE
T1 - ENTRANCE TEMPERATURE
M - VISCOSITY
RE - REYNOLDS NUMBER
F - FRICTION FACTOR

CON- SINT L TILT ANGLE
G - RATIO OF SPECIFIC HEATS
GAMMA - RATIO OF SPECIFIC HEATS
R1 - RADIALS AT ENTRANCE

Y0 - SQUARE OF ENTRANCE MACH NUMBER - INITIAL ESTIMATE
SUPPLIED BY CALLING PROGRAM

FACT OR - RH*RC*L*C

DELX - LENGTH OF X INTERVAL (STEP SIZE)

DLY - FIlM THICKNESS AT MIDPOINT OF X INTERVAL

HR - RATIO OF FILM THICKNESS TO RADIUS FOR SEALS WITH RADIAL

EXPANSION

******

FK1 * - INTERMEDIATE VALUES OF THE DERIVATIVE CY/CX IN THE
FK2 * RUNG-E-KUTTA FORMULA

******

ARITHMETIC FUNCTION DYDX DEFINES THE DERIVATIVE OF THE SQUARE CF
THE MACH NUMBER WITH RESPECT TO X

ARITHMETIC FUNCTION HFUNC DEFINES THE FIlM THICKNESS AS A FUNCTION
OF X

SUBROUTINE RX(ISCON)
DOUBLE PRECISION DYDX,CON,F,G,R,VC,DELX,R1,FK1,FK2,FK3,FK4,FI,
1,DELX,FFFLNC,Hfunc,SIGN,HRT,XTOL,X,Y,H
REAL LSS,MU,MLIN
COMMON/STAY/S,NX(2),X(2),H(2),H(2),LTSTAR
COMMON/CONS/GAMMA,RDF,S1,SIGN,EX(6),1C,PC,F3,PG,GS,LSS,
1,MLIN,PI,RLNIV(2),CVM(11,2),ASI
D Y DX(Y,F,CON,F,G,HR) = 2.0C*Y*(1.0D0+5.0D0*(C-1.0D0)*Y)*(F*G+Y-CCN-
1)*HR/2/(1.0D0-Y)

Hfunc(X,F,CON) = H*X*CON
INITIAL STEPS - TRANSFER PERMANENTLY STORED SINGLE PRECISION
CONSTANTS TO DOUBLE PRECISION VARIABLES

G = GAMMA
R1 = SR1
CON = SCN
SIGN = SIGN
FACTOR = 1.0
X(1) = C.CC
YO = Y(1)**2
HR = C.CC
IF (R1.EQ.C.WC) SR1 = 1.0

10C Y(1) = YO
NST = 11
N1 = 2
N2 = 11
DELX = RCIF/FACTOR
NN = ALCGIO(RCIF)
XTOL = RCIF**10.0**((NN-4)
NOTE = 0

RCONST = 2.0*CNVT(1.C, NSI)*PC*SR1*H(1)*SQR(T(1)) *GAMMA*CNVT(11, NSI)
1 /RCAS/TOD/CNVT(6, NSI)/1.0+50*(GAMMA-1.0)*Y(1)/LCSS**2)**
2 ((GAMMA+1.0)/2.0/(GAMMA-1.0))
T1 = TC/(1.0+50*(GAMMA-1.0)*Y(1)/LCSS**2)

RUNC = KLTTA SOLUTION

20C DO 30C I=N1, N2
II = I
X(I) = X(I-1)+DELX
R = R1*X(I-1)*SIGN
IF (R1.EQ.C.WC) HR = H(I-1)/R
T = T1*(1.0+50*(GAMMA-1.0)*Y(I-1))/1.0+50*(GAMMA-1.0)*Y(I-1))
MU = MLIN
IF (GAMMA.EQ.1.4) ML = CNVT(1, NSI)*1.5/(T*CNVT(2, NSI))
RE = RECNST/ML
IF (GAMMA.EQ.1.4) RE = RE/R
F = FRLNC(RE)
FK1 = DELX*DVCY(X(I-1), H(I-1), CCN, F, G, HF)
R = X(I-1)+50*DELX*SIGN*R1
HI = FRLNC(X(I-1)+50*DELX, H(I), CCN)
IF (R1.EQ.C.WC) HR = HI/R
T = T1*(1.0+50*(GAMMA-1.0)*Y(I-1))/1.0+50*(GAMMA-1.0)*
1 *(Y(I-1)+50*FK1))
MU = MLIN
IF (GAMMA.EQ.1.4) MU = CNVT(1, NSI)*T**1.5/(T*CNVT(2, NSI))
RE = RECNST/ML
IF (GAMMA.EQ.1.4) RE = RE/R
F = FRLNC(RE)
FK2 = DELX*DVCY(X(I-1)+50*FK1, HI, CCN, F, G, HR)
T = T1*(1.0+50*(GAMMA-1.0)*Y(I))/1.0+50*(GAMMA-1.0)*
1 *(Y(I-1)+50*FK2))
MU = MLIN
IF (GAMMA.EQ.1.4) ML = CNVT(1, NSI)*T**1.5/(T*CNVT(2, NSI))
RE = RECNST/ML
IF (GAMMA.EQ.1.4) RE = RE/R

52
F = FRFLNC(RE)
FK3 = [DELX*DYDX*(Y(I-1)+.5DC*FK2,H1,CCH,F,G,HR)
R = X(I)*SIGN+R]
HI(Y) = FRFLNC(X(I),H1,CON)
IF (R1,NE,C,DC) HR=H1/R
T = T*(1+C*50*(GAMMA-1.0)*Y(I)/1.0*.50*(GAMMA-1.0)*)
1 (Y(I-1)+FK3)
MU = M/(1.0)
IF (GAMMA=EQ.1.4) ML=CNVT(1,NSI)*T**1.5/(T+CNVT(2,NSI))
RE = RCNST/ML
IF (R1,NE,C,DC) RE=RE/R
F = FRFLNC(RE)
FK4 = [DELX*DYDX*(Y(I-1)+FK3,H1,CCH,F,G,HR)
DELY = (FK1+2.0C*(FK2+FK3)+FK4)/6.0
Y(I) = Y(I-1)+DELY
28C IF (CAES(1.00-Y(I))*L.E.1.0-0) GC TO 600
C FLOW MUST REMAIN SUBSONIC UNTIL EXIT - IF Y(I) EXCEEDS 1.0 AT ANY
C POINT, LOWER DELXY
C IF ((Y(I-1)+.5DC*FK1,GT.1.0,DC.GR.Y(I-1)+.500*FK2,GT.1.0,DC)) OR
1 (Y(I-1)+FK3,GT.1.0,DC.OR.Y(I)+.500*FK2,GT.1.0,DC)) GC TO 320
IF (DELY.LE.0.00) GC TO 41C
IF (DELY.GT.1.00) GC TO 32C
IF (Y(I).LT.2.00) GC TO 32C
IF (CAES(X(I)-RDIF),GT.XTCL) GC TO 290
II = II-1
IF (NOTE.EQ.0) GC TO 315
25C IF (I.CE.201) GC TO 400
20C CONTINUE
C 21C N1 = N1+1
GO TO 22C
215 NOTE = 1
22C IF (II.CE.11) N1=II
DELXY = DELX/10.0C
33C N2 = N1+9
GO TO 22C
C IF INITIAL GUESS CF Y0 WAS TCC LCK, RAISE IT
C 46C IF (1.0C-Y(I)+1.0E.5DC) GC TO 42C
41C Y0 = YC+1.0C
GO TO 1CC
C IF NUMBER OF STEPS EXCEEDS THE SIZE OF THE ARRAY, ELIMINATE POINTS
C WHERE THE VALUE OF THE FUNCTION IS NOT CHANGING RAPIDLY
C 42C DELXY = RDIF/50.0C
INC = NST
N = 2C1
IF (N2.LT.2C1) N=N2
DO 440 I=NST,N
IF (CAES(X(I)-RDIF),LE.XTCL) GC TO 430
IF (I.EQ.1.0P+1,LE.N) GC TO 43C
IF (Y(I).LE.Y,(IND-1)+2DELY) GC TO 430
IF (Y(I).LE.Y,(IND-1)+20-1) GC TO 440
43C X(IND) = X(I)
IND = IND+1
V(INC1) = Y(I)
INC = INC + 1

44C CONTINUE

NST = INC - 1
Y1 = INC
Y2 = N1 + 5
IF (NST LE 50) GO TO 200
FACTOR = FACTOR / 2.0
GO TO 1CC

C
C Satisfactory x* found - solution complete

C
60C N = 11
DO 65C I = 1, N
65C Y(I) = CSORT(Y(I))
IF (R1 .EQ. G .OR. G) SR1 = G.0

C
RETURN
END

C
C NUMERICAL INTEGRATION BY SIMPSON'S RULE
C
C INTEGRAL OF Y DX FROM XMIN TO XMAX = (H/3) * (YO + 4Y1 + Y2)
WHERE YC = Y EVALUATED AT XMIN
Y1 = Y EVALUATED AT (XMIN + XMAX) / 2
Y2 = Y EVALUATED AT XMAX
H = (XMAX - XMIN) / 2 (STEP SIZE)

C
CALL VECTOR VARIABLES

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FRAC - FRACTION OF ERROR TOLERANCE APPLICABLE TO NTH
SUBDIVISION

*****
TEST* - TEST VALUE FOR ERROR IN INTEGRAL
NTEST*
*****
Q - TEST VALUE OF FINAL ANSWER

FUNCTION SIMPS1(XMIN, XMAX, FLNCL, KER)
DIMENSION V(200),H(200),A(200),B(200),C(200),F(200),E(200),NE(200)
DIMENSION V(200),H(200),A(200),B(200),C(200),F(200),E(200),NE(200)
EQUVALENCE (E,NE),(TEST,NTEST)

DEFINE STARTING VALUES

T = 3.0*E-5
V(1) = XMIN
H(1) = 0.5*(XMAX- XMIN)
A(1) = FLNCL(XMIN)
B(1) = FLNCL(XMIN+H(1))
C(1) = FLNCL(XMAX)
P(1) = T*(A(1)+4.0*B(1)+C(1))
E(1) = P(1)
ANS = P(1)
N=1
FRAC = 2.0*7
1 FRAC = C.5*FRAC

BEGIN INTEGRATION USING MORE SUBINTERVALS WHERE VALUE OF INTEGRAND
IS CHANGING RAPIDLY

2 TEST = ABS(FRAC*ANS)
K = N
DO 7 I = 1, K
IF (NTEST.GT.IABS(NE(1))) GC TO 7
5 N = N + 1
V(N) = V(I) + H(I)
H(N) = 0.5*H(I)
A(N) = B(I)
B(N) = FLNCL(V(N)+H(N))
C(N) = C(I)
P(N) = H(N)*P(I)
Q = P(I)
H(I) + H(N)
B(I) = FLNCL(V(I)+H(I))
C(I) = A(N)
P(I) = T*(A(I)+4.0*B(I)+C(I))
Q = P(I) + P(N-Q)
ANS = ANS + Q
E(I) = Q
E(N) = Q
IF (N.GE.200) GO TO 13
7 CONTINUE
IF (N.GT.K) GO TO 2
Q = 0.0
DO 11 I = 1, N
11 Q = Q + E(I)
12 IF (ABS(Q)-T*ABS(ANS)) 14, 14, 1
13 KER = KER + 1
14
55
ACCLMLLATE FINAL ANSWER

14 ANS=Q*C
   DO 16 J=1,N
16 ANS=ANS+F(J)
   SIMPS1=(ANS+Q/3C,C)/3C

17 RETURN
   END

PROGRAM VARIABLES

***************

XX - CHARACTERISTIC FILM THICKNESS
YY - SEALING DAM FORCE
CDY - AXIAL FILM STIFFNESS
MAX - NUMBER OF FILM THICKNESSES
MACH - MACH NUMBER
REP - PRESSURE FLOW REYNOLDS NUMBER

******

X *
Y *
CY *
A *** WORKING VARIABLES IN NUMERICAL DIFFERENTIATION
S1 *
S2 *
P2 *
KY *

******

LAGRANGE NUMERICAL DIFFERENTIATION OVER MAXIMUM OF 5 POINTS
TO DETERMINE AXIAL FILM STIFFNESS

SUBROUTINE STFASS
REAL MACH
DIMENSION X(2C), Y(20), DY(2C), A(5,5)
COMMON/CONSTS/E(16),RELAM,RETURN,D2(10),CNVT(23)
COMMON/ARRAYS/D3(231),MACH(11,2C),D4(660),REP(11,20),C5(480),
1 YY(2C),DDY(2C),D6(6C),XX(2C),D7(6C)
COMMON/TRAYS/CE(1207),MAX,TSTAK

C

ELIMINATE INVALID POINTS AND ARRANGE VALID POINTS IN ASCENDING
ORDER. IF THERE ARE LESS THAN 2 VALID POINTS, NC DIFFERENTIATION
IS POSSIBLE.

C

DO 50 K=1,MAX
   50 DEX(M) = C.

C

DO 40C INC=1,4
   MM = C
   10C DO 11C K=1,MAX
      GO TO (1,2,3,4),IND
   11C IF (MACH(11,M),C.E.1,C.AND.REP(6,4).L.E.RELAM) CC TO 10C
GO TO 110
2 IF (MACK(11,M) .GE. 1.0 .AND. REP(6,M) .GE. RETLRB) GC TC 105
GO TO 110
2 IF (MACK(11,M) .LT. 1.0 .AND. REP(6,M) .LE. RETLRM) GC TC 105
GO TO 110
4 IF (MACK(11,M) .LT. 1.0 .AND. REP(6,M) .GE. RETLRB) GC TC 105
GO TO 110
1C5 MM = MM + 1
X(MM) = XX(M)
Y(MM) = YY(M)
11C CONTINUE
IF (MM .LT. 2) GO TO 4C
13C CALL SCRTXY(X,Y,MM)
C SET UP MATRIX OF X DIFFERENCES FOR EACH POINT X(K)
C
20C N = MINC(MM, 5)
DO 25C K = 1, MM
IST = MAX(K-2, 1)
IST = MINC(MM-K+1, IST)
IN = IST*N-1
DO 211 I = IST, IN
I = I - IST + 1
DO 21C J = IST, IN
J = J - IST + 1
A(I, J) = X(I) - X(J)
21C CONTINUE
211 CONTINUE
C FORM SLPS AND PRODUCTS FOR DERIVATIVE FORMULA
C
22C S1 = C
S2 = C
P2 = 1.
DO 231 I = IST, IN
IF (II .EQ. K) GO TO 231
I = I - IST + 1
P1 = X(I) - X(K)
S2 = S2 - P1/P1
P2 = P2*P1
DO 23C J = 1, N
IF (I .NE. J) P1 = P1*A(I, J)
23C CONTINUE
S1 = S1 + Y(I)/P1
231 CONTINUE
IF ((N/2) .NE. N) S2 = S2
C DERIVATIVE
C
KY = S2 + Y(K) + P2*S1
DY(K) = KY
25C CONTINUE
C PUT CALCULATED DERIVATIVES IN ORDER TO CORRESPOND TO INPUT XX
C ARRAY
C
30C DO 32C M = 1, MAX
DO 31C I = 1, MM
IF (XX(M) .NE. XX(II)) GO TO 3IC
IF ((N/2)*2 .NE. M) GO TO 311

CCY(M) = -CCY(11)
GO TO 320

311 CCY(M) = CCY(11)
GO TO 320

31C CONTINUE
32C CONTINUE
40C CONTINUE
C RETURN
END

C FUNCTION FOR FINDING LOCAL FRICTION FACTOR AS A FUNCTION OF
C REYNOLDS NUMBER
C
C DOUBLE PRECISION FUNCTION FRFUNC(RE)
COMMON/CONSTS/E*1(4),XLAM,XTLRB,CCALAM,CCNTRB,RELAM,RETB,ETX2/(33)
DOUBLE PRECISION X1,X2,X3,Y2
C LAMINAR FLOW
C IF (RE*.ET.RELAM) GO TO 11C
FRFUNC = CONLAM/RE**XLAM
RETURN
C TRANSITION FLOW
10C IF (RE*.ET.RETURB) GO TO 11C
X1 = ALCG(RELAM)
X2 = ALCG(RETURB)
X3 = ALCG(RE)
Y2 = ALCG(CONTRB-XTLRB*X2-2.0*(ALCG(CONTRB/CCALAM)+XLAM*X1-1)*XTLRB*X2)*((X3*(X3-1.500*(X1+X2)+3.000*X1*X2)-5000*X2)**2
2 *((2.000*X1-X2))/((X2-X1)**3
FRFUNC = DEXP(Y2)
RETURN
C TURBULENT FLOW
C 11C FRFUNC = CONTRB/RE**XTLRB
RETURN
C END
C INTEGRAND OF FORCE INTEGRAL

FUNCTION FFLNC(X)
COMMON/CONSTS/DD(12),P3,DDD(3C)
FFLNC = PRESS(X)-P3
RETURN
END

C INTEGRAND OF CENTER OF PRESSURE INTEGRAL

FUNCTION XCFUNC(X)
COMMON/CONSTS/DD(12),P3,DDD(3C)
XCFUNC = (PRESS(X)-P3)*X
RETURN
END

C ARRANGE POINTS (X,Y) IN ORDER OF ASCENDING X

SUBROUTINE SORTXY(X,Y,N)
DIMENSION X(10C), Y(10C)
NN= N-1

DO 10C I=1,NN
II = I
CO 10C J=2,N
IF(X(J) .GE. X(I)) GO TO 10C
T = X(J)
X(J) = X(I)
X(I) = T
T = Y(J)
Y(J) = Y(I)
Y(I) = T
10C CONTINUE
11C CONTINUE

RETURN
END
SUBROUTINE GRIFIC
LOGICAL PWR, NRM, PL1
REAL MACH, LOSS, NU
COMMON/ARRAYS/X(11), P(11,2C), MACH(11,20), T(11,20),
1 RH(11,20), REP(11,2C), FRIC(11,2C), H(11,20), XCHAR(20),
2 PCH(2C), FORCE(2C), STIFF(20), FBAR(20), E1 (60), HMEF(20),
2 E2(60)
COMMON/CONSTS/CRIF, N1, RECCM(6), TC, F3, PT, RGF, LC, NU, PI,
1 RLIV(2), CVT(11,2), NSI
COMMON/CTITLE/TITLE(12)
COMMON/LOGLCL/PWR, NRM, PL1

WRITE (6, 1C)
1C FORMAT (1H1, 47H FLOTS CANNOT BE MADE BY THE SUBROUTINE SUPPLIED)
RETURN
END

BLOCK DATA SUBROUTINE ECR CONSTANTS

COMMON/CONSTS/X(17), P1, RLIV(2), CVT(11,2), NSI
COMMON/PRNT/C4(14), C2(14), C3(4), C4(4), C5(4), C6(4), C7(4), C8(4), BLANK
DATA P1, (RLIV(1), I=1, 2)/ 3.1415927, 8.3436E3, 1545.4 /
DATA (CVT(11,1), I=1, 11) / -1459E-5, 110.3, 2*1, .5051554E2, 1
1.
DATA (CVT(1,2), I=1, 11) / 1.57635E-1C, 198.6, 720.0, 13.405833, 1
1 13.683, 1728., 45.833333, 42.42, 3300U.0, 4.4756636, 32.174/
DATA (C1(I), I=1, 4) / 6H, PO, 6HER, 6F / 12
DATA (C2(I), I=1, 4) / 6HIMFS, 6HICLE, 6HS QUAN, 6HTITIES /
DATA (C3(I), I=1, 4) / 6H PRESS, 6HLRE DI, 6HSTRIBU, 6HTICS /
DATA (C4(I), I=1, 4) / 6HPCHER, 6H, 6XCH(6FBAR) /
DATA (C5(I), I=1, 4) / 6HFORCE, 6H, 6H PRES, 6HSURE /
DATA (C6(I), I=1, 4) / 6HTEMPP, 6HATLRE, 6H DENT, 6HSITY /
DATA (C7(I), I=1, 4) / 6HMACH N, 6HLMBER, 6H RE NU, 6F*REF /
DATA (C8(I), I=1, 4) / 6HFRICT, 6HFACCTR, 6H, 6F /
DATA BLANK/6H /

END
# APPENDIX D

## SAMPLE OUTPUT

### INPUT DATA

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Value</th>
<th>Physical Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td>Specific Heat</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td>Thermal Conductivity</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>Thermal Conductivity</td>
<td></td>
</tr>
</tbody>
</table>

### OUTPUT DATA

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Value</th>
<th>Physical Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td>Specific Heat</td>
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</tr>
<tr>
<td>Volume</td>
<td></td>
<td>Thermal Conductivity</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>Thermal Conductivity</td>
<td></td>
</tr>
</tbody>
</table>

### NOTES

- **Laminar Flow**
- ** Transitional Region**
- **Turbulent Flow**

### NURBS CURVES

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Value</th>
<th>Coordinate</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

### MACH NUMBER

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td></td>
</tr>
</tbody>
</table>
### Table 1: Mach/Number Density Flow

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Density</th>
<th>Pressure</th>
<th>Temperature</th>
<th>Friction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>0.150</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>0.15E+00</td>
</tr>
<tr>
<td>0.200</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>0.20E+00</td>
</tr>
<tr>
<td>0.250</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>0.25E+00</td>
</tr>
<tr>
<td>0.300</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>0.30E+00</td>
</tr>
</tbody>
</table>

### Table 2: Mach/Number Density Shock Flow

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Density</th>
<th>Pressure</th>
<th>Temperature</th>
<th>Friction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>0.150</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>0.15E+00</td>
</tr>
<tr>
<td>0.200</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>0.20E+00</td>
</tr>
<tr>
<td>0.250</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>0.25E+00</td>
</tr>
<tr>
<td>0.300</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>0.30E+00</td>
</tr>
</tbody>
</table>

### Table 3: Mach/Number Density Freestream Flow

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Density</th>
<th>Pressure</th>
<th>Temperature</th>
<th>Friction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>0.150</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>1.50E+00</td>
<td>0.15E+00</td>
</tr>
<tr>
<td>0.200</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>2.00E+00</td>
<td>0.20E+00</td>
</tr>
<tr>
<td>0.250</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>2.50E+00</td>
<td>0.25E+00</td>
</tr>
<tr>
<td>0.300</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>3.00E+00</td>
<td>0.30E+00</td>
</tr>
</tbody>
</table>
### Table 1: Parameters for $0.176E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018E+04</td>
<td>0.014E+04</td>
<td>0.017E+04</td>
<td>0.013E+04</td>
<td>0.020E+04</td>
<td>0.015E+04</td>
<td>0.025E+04</td>
</tr>
</tbody>
</table>

### Table 2: Parameters for $0.203E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.020E+04</td>
<td>0.016E+04</td>
<td>0.021E+04</td>
<td>0.017E+04</td>
<td>0.027E+04</td>
<td>0.018E+04</td>
<td>0.030E+04</td>
</tr>
</tbody>
</table>

### Table 3: Parameters for $0.277E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.027E+04</td>
<td>0.020E+04</td>
<td>0.029E+04</td>
<td>0.022E+04</td>
<td>0.032E+04</td>
<td>0.022E+04</td>
<td>0.036E+04</td>
</tr>
</tbody>
</table>

### Table 4: Parameters for $0.301E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.030E+04</td>
<td>0.024E+04</td>
<td>0.034E+04</td>
<td>0.026E+04</td>
<td>0.038E+04</td>
<td>0.025E+04</td>
<td>0.041E+04</td>
</tr>
</tbody>
</table>

### Table 5: Parameters for $0.354E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.035E+04</td>
<td>0.029E+04</td>
<td>0.039E+04</td>
<td>0.028E+04</td>
<td>0.043E+04</td>
<td>0.029E+04</td>
<td>0.046E+04</td>
</tr>
</tbody>
</table>

### Table 6: Parameters for $0.413E+04$ Meters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$M$</th>
<th>$H$</th>
<th>$P$</th>
<th>$T$</th>
<th>$R$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.041E+04</td>
<td>0.035E+04</td>
<td>0.047E+04</td>
<td>0.036E+04</td>
<td>0.051E+04</td>
<td>0.036E+04</td>
<td>0.055E+04</td>
</tr>
<tr>
<td>X</td>
<td>MACH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.127E-03</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.254E-03</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.508E-03</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.762E-03</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.889E-03</td>
<td>0.30E-04</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.114E-02</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.147E-02</td>
<td>0.30E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Y</th>
<th>MACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.127E-03</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.254E-03</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.508E-03</td>
<td>0.30E-04</td>
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<td>0.762E-03</td>
<td>0.30E-04</td>
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<td>0.889E-03</td>
<td>0.30E-04</td>
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<tr>
<td>0.114E-02</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.147E-02</td>
<td>0.30E-04</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Z</th>
<th>MACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.127E-03</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.254E-03</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.508E-03</td>
<td>0.30E-04</td>
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<tr>
<td>0.762E-03</td>
<td>0.30E-04</td>
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<tr>
<td>0.889E-03</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.114E-02</td>
<td>0.30E-04</td>
</tr>
<tr>
<td>0.147E-02</td>
<td>0.30E-04</td>
</tr>
</tbody>
</table>
SAMPLE PROBLEM - AREA EXPANSION PROGRAM = U. S. UNITS

INPUT DATA -

- SIMPLE PROBLEM -
  - EXPANSION FRACTION -
    - UNITS

INPUT DATA -

- SIMPLE PROBLEM -
  - EXPANSION FRACTION -
    - UNITS

CALCULATED DATA -

- DIMENSIONLESS QUANTITIES
- PRESSURE DISTRIBUTIONS
- PLOT

- / - CHECKED FLOW
- / - TRANSITION REGION
- T - TURBULENT FLOW

- *******************************

- C - LAMINAR
- / - TURBULENT

- *******************************
<table>
<thead>
<tr>
<th>( \text{FLUID} )</th>
<th>( \text{DENSITY} )</th>
<th>( \text{VISCOSITY} )</th>
<th>( \text{INTERCEPT} )</th>
<th>( \text{SLOPE} )</th>
<th>( \text{R}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.000</td>
<td>0.040</td>
<td>0.000</td>
<td>0.000</td>
<td>0.999</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.825</td>
<td>0.045</td>
<td>0.002</td>
<td>0.001</td>
<td>0.998</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.785</td>
<td>0.040</td>
<td>0.003</td>
<td>0.002</td>
<td>0.997</td>
</tr>
<tr>
<td>Glycerin</td>
<td>1.265</td>
<td>0.050</td>
<td>0.004</td>
<td>0.003</td>
<td>0.996</td>
</tr>
</tbody>
</table>

**Notes:**
- \( \text{FLUID} \) denotes the type of fluid.
- \( \text{DENSITY} \) is in units of g/cm³.
- \( \text{VISCOSITY} \) is in units of cP.
- \( \text{INTERCEPT} \) and \( \text{SLOPE} \) are coefficients for a linear regression model.
- \( \text{R}^2 \) represents the coefficient of determination.
### Table 1: Mach Number and Velocity at Various Pressure Levels

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Velocity</th>
<th>Pressure</th>
<th>Temperature</th>
<th>Re(PI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 2: Mass Flow and Density at Various Pressure Levels

<table>
<thead>
<tr>
<th>Mass Flow</th>
<th>Density</th>
<th>Pressure</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 3: Efficiency and Loss Coefficient at Various Pressure Levels

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Loss Coefficient</th>
<th>Pressure</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

---

### Table 4: Friction and Mach Number at Various Pressure Levels

<table>
<thead>
<tr>
<th>Friction</th>
<th>Mach Number</th>
<th>Pressure</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>MACH</td>
<td>VELOCITY</td>
<td>DENSITY</td>
<td>PRESSURE</td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>0.5</td>
<td>0.647</td>
<td>65.2</td>
<td>67.9</td>
</tr>
<tr>
<td>0.6</td>
<td>0.657</td>
<td>65.9</td>
<td>67.9</td>
</tr>
<tr>
<td>0.7</td>
<td>0.667</td>
<td>66.6</td>
<td>67.9</td>
</tr>
<tr>
<td>0.8</td>
<td>0.677</td>
<td>67.4</td>
<td>67.9</td>
</tr>
<tr>
<td>0.9</td>
<td>0.687</td>
<td>68.2</td>
<td>67.9</td>
</tr>
<tr>
<td>1.0</td>
<td>0.697</td>
<td>69.0</td>
<td>67.9</td>
</tr>
<tr>
<td>1.1</td>
<td>0.707</td>
<td>70.0</td>
<td>67.9</td>
</tr>
<tr>
<td>1.2</td>
<td>0.717</td>
<td>71.0</td>
<td>67.9</td>
</tr>
<tr>
<td>1.3</td>
<td>0.727</td>
<td>72.1</td>
<td>67.9</td>
</tr>
<tr>
<td>1.4</td>
<td>0.737</td>
<td>73.2</td>
<td>67.9</td>
</tr>
<tr>
<td>1.5</td>
<td>0.747</td>
<td>74.3</td>
<td>67.9</td>
</tr>
<tr>
<td>1.6</td>
<td>0.757</td>
<td>75.4</td>
<td>67.9</td>
</tr>
<tr>
<td>1.7</td>
<td>0.767</td>
<td>76.6</td>
<td>67.9</td>
</tr>
<tr>
<td>1.8</td>
<td>0.777</td>
<td>77.9</td>
<td>67.9</td>
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<tr>
<td>1.9</td>
<td>0.787</td>
<td>79.1</td>
<td>67.9</td>
</tr>
<tr>
<td>2.0</td>
<td>0.797</td>
<td>80.4</td>
<td>67.9</td>
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<tr>
<td>2.1</td>
<td>0.807</td>
<td>81.7</td>
<td>67.9</td>
</tr>
<tr>
<td>2.2</td>
<td>0.817</td>
<td>83.0</td>
<td>67.9</td>
</tr>
<tr>
<td>2.3</td>
<td>0.827</td>
<td>84.4</td>
<td>67.9</td>
</tr>
<tr>
<td>2.4</td>
<td>0.837</td>
<td>85.8</td>
<td>67.9</td>
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<tr>
<td>2.5</td>
<td>0.847</td>
<td>87.3</td>
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<tr>
<td>2.6</td>
<td>0.857</td>
<td>88.8</td>
<td>67.9</td>
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<td>0.867</td>
<td>90.3</td>
<td>67.9</td>
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<tr>
<td>2.8</td>
<td>0.877</td>
<td>91.9</td>
<td>67.9</td>
</tr>
<tr>
<td>2.9</td>
<td>0.887</td>
<td>93.5</td>
<td>67.9</td>
</tr>
<tr>
<td>3.0</td>
<td>0.897</td>
<td>95.1</td>
<td>67.9</td>
</tr>
<tr>
<td>3.1</td>
<td>0.907</td>
<td>96.8</td>
<td>67.9</td>
</tr>
<tr>
<td>3.2</td>
<td>0.917</td>
<td>98.6</td>
<td>67.9</td>
</tr>
<tr>
<td>3.3</td>
<td>0.927</td>
<td>100.4</td>
<td>67.9</td>
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<tr>
<td>3.4</td>
<td>0.937</td>
<td>102.2</td>
<td>67.9</td>
</tr>
<tr>
<td>3.5</td>
<td>0.947</td>
<td>104.0</td>
<td>67.9</td>
</tr>
<tr>
<td>3.6</td>
<td>0.957</td>
<td>105.9</td>
<td>67.9</td>
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<td>3.7</td>
<td>0.967</td>
<td>107.8</td>
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</tr>
<tr>
<td>3.8</td>
<td>0.977</td>
<td>109.7</td>
<td>67.9</td>
</tr>
<tr>
<td>3.9</td>
<td>0.987</td>
<td>111.7</td>
<td>67.9</td>
</tr>
</tbody>
</table>

**Note:** The table above represents the Mach number, velocity, density, pressure, and temperature for various conditions. The data is expressed in standard units (inches, feet, pounds per square inch, etc.).
REFERENCES


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas constant</td>
<td>$\mathcal{g} = \frac{\text{Universal gas constant}}{\text{Molecular weight}}$</td>
<td>J/kg-K</td>
</tr>
<tr>
<td>Seal surface area</td>
<td>$A = \pi \left(R_2^2 - R_1^2\right)$</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Flow length</td>
<td>$\Delta R = R_2 - R_1$</td>
<td>m</td>
</tr>
<tr>
<td>Flow width (mean)</td>
<td>$W = 2\pi \left(\frac{R_1 + R_2}{2}\right)$</td>
<td>m</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>$M = Wh\rho_u$</td>
<td>kg/sec</td>
</tr>
<tr>
<td>Volume flow rate</td>
<td>$Q = c_1M$</td>
<td>scms</td>
</tr>
<tr>
<td>Reynolds number due to rotational flow</td>
<td>$b\text{Re} = \bar{\rho}Vh \sqrt{\mu}$</td>
<td></td>
</tr>
<tr>
<td>Knudsen number</td>
<td>$Kn = \frac{2.96 M_{\text{max}}}{Re(p)}$</td>
<td>m</td>
</tr>
<tr>
<td>Mean free path</td>
<td>$\lambda = Kn \times h$</td>
<td></td>
</tr>
<tr>
<td>Viscosity of air (Sutherland's law)</td>
<td>$\mu_{\text{air}} = \frac{c_2 T^{1.5}}{T + c_3}$</td>
<td>N-sec/m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Power</td>
<td>$\mu A V^2/h$</td>
<td>W</td>
</tr>
<tr>
<td>Apparent temperature rise due to power</td>
<td>$\Delta T = \frac{c_4 \times \text{Power}}{M c_p}$</td>
<td>K</td>
</tr>
<tr>
<td>dissipation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear heat</td>
<td>$H = c_5 \times \text{Power}$</td>
<td>W</td>
</tr>
<tr>
<td>Torque</td>
<td>$\text{Power} / \text{Speed}$</td>
<td>ft-lb</td>
</tr>
<tr>
<td>Seal opening force</td>
<td>$F = W \int_0^{\Delta R} (P - P_3)dx$</td>
<td>N</td>
</tr>
<tr>
<td>Center of pressure</td>
<td>$x_c = \frac{W}{F} \int_0^{\Delta R} (P - P_3)dx$</td>
<td>m</td>
</tr>
<tr>
<td>Axial film stiffness</td>
<td>$S = -\frac{dF}{dh}$</td>
<td>N/m</td>
</tr>
</tbody>
</table>

<sup>a</sup> Constants in equations are as follows (for SI and U.S. units, respectively):
$c_1 = 5.051554 \times 10^{-3}$ (13.083); $c_2 = 1.4591 \times 10^{-6}$ (1.57639x10<sup>-10</sup>);
$c_3 = 110.3333$ (198.6); $c_4 = 1.0$ (42.42); and $c_5 = 1.0$ (42.42).

<sup>b</sup> Where $\bar{\rho}$ is density at midseal, $\mu$ is viscosity at midseal, and $V$ is mean rotational velocity.
### Table II. Variables in NameList/Seal/

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>SI Units</th>
<th>U.S. Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RINNER</td>
<td>Inner radius of seal</td>
<td>m</td>
<td>in.</td>
</tr>
<tr>
<td>ROUTER</td>
<td>Outer radius of seal</td>
<td>m</td>
<td>in.</td>
</tr>
<tr>
<td>RDFIN</td>
<td>Flow length</td>
<td>m</td>
<td>in.</td>
</tr>
<tr>
<td>MOLWT</td>
<td>Molecular weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP</td>
<td>Specific heat</td>
<td>J/kg-K</td>
<td>Btu/lbm-°R</td>
</tr>
<tr>
<td>MUIN</td>
<td>Reservoir viscosity. The program will calculate MUIN for air but not for other gases.</td>
<td>N·sec/m²</td>
<td>lb·sec/in.²</td>
</tr>
<tr>
<td>GAMMA</td>
<td>Ratio of specific heats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPEED</td>
<td>Rotational velocity</td>
<td>rps</td>
<td>rpm</td>
</tr>
<tr>
<td>CAPV</td>
<td>Seal-face speed</td>
<td>m/sec</td>
<td>ft/sec</td>
</tr>
<tr>
<td>XLAM</td>
<td>Exponent in friction factor - Reynolds number relation for laminar flow (eq. (22))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XTURB</td>
<td>Exponent in friction factor - Reynolds number relation for turbulent flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONLAM</td>
<td>Constant in friction factor - Reynolds number relation for laminar flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONTRB</td>
<td>Constant in friction factor - Reynolds number relation for turbulent flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RELAM</td>
<td>Maximum Reynolds number for laminar flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RETURB</td>
<td>Minimum Reynolds number for turbulent flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWRSKP</td>
<td>Logical variable. If it is set to .TRUE., calculations involving power are omitted.</td>
<td></td>
<td></td>
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<tr>
<td>NRMSKP</td>
<td>Logical variable. If it is set to .TRUE., normalized values of F and x_c will be omitted.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRSSKP</td>
<td>Logical variable. If it is set to .TRUE., printout of distributions across face of seal of P, T, ρ, u, M, ℓ, and Re will be omitted.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLTSKP</td>
<td>Array of logical variables. If any element is set to .TRUE., the corresponding plot will be omitted: PLTSKP(1) applies to plot of power against h. PLTSKP(2) applies to plot of x_c against h. PLTSKP(3) applies to plot of F against h. PLTSKP(4) applies to plot of P against x. PLTSKP(5) applies to plot of T against x. PLTSKP(6) applies to plot of ρ against x. PLTSKP(7) applies to plot of M against x. PLTSKP(8) applies to plot of Reynolds number against x. PLTSKP(9) applies to plot of mean friction factor against x.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSI</td>
<td>Numerical indicator for units. NSI = 1 means SI units. NSI = 2 means U.S. units.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### TABLE III. - VARIABLES IN NAMELIST/HDATA/

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMEAN</td>
<td>Mean film thickness</td>
<td>m, in.</td>
</tr>
<tr>
<td>ALPHA</td>
<td>Tilt angle</td>
<td>rad, rad</td>
</tr>
<tr>
<td>NJ</td>
<td>Number of film thicknesses</td>
<td>---, ---</td>
</tr>
<tr>
<td>JDONE</td>
<td>Number of film thicknesses for which cards were punched in previous running of program</td>
<td>---, ---</td>
</tr>
</tbody>
</table>

### TABLE IV. - VARIABLES IN NAMELIST/RESDAT/

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1IN</td>
<td>Gas pressure at inner radius</td>
<td>N/m², lbf/in.²</td>
</tr>
<tr>
<td>P2IN</td>
<td>Gas pressure at outer radius</td>
<td>N/m², lbf/in.²</td>
</tr>
<tr>
<td>PRIN</td>
<td>Ratio of sealed-gas pressure to ambient pressure, ( P_0/P_3 )</td>
<td>---, ---</td>
</tr>
<tr>
<td>TOIN</td>
<td>Sealed-gas temperature (upstream reservoir temperature), ( T_0 )</td>
<td>K, °F</td>
</tr>
<tr>
<td>LOSS</td>
<td>Entrance velocity loss coefficient</td>
<td>---, ---</td>
</tr>
<tr>
<td>INCODE</td>
<td>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:</td>
<td>---, ---</td>
</tr>
<tr>
<td></td>
<td>INCODE = 1 means a new title card is expected.</td>
<td>---, ---</td>
</tr>
<tr>
<td></td>
<td>INCODE = 2 means new SEAL data are expected.</td>
<td>---, ---</td>
</tr>
<tr>
<td></td>
<td>INCODE = 3 means new HDATA data are expected.</td>
<td>---, ---</td>
</tr>
<tr>
<td></td>
<td>INCODE = 4 means new RESDAT data are expected.</td>
<td>---, ---</td>
</tr>
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</table>
TABLE V. - INPUT DATA FOR SAMPLE PROBLEM

|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|

**SAMPLE PROBLEM - AREA EXPANSION PROGRAM - SI UNITS**
- \$SEAL RINNER=0.082931, RROUT=0.084201, RDIFIN=0.05, MOLWT=28.96, CP=1004.16,
- \$GAMMA=1.4, MUIN=0.0, SPEED=0.0, CAPV=66.96, XLAM=1.0, XTRUB=2.5, CUNLAM=24.0,
- CONTRB=0.079, RELAM=23000.0, RETURN=3000.0, PWRSPKF=F, PRSSKP=F, RNSKP=F,
- PLTSKP=9#F, NSI=1, WIDTH=0.0.$
- \$DATA HMEAN=1.762E-5, 1.016E-5, 1.270E-5, 1.524E-5, 1.778E-5, 2.032E-5, 2.286E-5,$
- 2.540E-5, 2.794E-5, 3.049E-5, 3.022E-5, 3.556E-5, 3.158E-5, 3.604E-5, 4.064E-5, 5.6#E-5,$
- ALPHA=20*0.01, NJ=14, JCODE=14.$
- \$RESQP P1IN=448159.22, P2IN=133423.59, PRIN=0.0, TOIN=31.1111, LOSS=1.0,$
- INCGNE=1.$

**SAMPLE PROBLEM - AREA EXPANSION PROGRAM - U. S. UNITS**
- \$SEAL RINNER=3.225, RROUT=3.315, RDIFIN=0.0, WIDTH=0.0, MOLWT=28.966, CP=2.4,$
- MUIN=0.0, GAMMA=1.4, CAPV=200.0, SPEED=0.0, XLAM=1.0, XTRUB=2.5, CUNLAM=24.0,$
- CONTRB=0.079, RELAM=23000.0, RETURN=3000.0, PWRSPKF=F, PRSSKP=F, RNSKP=F,
- PLTSKP=9#T, NSI=2.$
- \$DATA HMEAN=3E-3, 3.4E-3, 3.5E-3, 3.6E-3, 3.7E-3, 3.8E-3, 3.9E-3, 4.0E-3, 4.1E-3, 4.2E-3,$
- 4.3E-3, 4.4E-3, 4.5E-3, 4.6E-3, 4.7E-3, 4.8E-3, 4.9E-3, 5.0E-3, 5.1E-3, 5.2E-3,$
- ALPHA=20*0.01, NJ=14, JCODE=14.$
- \$RESQP P1IN=65., P2IN=15., PRIN=0.0, TOIN=100., LOSS=1.0, INCGNE=1.$
TABLE VI. - PARAMETERS IN COMMON BLOCK/ARRAYS/

<table>
<thead>
<tr>
<th>Array</th>
<th>Symbol</th>
<th>Array dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>(11)</td>
<td>Distance across face of seal</td>
</tr>
<tr>
<td>2</td>
<td>P</td>
<td>(11, 20)</td>
<td>Pressure</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>(11, 20)</td>
<td>Mach number</td>
</tr>
<tr>
<td>4</td>
<td>u</td>
<td>(11, 20)</td>
<td>Leakage flow velocity (x-direction)</td>
</tr>
<tr>
<td>5</td>
<td>T</td>
<td>(11, 20)</td>
<td>Temperature</td>
</tr>
<tr>
<td>6</td>
<td>ρ</td>
<td>(11, 20)</td>
<td>Density</td>
</tr>
<tr>
<td>7</td>
<td>Re(p)</td>
<td>(11, 20)</td>
<td>Pressure-flow Reynolds number</td>
</tr>
<tr>
<td>8</td>
<td>T̄</td>
<td>(11, 20)</td>
<td>Mean friction factor</td>
</tr>
<tr>
<td>9</td>
<td>h</td>
<td>(11, 20)</td>
<td>Film thickness</td>
</tr>
<tr>
<td>10</td>
<td>Xc</td>
<td>(20)</td>
<td>Dimensionless center of pressure</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>(20)</td>
<td>Power</td>
</tr>
<tr>
<td>12</td>
<td>S</td>
<td>(20)</td>
<td>Axial film stiffness</td>
</tr>
<tr>
<td>13</td>
<td>F̄</td>
<td>(20)</td>
<td>Pressure profile factor</td>
</tr>
<tr>
<td>14</td>
<td>h₁</td>
<td>(20)</td>
<td>Film thickness at entrance</td>
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<td>15</td>
<td>h₂</td>
<td>(20)</td>
<td>Film thickness at exit</td>
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<td>16</td>
<td>α</td>
<td>(20)</td>
<td>Tilt angle</td>
</tr>
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<td>17</td>
<td>hₘ</td>
<td>(20)</td>
<td>Mean film thickness</td>
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<td>18</td>
<td>x*</td>
<td>(20)</td>
<td>Choking flow length</td>
</tr>
<tr>
<td>19</td>
<td>p*</td>
<td>(20)</td>
<td>Choking pressure</td>
</tr>
<tr>
<td>20</td>
<td>A*</td>
<td>(20)</td>
<td>Area at point of choking</td>
</tr>
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</table>
### TABLE VII. - PARAMETERS IN COMMON BLOCK/CONSTS/

<table>
<thead>
<tr>
<th>Word</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>2</td>
<td>$\Delta R$</td>
<td>Flow length</td>
</tr>
<tr>
<td>3</td>
<td>$R_0$</td>
<td>Radius of seal at entrance</td>
</tr>
<tr>
<td></td>
<td>SIGN</td>
<td>If SIGN &gt; 0, flow is radially outward; if SIGN &lt; 0, flow is radially inward.</td>
</tr>
<tr>
<td>4</td>
<td>$n_t$</td>
<td>Exponent in friction factor - Reynolds number relation for laminar flow</td>
</tr>
<tr>
<td>5</td>
<td>$n_t$</td>
<td>Exponent in friction factor - Reynolds number relation for turbulent flow</td>
</tr>
<tr>
<td>6</td>
<td>$k_t$</td>
<td>Constant in friction factor - Reynolds number relation for laminar flow</td>
</tr>
<tr>
<td>7</td>
<td>$k_t$</td>
<td>Constant in friction factor - Reynolds number relation for turbulent flow</td>
</tr>
<tr>
<td>8</td>
<td>$(Re)_l$</td>
<td>Upper limit on Re for laminar flow</td>
</tr>
<tr>
<td>9</td>
<td>$(Re)_t$</td>
<td>Lower limit on Re for turbulent flow</td>
</tr>
<tr>
<td>10</td>
<td>$T_0$</td>
<td>Sealed-gas-reservoir temperature</td>
</tr>
<tr>
<td>11</td>
<td>$P_0$</td>
<td>Sealed-gas-reservoir pressure</td>
</tr>
<tr>
<td>12</td>
<td>$P_3$</td>
<td>Ambient pressure</td>
</tr>
<tr>
<td>13</td>
<td>$P_{tol}$</td>
<td>Pressure tolerance to stop iteration on exit pressure for subcritical flow</td>
</tr>
<tr>
<td>14</td>
<td>$\mathcal{R}$</td>
<td>Gas constant</td>
</tr>
<tr>
<td>15</td>
<td>$C_L$</td>
<td>Entrance velocity loss coefficient</td>
</tr>
<tr>
<td>16</td>
<td>$\mu_0$</td>
<td>Sealed-gas-reservoir viscosity</td>
</tr>
<tr>
<td>17</td>
<td>$\pi$</td>
<td>3.1415927</td>
</tr>
<tr>
<td>18</td>
<td>$\mathcal{R}_u(2)$</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>19</td>
<td>CNVT(11,2)</td>
<td>Constants needed for internal calculations</td>
</tr>
<tr>
<td>20</td>
<td>NSI</td>
<td>Numerical indicator for system of units being used: NSI = 1 means SI units; NSI = 2 means U.S. units.</td>
</tr>
</tbody>
</table>
TABLE VIII. - CONSTANTS FOR INTERNAL CALCULATIONS

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

TABLE IX. - PARAMETERS IN COMMON BLOCK/TRAYS/

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

Figure 1. - Model and notation of sealing faces, including control volume for quasi-one-dimensional flow with area change.
Figure 2. - Model of sealing dam with small tilt angle (not to scale). Sealed gas is in inner cavity region; upper ring removed for clarity in top view.

Figure 3. - Lengths and stations used in analysis. Subsonic case with negatively tilted surface and radial inward flow situation is shown.
Figure 4. - Heirarchy of subprogram calls.
Figure 5. - Computer plots for sample problems, evaluated at film thickness of 12.7 micrometers (0.5 mill).
Figure 5. - Concluded.
Figure 6. Comparison of variable-area approximate analysis with exact compressible-viscous-flow solution for pure radial flow. Parallel film; film thickness, 12.7 micrometers (0.5 mil); sealed-gas-reservoir pressure, 45 N/cm² (65 psia); exit pressure, 10.3 N/cm² (15 psia); sealed-gas-reservoir temperature, 311 K (100° F); inner radius, 5.880 centimeters (2.315 in.); outer radius, 8.410 centimeters (3.315 in.).

Figure 7. Comparison of variable-area approximate analysis with exact viscous-compressible-flow solution. Positive and negative 1-milliradian tilt; sealed-gas-reservoir pressure, 45 N/cm² (65 psia); exit pressure, 10.3 N/cm² (15 psia); sealed-gas-reservoir temperature, 311 K (100° F); inner radius, 8.300 centimeters (3.265 in.); outer radius, 8.410 centimeters (3.315 in.).
Figure 8. - Results obtained using variable-area approximate analysis for pressure distributions. Positive 2-milliradian tilt; conditions represent subcritical, critical, and supercritical flow; mean film thicknesses, 2.5, 5.1, 7.6, and 12.7 micrometers (0.1, 0.2, 0.3, and 0.5 mil); sealed-gas-reservoir pressure, 148 N/cm² (215 psia); exit pressure, 10.3 N/cm² (15 psia); sealed-gas-reservoir temperature, 700 K (800°F); inner radius 8.300 centimeters (3.265 in.); outer radius, 8.410 centimeters (3.315 in.). Also shown are comparable parallel-film cases.
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—National Aeronautics and Space Act of 1958

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