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FLOWNET: A COMPUTER PROGRAM FOR CALCULATING SECONDARY FLOW CONDITIONS IN A NETWORK OF TURBOMACHINERY

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16. Abstract

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ABSTRACT

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SUMMARY

The computer program described in this report calculates the secondary flow conditions in a network of turbomachine components. The types of components that can be treated are face seals, narrow slots, and pipes. The program can treat networks containing up to fifty flow components and twenty-five unknown network pressures.

The program requires the network parameters, the flow component parameters, the reservoir conditions, and the gas properties as input. It will then calculate all unknown pressures and the mass flow rate in each flow component in the network.

The network solution is obtained using a least squares technique. The mathematical models of the least squares technique and the fluid flow are not contained in this report. They are described in publications which are referenced in this report.

A portion of the computer program is written in structured FORTRAN (SFTRAN). The rest of the program is written in FORTRAN IV.

The program must be run in an interactive (conversational) mode. A sample problem is included.

INTRODUCTION

The computer program described in this report calculates the secondary flow conditions in a network of turbomachine components. The types of components that may be considered are shaft face seals, narrow slots, and pipes. The mathematical model for the flow conditions is described in reference 1. The user may add other flow models to the program. The way in which this is done is described in this report.

The approach used to obtain the network solution is an iterative procedure which relies on a least squares search technique. The mathematical models employed by the least squares search technique are presented in this report and in reference 2.

FLOWNET is comprised of an executive program, a flow model subroutine, a least squares search subroutine, and an interpolation routine. The flow model subroutine is a modified version of the computer program described in reference 1. The executive program is written in Structured FORTRAN (SFTRAN). The rest of the program is written in FORTRAN IV.

FLOWNET has been run on an IBM 360/67 time sharing system at the Lewis Research Center (ref. 5). This report is intended to serve as a user's guide for the computer program FLOWNET.

SAMPLE FLOW NETWORK

Figure 1 shows a relatively simple flow network. There are two flow paths in the network. The two paths are connected in series between two pressure reservoirs (nodes). The assumed mass flow direction is indicated by the arrows and, of course, this will be the direction of the mass flow if $P_2 > P_1 > P_3$. An integer has been assigned to each node. This designates the inlet and outlet node numbers of both flow paths.

As an example of the application of FLOWNET to this network assume that the pressures at nodes 2 and 3 are known (fixed). Assume, also, that no mass is lost from the network. This requires that the mass flow into each node be equal to the mass flow out of that node. In this example, the problem is to solve for the pressure P_1 at node 1. The program FLOWNET solves for the particular pressure at node 1 which causes the net mass flow at node 1 to be zero. In obtaining this solution the total mass flow in the system is also learned.

ASSUMPTIONS

To find the solution for a given flow network, several assumptions are made:

1. Each node (a point in a flow network where one or more flow paths have an inlet or outlet connection) can be treated as a large reservoir in which flow velocities

are negligible. There is, thus, no ambiguity in the meanings of node temperature and pressure.
2. A unique, steady-state solution exists.
3. The fluid temperature at each node is known and there is no heat transfer in the network.

These assumptions allow the problem to be reduced to the solution of a set of simultaneous equations, which express the conservation of mass flow at each node in the network. The method used in FLOWNET to solve this set of equations is described in the next section.

METHOD OF SOLUTION

The method used in FLOWNET to find network solutions is described in this section. For each flow path in the network let the mass flow be given by the function $\dot{M}_{i,k}(P_i, P_j, T)$. The subscript i refers to the flow path's inlet node and j refers to its outlet node. If all the pressures P, and temperatures T, are specified then the functions $\dot{M}_{i,j}$ may be obtained by use of a flow module (a subroutine which calculates the mass flow for a specific type of flow path). At any node K, which is neither a source nor a sink, the mass flow equation is obtained by adding all mass flow in flow paths having the Kth node as the outlet node and subtracting all mass flows in flow paths having the Kth node as the inlet node, that is,

$$R_K = \sum_{\text{all } i} \dot{M}_{i,K} - \sum_{\text{all } j} \dot{M}_{K,j} \qquad (1)$$

where R_K is called the residual at the Kth node. Conservation of mass flow requires that $R_K = 0$ for all K. FLOWNET obtains the network solution by solving for the set of pressures which results in $R_K = 0$ for all K.

The strategy used in FLOWNET to find this network solution is the least-squares method. In this method the sum of the squares residuals,

$$\sum_{\text{all } K} R_K^2$$

is calculated. Then a systematic search is made in parameter space, here the unknown node pressures, for a minimum in the sum of the squares residuals, that is,

$$R \equiv \sum_{\text{all } K} R_K^2 = \text{a minimum} \qquad (2)$$

The first set of mass flow functions generated and used to satisfy equation (2) yields only the first approximation to the correct values of the unknown pressures in the flow network. This first set of mass flow functions is generated using user supplied estimates of the unknown pressures. Thus, they are not, in general, the true functions for the balanced flow network. Thus, iterations must be performed until the values of the unknown pressures found by the least-squares search routine are nearly equal to those values used to generate the mass flow functions. The iterations continue until this self consistent solution is found.

Model Function for Mass Flow

The least squares search routine used by FLOWNET requires the partial derivatives of the mass flow functions. The mass flow functions are obtained from rather complicated algorithms and, thus, cannot be differentiated analytically. The numerical differentiation of the mass flow functions is simplified by introducing a simple model function $F_{i,j}(P_i/P_j)$ defined as

$$\dot{M}_{i,j} = \frac{P_i}{T} \cdot F_{i,j}(P_r) \tag{3}$$

where the pressure ratio P_r is equal to P_i/P_j. With this model function the partial derivatives of the mass flow functions can be written in terms of ordinary derivatives of the model function with respect to the pressure ratio P_r.

GENERAL COMMENTS ON THE PROGRAM

The executive program is written in Structured FORTRAN (SFTRAN) reference 3. An SFTRAN pre-compiler is used to generate a FORTRAN IV version of the executive program. The rest of the program is written in FORTRAN IV. The entire program, FLOWNET, has been run on an IBM 360/67 time sharing system at the Lewis Research Center. Flow networks containing several types of flow paths can be treated by FLOWNET. Subroutine QUASS (ref. 1) is used to treat flow across face seals, through narrow slots, and through pipes. The user may also supply his own flow module, provided that the module be made to conform to certain interface requirements that are delineated later in this report.

Flow of Program Logic

The general flow of the program logic is shown in figure 2. The executive program reads the data required to define the flow network. This data is then used by the executive program to model the network for the rest of the program. The executive program then makes a series of calls to the appropriate flow module to calculate the mass flow functions $\dot{M}_{i,j}(P_i,P_j,T)$ for each flow path in the flow network. To calculate these mass flow functions, initial estimates of the unknown pressures must be used. The user must supply these estimates. When the calculation of all mass flow functions is finished the executive program calls the non-linear, least-squares search routine. This routine uses the mass flow functions and their derivatives to solve for that set of unknown pressures which minimizes the sum of the squares residuals (see equation(2)). This set of pressures, however, is only the first correction to the user's estimates of the unknown pressures. To obtain a self consistent solution to the network an iterative scheme is required. This iterative scheme is described in the next section.

Iterative Schemes Used By FLOWNET

In the previous section, the first pass through an iterative loop was described. The iterations continue as follows, see figure 2. The first set of unknown pressures calculated by the least-squares search routine are used to calculate a new set of mass flow functions. Then the least-squares search routine is called again to calculate a set of pressures that satisfies equation (2) for this second set of mass flow functions. This process continues until a particular built-in convergence criterion is satisfied, namely,

$$\left| \frac{P_K^{(i)} - P_K^{(i+1)}}{P_K^{(i)}} \right| \leq (\Delta P)_{max} \tag{4}$$

where,
the superscript refers to the iteration number, the subscript refers to the node number and $(\Delta P)_{max}$ is program input. When relationship (4) is satisfied for each unknown network pressure the solution is considered to be converged. Note in figure 2 that the least-squares search routine is iterative also. This is because of the non-linear nature of

the unknowns.

MISCELLANEOUS FEATURES OF FLOWNET

Several features have been built into FLOWNET which (1) cause the mass flow functions to be more accurate in the vicinity of the solution after each outer iteration (2) provide automatic treatment of flow reversal, and (3) permit the user to treat other types of flow components by adding his own flow module to the program.

Solution Accuracy

In general, the converged solution will be accurate if all final mass flow functions are accurate in the vicinity of the solution. The user cannot insure this accuracy with input data (or any other feasible way) because this would require having a good knowledge of the converged solution, a priori. The first set of mass flow functions are generated using estimates of the unknown network pressures and a set of input pressure ratios. These pressure ratios may yield mass flow functions which are not accurate in the vicinity of the converged solution. This difficulty is overcome as follows. After each inner iteration, updated values of the unknown network pressures are available. These pressures are used to calculate a new pressure ratio for each flow path in the network. Then before generating the mass flow functions for the next outer iteration this new pressure ratio is placed into the existing pressure ratio array and an existing pressure ratio value is discarded. Thus, after each outer iteration the mass flow functions are more accurate in the vicinity of the solution.

Flow Reversal

The program is also designed to handle so-called flow reversal. This situation occurs when the user inadvertently reverses the definition of inlet and outlet nodes in the input data so that $P_{in} < P_{out}$. This can also occur if the user expects a particular node, where the pressure is unknown, to be an inlet node and the calculation (converged solution) shows it to be an outlet node. Again $P_{in} < P_{out}$ is obtained. The program handles these situations by interchanging the definitions of the inlet and outlet nodes of the path or paths in question. The user is informed that these definitions have been changed.

User Supplied Flow Module

FLOWNET has a provision for the user to supply an additional flow module. The user may want to consider flow components having flow characteristics that are not described by QUASC (ref. 1). A subroutine that describes the desired flow characteristics may then be added by the user. This user supplied flow module must be made to interface with FLOWNET. This interfacing is achieved as follows.

(1) The flow module must be called SUBROUTINE ADDFLO.

(2) The flow module must not have an argument vector.

(3) The following labeled COMMON statement must appear in the subroutine.

COMMON/MODULE/ONLYIN,MDONLY,PINLET,PRATIO,TO,INPUT,FLOW,IPATH

The values of all quantities in COMMON/MODULE/, except FLOW, are established by the executive program. The values of these quantities determine: (1) The purpose of the call to the flow module by the executive program (there are three purposes) and (2) the values of the inlet pressure PINLET, the pressure ratio PRATIO, and the temperature TO, to be used by the flow module to calculate the mass flow FLOW.

On a given call to the flow module, the purpose of the call is determined by the values of the integer INPUT, and the logical ONLYIN. When INPUT equals one and ONLYIN is .TRUE. the flow module must read the flow path input data and write this data into the high speed printer output dataset. No calculations need be done on this call. When INPUT equals one and ONLYIN is .FALSE. the flow module must read the flow path input data and calculate the mass flow. When INPUT equals three and ONLYIN is .FALSE. the flow module calculates the mass flow. The flow path input data must not be read on this call. The logical MDONLY always has the value .TRUE.. The user's flow module may do more than calculate mass flow. It may, for example, calculate radial profiles. MDONLY may be used to skip unnecessary calculations and/or output. An example of how the quantities in COMMON/MODULE/ are used in a flow module is shown below.

SAMPLE FLOW MODULE

```
      SUBROUTINE ADDFLO
               .
               .
               .
      LOGICAL ONLYIN,MDONLY
      COMMON/MODULE/ONLYIN,MDONLY,PINLET,PRATIO,TO,INPUT,FLOW,IPATH
               .
               .
               .
      IF (INPUT.EQ.1) GO TO 5
      IF (INPUT.EQ.3) GO TO 10
    5 READ THE FLOW PATH INPUT DATA
   10 IF (.NOT. ONLYIN) GO TO 20
   15 WRITE THE FLOW PATH INPUT DATA
      GO TO 25
   20 CONTINUE
               .
               .
               .
      P0 = PINLET
      P3 = P0/PRATIO
      TEMP = TO
               .
               .
               .
      MASS FLOW = F(P0,P3,TEMP)
      FLOW = MASS FLOW
      IF (MDONLY) GO TO 25
               .
               .
               .
      (Other calculations and/or output not desired for flow
       network usage)
               .
               .
               .
   25 CONTINUE
      RETURN
      END
```

INPUT DATA

The input data required by FLOWNET are of two general types. The first type is the flow network data. This data is read by the executive program. Other data are related to specific flow paths in the network. This flow path data is read by subroutine QUASC.

Network Data

The network input data is read by the main program. This data must be read from unit 4. The first card in the network data is a title card. The title card is used to identify the particular network to be treated. Card columns 1 to 72 of one card may be used and this card is read by format (18A4). The rest of the network input data is in namelist format. There are three namelists with the names PATHSP, NODESP, and PARAM. The cards following the title card have the data in NAMELIST/PATHSP/. This data is listed in TABLE I. The next cards have the data in NAMELIST/NODESP/. This data is listed in TABLE II. The last cards in the network input dataset have the data in NAMELIST/PARAM/. This data is listed in TABLE III.

Flow Path Data

The flow path data must be read from unit 5. This data is read by subroutine QUASC. The first card required by subroutine QUASC is a title card. The title identifies the data for the given flow path. The title card uses columns 1 to 72 of one card and is read by format (18A4). The next cards required by subroutine QUASC contain the parameters in NAMELIST/SDATA/. These parameters are listed in TABLE IV. Some of the parameters in NAMELIST/SDATA/ differ from those in the version of QUASC described in reference 1.

Also, some of these quantities must always be the same value in the modified version of QUASC used in this report. When this is the case, TABLE IV shows the value that must be used. The next card contains the integer NJ, which is the number of film thicknesses to be considered for a given flow path. When solving flow network problems, only one film thickness per flow path can be considered. Thus the value of NJ is always 1 and is read by format (I3). The last card in the flow path data for subroutine QUASC has the value of the film thickness and is read by format (F12.6). The NAMELIST/PDATA/ used in program QUASC (ref. 1) is not used in subroutine QUASC.

A set of the data described in this section must be included in the flow path dataset for each flow path in the flow network.

SAMPLE NETWORK DATA

Figure 3 shows a relatively simple flow network. The arrows indicate the direction of the mass flow in the network. The circled numbers are the integers arbitrarily assigned to each flow path. Note that there is only one node where the pressure is unknown and this must be numbered node 1. P_J is the pressure at the Jth node. T_0 is the total temperature of the gas. The first estimate of the pressure at node 1 may be obtained by assuming a linear pressure distribution across paths 1 and 3, if a better estimate is not available.

Table V is the set of network data which would be used to describe the network of fig. 3.

RUNNING THE PROGRAM

In this section it is assumed that the reader is familiar with the IBM 360 time sharing system (ref. 5). To initiate running FLOWNET it is necessary to datadef the required input and output datasets and the joblibrary that contains the program object modules. The flow network input must be read from logical unit 4. The flow module input must be read from logical unit 5. Logical units 8 and 9 are used for keyboard input and output, respectively, to interact with the program. Logical unit 6 is used for program output obtained from the high speed printer. A typical set of data definitions are:

```
ddef   ft04f001,vs,network.input
ddef   ft05f001,vs,flow.path.input
ddef   ft06f001,vs,network.solution
ddef   library,vp,object.flownet,option=joblib
```

Logical units 8 and 9 are defaulted to the keyboard. After the above data definitions have been performed, program execution is initiated by simply entering the following at the keyboard,

USER: CALL MAIN (name of the main program object module)

This command causes the first set of mass flow functions to be calculated, i.e., the first outer iteration is initiated. One mass flow function is calculated for each flow path in the flow network. These functions are calculated using the known pressures and temperatures in the flow network, the user' estimates of the unknown pressures, and the input values of the pressure ratios. After these functions are calculated the following prompt appears at the keyboard,

MAIN: OUTPUT FLOW FUNCTIONS FOR THIS ITERATION?

The user then responds,

USER: y (or n)

to obtain (or suppress) the output of the mass flow functions for this iteration on the high speed printer. After this, the non-linear least squares search routine, NONLIN is called by the main program. This initiates the inner iterations. The user is prompted to interact with NONLIN as follows,

NONLIN: ENTER (1,2) FOR (CONVERSATION,BATCH)

USER: 1

Note that NONLIN is a general purpose program. However, when used with FLOWNET it can be used in a conversational (interactive) mode only. Thus, the user always replies with the number one to this prompt.

NONLIN: NEW STARTING VALUES ONLY?

USER: no (or yes)

The user must respond "no" the first time this prompt is given. A "yes" response indicates a desire for restart or failure-recovery procedures. In this case NONLIN would immediately prompt for a new set of non-linear parameters; here the unknown pressures in the flow network. The "no" response, however, causes the following prompt.

NONLIN: ENTER NF, NP, NQ, NN, OR QUIT

(For a problem having only non-linear parameters, the unknown network pressures in this case, NF and NN are the only quantities that have non-zero values. NN is the number of data points to be fit. NF is the number of non-linear parameters being used to fit the data. Thus NN and NF have the same values. This value is equal to the number of unknown pressures in the flow network.)

USER: &data nn=2, nf=2 &end

(This response is for a flow network with two unknown pressures. Note the use of NAMELIST/DATA/. Had the response been (&data quit=.true. &end), the inner iteration loop would have been terminated and a new set of mass flow functions would have been calculated.)

The prompts and typical responses proceed as follows.

NONLIN: ENTER INITIAL NON-LINEAR PARAMETERS

USER: &data phi(1)=200.0, phi(2)=25.0 &end

(The phi's are the current estimates for the unknown pressures. Again, note the use of NAMELIST/DATA/)

NONLIN: ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)

USER: 3 (or 1 or 2 or 4)

(GRAD,LIN,SPIRAL, and COMP2 are four different search techniques. The search tehniques are described in Appendix A and reference 2. The user may use any of them, however, the SPIRAL method has generally been the most successful on the problems solved with FLOWNET at LeRC.)

At this point NONLIN begins search procedures according to the method selected. Each time NONLIN determines a new set of PHI values (unknown pressures) an interchange takes place of which the following is typical:

NONLIN: R = 1.40524 E-3

PHI = 2.22054 E 02 1.64304E 01

ANSWERS GOOD ENOUGH?

USER: no (or yes)

NONLIN: ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)

USER: 2 (or 1 or 3 or 4)

This interchange continues until the user's response is "yes", in which case the final values of R and PHI are displayed as follows,

FINAL RESULTS

R = 1.876544 E-09

PHI = 2.19386 E 01
1.62569 E 01

where R is the value of the sum of the squares residual (eqn. 2) and the PHI's are the related values of the unknown network pressures. (These are not necessarily the final results for the converged network solution. They are the results at the end of the current inner iteration.) The user is then prompted with,

NONLIN: NEW STARTING VALUES ONLY?

USER: no

NONLIN: ENTER NF, NP, NQ, NN, OR QUIT

USER: &data quit = .true. &end

At this point, the inner iteration is stopped and program control returns to the executive program. A check is made there to see if the current values of the unknown pressures are such that they may be considered the converged solution. If so, this solution is printed out and the program comes to a terminated stop. Alternatively, if the current values of the unknown pressures do not satisfy the convergence criterion, equation (3), then the next outer iteration is begun by calculating the next set of mass flow functions. These functions are generated using the set of values of unknown pressures just calculated by NONLIN (the last inner iteration). The procedure just described continues until the convergence criterion is satisfied.

OUTPUT

Because FLOWNET is run in an interactive mode there is program output at the computer terminal in addition to the high speed printer output. The computer terminal output and the high speed printer output are described in the next two sections.

Computer Terminal Output

The purpose of the computer terminal output is to give the user information about the status of the solution at the end of each outer iteration. The first output at the terminal tells the user how closely the mass flow conservation equations are satisfied for the current set of mass flow functions at each node where the pressure is unknown. This output consists of the following information at each node where the pressure is unknown.

1) MD(NET) - The net mass flow (=0. when the mass

conservation equation is satisfied exactly.)

2) MD(MIN) - The magnitude of the smallest mass flow component.
3) MD(NET)/MD(MIN) - The scaled net mass flow.

The values of the scaled net mass flows are particularly helpful. They are the best measure of how closely the mass flow conservation equations are satisfied. The sum of the squares residual R, and the values of the net mass flow can actually be misleading if used to decide how good the solution is because they are dimensional quantities.

The next output at the terminal is the scaled values of the pressure changes from the beginning of one outer iteration to the end of the corresponding inner iteration. This quantitiy is called DELTAP/P and is equal to the left hand side of equation (6). Its value at each node where the pressure is unknown is displayed at the terminal.

High Speed Printer Output

The high speed printer output, hereafter called the computer output, consists of the input data, calculated parameters, intermediate network solutions, and the converged network solution.

The first page of computer output is the input referred to previously as the network input (See TABLES I, II, and III.) The next output is the input and calculated parameters for the flow paths. There is one page of flow path output for each flow path in the flow network. This output is described in detail in reference 1.

The computer output immediately following the flow path output is printed each iteration. This is the output for the intermediate network solutions. It consists of,

(1) Mass flow function information and;
(2) Mass flow balance information.

The mass flow function information is printed each iteration (if the user asks for it). The first line of this output is the path number, the inlet pressure used to calculate the path's current mass flow functions P(INLET), and the path's current outlet pressure P(OUTLET). Following this line of output are the current values of the mass flow function MASS FLOW, and the values of the pressure ratio used to generate the mass flow functions PRATIO. This mass flow function information is output for each flow path in the flow network.

The mass flow balance information appears next in the computer output. This output is printed at the completion of each inner iteration and is, also, part of the computer terminal output. This output consists of the net mass flow at each node MD(NET), the smallest mass flow component at the node MD(MIN), and the scaled mass flow at the node MD(NET)/MD(MIN).

The final computer output is the converged solution for the flow network. This consists of the following for each flow path in the flow network; the path number, the inlet node number INNODE, the outlet node number OUTNODE, the inlet pressure P(INLET), the outlet pressure P(OUTLET), and the mass flow through the flow path MASS FLOW. A sample problem is given in Appendix B.

APPENDIX A

PROGRAM DESCRIPTION

This appendix contains a description of each of the four programs that comprise FLOWNET. A brief, general description is given for the flow module QUASC (ref. 1), the non-linear, least squares search routine NONLIN, and the interpolation routine INTERPOL used by FLOWNET. A more detailed description of the executive program is given.

DESCRIPTION OF THE EXECUTIVE PROGRAM

The executive program is written in Structured FORTRAN (SFTRAN). It consists of a main program and 7 subprograms. This section contains a functional description of each subpart of the executive program.

Main Program

The main program first reads in the flow network data. It then uses this data to construct arrays that provide a program description of the network geometry. After this, the main program provides the controlling logic for the inner and outer iteration loops and checks for convergence of the network solution at the end of each outer iteration.

Subroutine MDFUNC

This subroutine is called by the main program. It contains the controlling logic for calculating the mass flow functions for all flow paths in the flow network. After the mass flow functions have been calculated the user is prompted to enter Y(YES) or N(NO) to obtain or suppress the print out of the mass flow functions as part of the high speed printer output. The subroutine is called once per outer iteration.

Subroutine FPRDPR

This subroutine is called by the main program. It calculates an array of ordinary derivatives of the auxiliary functions $F_{i,j}(P_r)$ for each flow path in the flow network. The auxiliary function $F_{i,j}(P_r)$ is defined by the model mass flow function,

$$\dot{M}_{i,j} = \frac{P_i}{T} \cdot F_{i,j}(P_r) \qquad \text{(A1)}$$

These derivatives are obtained by a numerical differentiation scheme contained in the interpolation routine INTERPOL. The ordinary derivatives of $F_{i,j}(P_r)$ are calculated at each value of the pressure ratio currently in the pressure ratio array. The partial derivatives of the mass flow functions are required by the non-linear, least squares search routine NONLIN. They are obtained from the model mass flow function and the ordinary derivatives of the auxiliary function. This subroutine is called once per outer iteration.

Subroutine YVALUE

This subroutine is called by the non-linear, least squares search routine. It is used as a means of communication between the executive program and the general purpose least-squares search routine NONLIN. The subroutine passes the following information to the search routine for all non-fixed nodes in the network:

(1) The input values of the net mass flow.
(2) The calculated value of the net mass flow for values of the unknown pressures selected by the search routine. These values are obtained by interpolation on the arrays of mass flow functions.
(3) The partial derivatives of the mass flow functions for values of the unknown pressures selected by the search routine. These values are obtained by interpolation on the arrays of the partial derivatives of the mass flow functions.

Subroutine CLOSER

This subroutine is called by the main program. It is called after each outer iteration. At the end of each outer iteration new iterates for the unknown pressures are available. These new iterates are used in this subroutine to calculate updated pressure ratios for all flow paths in the network. These updated pressure ratios are then inserted into the existing pressure ratio arrays. An existing pressure ratio value is discarded from the array. The pressure ratio values for each flow path remain monotonic increasing in the array.

Subroutine FLOWS

This subroutine is called by SUBROUTINE YVALUE. It computes a component of mass flow at a particular node each time it is called. It also assigns the correct algebraic sign to the mass flow. The magnitude of the flow in a given flow path is determined by interpolation in the corresponding mass flow function array. The subroutine is called K times for each non-fixed node, where K is the number of flow paths with inlet or outlet at the node. These mass flow components are used by SUBROUTINE YVALUE to calculate the net mass flow at each node for the set of pressures currently being used by the least-squares search routine NONLIN.

Subroutine PDERIV

This subroutine is called by SUBROUTINE YVALUE. At a given non-fixed node it calculates all required partial derivatives of the mass flow functions. One partial derivative is calculated per call to SUBROUTINE PDERIV. The algebraic sum of these partial derivatives is the desired partial derivative of the net mass flow function at a given node.

Subroutine BALANS

This subroutine is called by the main program. The subroutine calculates and prints mass flow balance information at each node where the pressure is unknown. For each such node the scaled and unscaled net mass flow is calculated and printed out. The scaled net mass flow at a node is equal to the net mass flow divided by the smallest component of the mass flow at the node.

DESCRIPTION OF SUBROUTINE QUASC

A brief, general description of the flow module QUASC is given in this section. Reference 1 contains a complete description of the program.

Subroutine QUASC is a modified version of the computer program described in reference 1. It is called by the executive program. It calculates the mass flow of a viscous fluid through narrow passages with parallel walls. However, if one assumes that the equivalent hydraulic diameter of a narrow slot equals twice the distance between walls, then QUASC can also be used to calculate flow in other types of ducts with constant cross-sectional area. For example, a pipe (circular cross-section) with radius r may be assumed equivalent to a slot with a gap equal to r and a width equal to πr (so as to have the same flow area).

The mathematical model used to calculate the mass flow in subroutine QUASC is developed in reference 4 and summarized in reference 1. The analysis includes fluid inertia, viscous friction, and entrance losses. The model is valid for both completely subsonic flow and choked flow. It is also valid for both laminar and turbulent flow regimes.

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

The following assumptions were made in the analysis:

1. The area expansion due to radius increase is neglected.

2. The flow is adiabatic.

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

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

5. The fluid behaves as a perfect gas.

6. The sealing surfaces are parallel.

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

The set of equations in the mathematical model cannot be solved explicitly. Thus, iterative procedures are used.

There are three types of flow considered: (1) critical flow, when the exit Mach number is 1 and the exit pressure equals the ambient pressure; (2) supercritical flow, when the exit Mach number is 1 and the exit pressure is greater than the ambient pressure; and (3) subcritical flow, when the exit Mach number is less than 1 and the exit pressure is equal to the ambient pressure (flow is entirely subsonic).

Because the boundary conditions on the mathematical model are slightly different for each type of flow, the solution of the equations is slightly different for each type.

DESCRIPTION OF NONLIN

NONLIN is a general purpose, least squares search routine. In the program FLOWNET, this routine is called by the executive program to perform the inner iterations (see figure 2). The user is first prompted for input data, including initial values for the NF non-linear parameters. These non-linear parameters are called PHI in NONLIN. The user is then invited to choose one of four possible search techniques. These methods are called GRAD for the gradient method, LIN for the linear method, SPIRAL, (reference 2) a compromise method and COMP2 for the second compromise method.

NONLIN first determines the lowest possible sum of squares residual R using the initial parameters PHI, and then searches for a still lower value by modifying the PHI values according to the search technique selected.

If the method GRAD is selected, NONLIN calculates a vector which points in the direction of steepest descent from the current point P in non-linear parameter space. An initial step is taken in this direction: if R decreases, another step is taken; if R increases, the distance is halved and R calculated again. This process continues until, in the first case, R begins to increase, or, in the second case, a value is found which is lower than at the initial point P.

If the method LIN is selected, NONLIN calculates a vector which, when added to P, gives the point L which would yield a minimum R if the linear approximation were valid. If the value is higher than at the point P, however, backward steps along the line LP are taken until either a lower value is found or the method is judged to be fruitless, in which case the method GRAD is invoked.

Two compromise methods are also available. If SPIRAL is selected, points are examined along a curve in parameter space which begins at L and swings out so that it approaches P along the direction of steepest descent. (At the same time NONLIN examines a second curve, which is the mirror image of the first with respect to a line bisecting the angle between the steepest descent vector and the linear vector. The second curve is examined until the two intersect.) This method is useful when the path of the minima leading from the point P to the actual minimum point curves and crosses the line PL. If the first attempt fails, the starting point (measured from P) is taken to be half the original distance, and so on until four spirals are examined. If all four attempts fail, the method GRAD is invoked.

The second compromise method, COMP2, begins by finding a lower value of R along the line of steepest descent. Then a second lower value is sought, this time along the line PL. If both attempts are successful, the line joining the two points is examined to determine a still lower value; if not, improvement along the line of steepest descent is sought by means of REFINE. All four methods eventually make use of REFINE, which is designed to examine the sum of squares along a given line PP' to determine a "best" value. In the case of GRAD, LIN, and SPIRAL, the point P is the current point and the point P' has been determined by the selected method; in the case of COMP2, P has the higher and P' the lower value of R for the two points found. First the midpoint of PP' is examined: if its sum of squares is lower than at P', a parabolic interpolation is performed; if higher, a point equally distant on the other side of P' is examined. This process continues until a parabolic interpolation can be performed. The user is then informed of the best value of R found, together with the associated non-linear parameter values, and invited to continue from this point, if desired, by again choosing a search technique. If the user is satisfied, however, he is informed of the best values found for all parameters, and the final sum of squares.

Failure Conditions In NONLIN

There are two normal failure conditions which NONLIN may encounter; the user is informed of them by the messages SINGULAR MATRIX or STEPG FAILED, and the program FLOWNET halts. Singular or near-singular matrices are not uncommon in least squares searching. Often, however, this failure condition has resulted from erroneous network input data (see TABLES I, II, and III). The message STEPG FAILED indicates that NONLIN was searching for a minimum in the direction of steepest descent (GRAD), but was unsuccessful. This failure may result from granularity in the hypersurface which NONLIN is examining. It may be that the difficulty is confined to a small region about the current point P in parameter space, and will not recur if the search is resumed at a different point. To determine this, after a failure message is received, the user must change his trial values of the unknown pressures in the flow network. The user is on his own if he obtains either of these failure conditions.

DESCRIPTION OF INTERPOL

INTERPOL contains the interpolation and numerical differentiation routines used by FLOWNET. Double 3-point Lagrangian interpolation is used. In this method, two parabolas are fitted to the given data; one to the 3 points centered below the argument value and one to the three points centered above the argument. A weighted average of these two values is the resulting interpolation value. This double, 3-point method provides smoother behavior between tabular values than can be obtained with single, 3-point

Lagrangian interpolation. Also, this method provides a function that has a continuous first derivative.

Subprograms

Following is a list of subprograms contained in INTERPOL. Assume that

A is an argument table name
F is a function table name
NA is the length of A
X is the argument value for which the interpolated value is desired

Then
FNTRP(A,F,X,NA) provides the value of a real function,
DNTRP(A,F,X,NA) provides the derivative of a real function.

These functions make use of five other functions in INTERPOL. The names of these other functions are: FNTRPA, FNTRPC, DNTRPC, LIMIT, and TLU.

APPENDIX B

SAMPLE PROBLEM

An example of the use of the computer program FLOWNET is given in this appendix. Included are the flow network data, the flow path data, the computer terminal output, and the high speed printer output (computer output) related to the sample problem. Figure 4 is a schematic representation of the flow network used for the sample problem. The unknown pressures are at nodes 1 through 6. The system inlet pressure is 300 psia and the gas used is air.

Network Data for Sample Problem

```
           SAMPLE PROBLEM - U.S. CUSTOMARY UNITS
&PATHSP INLET=8,1,1,2,2,3,3,6,4,5,
        OUTLET=1,4,2,6,3,9,9,10,5,7,
        FLOTYP=10*1, SAME(1,2)=4, SAME(2,4)=2, SAME(3,7)=6,
        NTPATH=10, SAMEPR=T  &END
&NODESP NTNODE=10, FIXED=6*F,19*T, MDNET=25*0.0, TO=25*70.0,
        PRESS=70.0, 25.0, 15.0, 25.0, 20.0, 15.0,
              14.7, 300.0, 14.7, 14.7  &END
&PARAM NPRAT(1)=10*8, DELPMX=0.05,
       PRAT(1,1)=1.0, 1.01, 1.05, 1.1, 1.5, 2.0, 3.0,
                4.0  &END
```

Flow Path Data For Sample Problem

```
FIRST QUASC SEAL ( PATH ONE )
 &SDATA R1IN=2.7, R2IN=0.0, RDIFIN=0.8, WIDTH=0.0, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=1  &END
  1
        0.01
FIRST VENT - 4 PIPES, I.D.=0.5 IN., H=0.25 IN. ( PATH TWO )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=41.0, WIDTH=0.785, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=2  &END
  1
       0.250
SECOND QUASC SEAL ( PATH THREE )
 &SDATA R1IN=2.5, R2IN=0.0, RDIFIN=0.8, WIDTH=0.0, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=3  &END
  1
       0.01
SECOND VENT - 2 PIPES, I.D.=0.5 IN., H=0.25IN. ( PATH FOUR )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=41.0, WIDTH=0.785, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=4  &END
  1
      0.250
THIRD QUASC SEAL ( PATH FIVE )
 &SDATA R1IN=2.375, R2IN=0.0, RDIFIN=0.8, WIDTH=0.0, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=5  &END
  1
       0.01
```

```
FIVE EIGHTS PIPE, I.D.=0.625 IN., H=0.313 ( PATH SIX )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=60.0, WIDTH=0.982, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=6  &END
  1
      0.313
SIX - HALF INCH VENTS AT EXIT, I.D.=0.5 IN., H=0.25 IN. ( PATH SEVEN )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=24.0, WIDTH=0.785, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=7  &END
INCH AND A HALF LINE, I.D.=1.5 IN., H=0.75 IN. ( PATH EIGHT )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=185.67, WIDTH=2.36, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=8  &END
  1
       0.75
TWO INCH VENT PIPE, I.D.=2 IN., H=1 IN ( PATH NINE )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=8.0, WIDTH=3.14, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=9  &END
  1
       1.00
THREE INCH VENT PIPE, I.D.=3 IN., H=1.5 IN. ( PATH TEN )
 &SDATA R1IN=1.0, R2IN=0.0, RDIFIN=304.0, WIDTH=4.71, MOLWT=29.0,
 CP=0.24, GAMMA=1.4, MU=0.0, SPEED=0.0, CAPV=0.0, XLAM=1.0,
 XTURB=0.25, CONLAM=24.0, CONTRB=0.079, RELAM=2300.0, RETURB=3000.0,
 PWRSKP=T, PRSSKP=T, NRMSKP=T, PLTSKP=8*T, NOSI=T, SKPH=F, LOSS=0.5,
 IPATH=10  &END
  1
       1.50
```

Sample Problem Computer Terminal Output


```
  OUTPUT FLOW FUNCTIONS FOR THIS ITERATION?
Y
ENTER (1,2) FOR (CONVERSATIONAL,BATCH)
1
NEW STARTING VALUES ONLY?
N
ENTER NF,NP,NQ,NN, OR QUIT
 &DATA  NN=6, NF=6  &END
ENTER INITIAL NON-LINEAR PARAMETERS
 &DATA  PHI=70.0, 25.0, 15.0, 25.0, 20.0, 15.0  &END
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 8.058E-02
PHI= 6.812E 01   2.493E 01   1.485E 01   2.492E 01   1.749E 01   1.514E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 3.569E-02
PHI= 6.172E 01   2.380E 01   1.485E 01   2.045E 01   1.659E 01   1.528E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 5.086E-03
PHI= 6.069E 01   2.279E 01   1.485E 01   2.002E 01   1.594E 01   1.528E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.631E-03
PHI= 6.093E 01   2.274E 01   1.481E 01   1.936E 01   1.586 01   1.522E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.410E-03
PHI= 6.054E 01   2.267E 01   1.482E 01   1.914E 01   1.581E 01   1.518E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 3.005E-04
PHI= 6.004E 01   2.253E 01   1.483E 01   1.907E 01   1.570E 01   1.514E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
```

```
3
  R= 1.084E-04
PHI= 6.013E 01   2.248E 01    1.482E 01    1.892E 01    1.568E 01    1.511E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 6.932E-06
PHI= 5.991E 01   2.232E 01    1.483E 01    1.883E 01    1.563E 01    1.508E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 3.700E-06
PHI= 5.994E 01   2.232E 01    1.482E 01    1.882E 01    1.563E 01    1.507E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 2.432E-07
PHI= 5.997E 01   2.233E 01    1.482E 01    1.882E 01    1.563E 01    1.507E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.295E-07
PHI= 5.997E 01   2.233E 01    1.482E 01    1.882E 01    1.563E 01    1.506E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 5.373E-08
PHI= 5.997E 01   2.233E 01    1.482E 01    1.882E 01    1.563E 01    1.506E 01
ANSWERS GOOD ENOUGH?
Y


FINAL RESULTS

    R= 5.372823E-08

  PHI= 5.996709E 01
       2.232632E 01
       1.482184E 01
       1.881750E 01
       1.563185E 01
       1.506396E 01
NEW STARTING VALUES ONLY?
N
ENTER NF,NP,NQ,NN, OR QUIT
```

```
&DATA  QUIT=T  &END


        MASS FLOW BALANCE INFORMATION AT NODES 1 TO 6
        *********************************************

 NODE NO.        MD(NET)         MD(MIN)         MD(NET)/MD(MIN)
 ********        *******         *******         ***************
        1     -3.326E-05      1.264E-01              -2.632E-04
        2     -4.181E-05      3.908E-02              -1.070E-03
        3      1.992E-05      8.811E-03               2.260E-03
        4      5.662E-06      5.444E-01               1.040E-05
        5     -6.026E-05      5.444E-01              -1.107E-04
        6     -2.164E-04      8.732E-02              -2.478E-03

   ITERATION   1
NODE NO.      DELTAP/P
       1     1.673E-01

       2     1.198E-01

       3     1.202E-02

       4     3.285E-01

       5     2.794E-01

       6     4.246E-03

  SOLUTION NOT CONVERGED



  BEGIN OUTER ITERATION NO.  2


  OUTPUT FLOW FUNCTIONS FOR THIS ITERATION?
Y
BEGIN NEXT INNER ITERATION
ENTER (1,2) FOR (CONVERSATIONAL,BATCH)
1
NEW STARTING VALUES ONLY?
Y
ENTER INITIAL NON-LINEAR PARAMETERS
 &DATA PHI=60.0, 22.3, 14.8, 18.8, 15.6, 15.0  &END
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.786E-04
PHI= 5.999E 01   2.230E 01   1.483E 01   1.894E 01   1.563E 01   1.520E 01
ANSWERS GOOD ENOUGH?
```

```
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 7.277E-05
PHI= 5.999E 01   2.231E 01   1.481E 01   1.898E 01   1.562E 01   1.518E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 3.787E-05
PHI= 5.999E 01   2.234E 01   1.481E 01   1.904E 01   1.563E 01   1.516E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 8.394E-06
PHI= 6.011E 01   2.232E 01   1.481E 01   1.906E 01   1.565E 01   1.515E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.051E-06
PHI= 6.007E 01   2.234E 01   1.481E 01   1.909E 01   1.566E 01   1.515E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 2.390E-07
PHI= 6.008E 01   2.234E 01   1.481E 01   1.909E 01   1.566E 01   1.515E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 8.751E-08
PHI= 6.007E 01   2.234E 01   1.481E 01   1.910E 01   1.566E 01   1.515E 01
ANSWERS GOOD ENOUGH?
N
ENTER (1,2,3,4) FOR (GRAD,LIN,SPIRAL,COMP2)
3
  R= 1.800E-08
PHI= 6.008E 01   2.234E 01   1.481E 01   1.910E 01   1.566E 01   1.516E 01
ANSWERS GOOD ENOUGH?
Y


FINAL RESULTS

    R= 1.800260E-08

  PHI= 6.007884E 01
```

```
        2.234119E 01
        1.480833E 01
        1.909781E 01
        1.566009E 01
        1.515520E 01
NEW STARTING VALUES ONLY?
N
ENTER NF,NP,NQ,NN, OR QUIT
 &DATA  QUIT=T  &END
```

MASS FLOW BALANCE INFORMATION AT NODES 1 TO 6

****

NODE NO.	MD(NET)	MD(MIN)	MD(NET)/MD(MIN)
********	*******	*******	***************
1	-1.281E-05	1.261E-01	-1.016E-04
2	1.194E-05	3.897E-02	3.064E-04
3	-5.729E-06	8.766E-03	-6.536E-04
4	1.318E-04	5.445E-01	2.420E-04
5	1.591E-05	5.445E-01	2.923E-05
6	-6.497E-06	8.712E-02	-7.457E-05

Sample Problem Printer Output

SAMPLE PROBLEM - U. S. CUSTOMARY UNITS

PATH NO.	NODE(IN)	NODE(OUT)	FLOTYP	EQUIV. PATHS
1	8	1	1	0
2	1	6	1	4
3	1	2	1	0
4	2	6	1	2
5	2	3	1	0
6	3	5	1	0
7	3	9	1	0
8	6	10	1	0
9	4	5	1	0
10	5	7	1	0

NODE NO.	FIXED	PRESSURE	TEMPERATURE	NET MASS FLOW
1	F	0.7000E 02	0.7000E 02	0.0000
2	F	0.2500E 02	0.7000E 02	0.0000
3	F	0.1500E 02	0.7000E 02	0.0000
4	F	0.2500E 02	0.7000E 02	0.0000
5	F	0.2000E 02	0.7000E 02	0.0000
6	F	0.1500E 02	0.7000E 02	0.0000
7	T	0.1870E 02	0.7000E 02	0.0000
8	T	0.3000E 03	0.7000E 02	0.0000
9	T	0.1470E 02	0.7000E 02	0.0000
10	T	0.1870E 02	0.7000E 02	0.0000

```
&PARAM
NPRAT= 10*6, 40*0
PRAT= 1.0, 1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999
1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999, 1.049999, 1.099999
1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0
4.0, 2*0.0, 1.0, 1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0
1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999, 1.049999
1.099999, 1.50, 2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999, 1.049999, 1.099999, 1.50
2.0, 3.0, 4.0, 2*0.0, 1.0, 1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0
2*0.0, 1.0, 1.009999, 1.049999, 1.099999, 1.50, 2.0, 3.0, 4.0, 402*0.0
DELPMX= 0.50E-01
NPX= 6
&END
```

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM FIRST QUASC SEAL (PATH ONE)

INPUT DATA -

R1,INCHES 2.7000	PO,PSIA 20.000	MOLECULAR WEIGHT 29.000	[illegible] *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 0.8000	PO/P3 4.000	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.0000	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.7900E-01
		V,FT/SEC 0.00	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 2.7000	PO,PSIA 300.000	MOLECULAR WEIGHT 29.000	CALCULATE *********
R2,INCHES 3.5000	P3,PSIA 70.000	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 0.8000	PO/P3 4.286	GAMMA 1.400	
FLOW WIDTH,INCHES 19.4779	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2640E-08	PLOT ********************
AREA,IN2 15.5823	GAS CONSTANT,LB-FT/LBM-F 53.28964	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   FIRST VENT - 8 PIPES, I.D.=0.5 IN, H=0.25 IN (PATH TWO)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 300.000	MOLECULAR WEIGHT 28.966	F=K/RE**M *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 41.0000	PO/P3 4.286	GAMMA 1.400	M(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.7650	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.7900E-01
		V,FT/SEC 0.00	M(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 70.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 42.0000	P3,PSIA 25.000	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 41.0000	PO/P3 2.800	GAMMA 1.400	
FLOW WIDTH,INCHES 0.7850	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 [illegible].2660E-09	FLOW ************************
AREA,IN2 5538.6250	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   SECOND QUASC SEAL (PATH THREE)

INPUT DATA -

R1,INCHES 2.5000	PO,PSIA 70.000	MOLECULAR WEIGHT 2?.???	[illegible] *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.2?0	K(LAMINAR) 2?.???
FLOW LENGTH,INCHES 0.8000	PO/P3 2.800	GAMMA 1.?00	?(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.0000	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2??0.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.?????-01
		V,FT/SEC 0.00	?(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 2.5000	PO,PSIA 70.000	MOLECULAR WEIGHT 2?.???	CALCULATE *********
R2,INCHES 3.3000	P3,PSIA 25.000	CP,BTU/LBM-DEG F 0.??0	
FLOW LENGTH,INCHES 0.8000	PO/P3 2.800	GAMMA 1.?00	
FLOW WIDTH,INCHES 18.2212	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.26?0?-0?	PLOT
AREA,IN2 14.5770	GAS CONSTANT,LB-FT/LBM-F 53.2896*	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   SECOND VENT - 2 PIPES, I.D.=0.5 IN, W=0.25 IN (PATH FOUR)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 70.000	MOLECULAR WEIGHT 28.966	F=K/RE**M *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K (LAMINAR) 24.000
FLOW LENGTH,INCHES 41.0000	PO/P3 2.600	GAMMA 1.400	M (LAMINAR) 1.00
FLOW WIDTH,INCHES 0.7850	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.79000E-01
		V,FT/SEC 0.00	M(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 25.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 42.0000	P3,PSIA 15.000	CP,BTU/LBM-DEG F 0.[illegible]00	
FLOW LENGTH,INCHES 41.0000	PO/P3 1.667	GAMMA 1.400	
FLOW WIDTH,INCHES 0.7850	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2680[illegible]	PLOT ***********************
AREA,IN2 5538.6250	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   THIRD QUASC SEAL (PATH FIVE)

INPUT DATA -

R1,INCHES 2.3750	PO,PSIA 25.000	MOLECULAR WEIGHT 29.000	F=K/RE**M *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 0.8000	PO/P3 1.667	GAMMA 1.400	M(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.0000	TO,DEG F 70.0	VISCOSITY,LB-SEC/FT2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.7900E-01
		V,FT/SEC 0.00	M(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 2.3750	PO,PSIA 25.000	MOLECULAR WEIGHT 29.000	CALCULATE *********
R2,INCHES 3.1750	P3,PSIA 15.000	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 0.8000	PO/P3 1.667	GAMMA 1.400	
FLOW WIDTH,INCHES 17.4358	TO,DEG F 70.000	VISCOSITY,LB-SEC/FT2 0.2680E-06	FLOW ***********************
AREA,IN2 13.9467	GAS CONSTANT,LB-FT/LBM-R 53.28964	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   FIVE-EIGHTS OIL DRAIN, I.D.=0.625, H=0.373 (PATH SIX)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 25.000	MOLECULAR WEIGHT 28.966	F=K/RE**N *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 60.0000	PO/P3 1.667	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.9920	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.7500E-01
		V,FT/SEC 0.00	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 61.0000	P3,PSIA 14.700	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 60.0000	PO/P3 1.020	GAMMA 1.400	
FLOW WIDTH,INCHES 0.9820	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2680E-08	PLOT ******************
AREA,IN2 11686.7188	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   SIX-HALF INCH VENTS AT EXIT, I.D.=0.5 IN, H=0.25 IN (PATH SEVEN)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	R=K/RE**M *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 24.0000	PO/P3 1.020	GAMMA 1.400	M(LAMINAR) 1.00
FLOW WIDTH,INCHES 0.7850	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. [illegible]	SPEED,RPM 0.0000	K(TURBULENT) 0.7900E-01
		V,FT/SEC 0.00	M(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 25.0000	P3,PSIA 14.700	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 24.0000	PO/P3 1.020	GAMMA 1.400	
FLOW WIDTH,INCHES 0.7850	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2640E-06	FLOW ************************
AREA,IN2 1960.3533	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEFF. 0.50	V,FT/SEC 0.00	

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

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   INCH AND A HALF LINE, I.D.=1.5 IN, H=0.75 IN (PATH RIGHT)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	F=K/RE**N *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 185.6700	PO/P3 1.020	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,INCHES 2.3600	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) [illegible]
		V,FT/SEC 0.00	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) [illegible]

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 186.6700	P3,PSIA 14.700	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 185.6700	PO/P3 1.020	GAMMA 1.400	
FLOW WIDTH,INCHES 2.3600	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2680E-0[illegible]	PLOT ********************
AREA,IN2 109467.7500	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM   TWO INCH VENT PIPE, I.D.=2 IN, H=1 IN (PATH TIME)

INPUT DATA -

R1,INCHES 1.0000	PO,PSIA 15.000	MOLECULAR WEIGHT 28.966	F=K/RE**N *********
R2,INCHES 0.0000	P3,PSIA 0.000	CP,BTU/LBM-DEG F 0.240	K(LAMINAR) 24.000
FLOW LENGTH,INCHES 8.0000	PO/P3 1.020	GAMMA 1.400	N(LAMINAR) 1.00
FLOW WIDTH,INCHES 3.1400	TO,DEG F 70.0	VISCOSITY,LB-SEC/IN2 0.0000	UPPER LIMIT RE (LAMINAR) 2300.0
	LOSS COEF. 0.50	SPEED,RPM 0.0000	K(TURBULENT) 0.7900E-01
		V,FT/SEC 0.00	N(TURBULENT) 0.2500
			LOWER LIMIT RE (TURBULENT) 3000.0

OUTPUT DATA -

R1,INCHES 1.0000	PO,PSIA 25.000	MOLECULAR WEIGHT 28.966	CALCULATE *********
R2,INCHES 9.0000	P3,PSIA 20.000	CP,BTU/LBM-DEG F 0.000	
FLOW LENGTH,INCHES 8.0000	PO/P3 1.250	GAMMA 1.400	
FLOW WIDTH,INCHES 3.1400	TO,DEG F 70.000	VISCOSITY,LB-SEC/IN2 0.2660E-08	PLOT *********************
AREA,IN2 251.3274	GAS CONSTANT,LB-FT/LBM-R 53.35222	SPEED,RPM 0.0000	
	LOSS COEF. 0.50	V,FT/SEC 0.00	

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

```
QUASI-ONE DIMENSIONAL COMPRESSIBLE FLOW SEAL PROGRAM     THREE INCH VENT PIPE, I.D.=3 IN, H=1.5 IN (PATH TEN)

INPUT DATA -

         R1,INCHES                  PO,PSIA                MOLECULAR WEIGHT             F=K/RE**N
          1.0000                    25.000                    28.966                    *********

         R2,INCHES                  P3,PSIA              CP,BTU/LBM-DEG F               K(LAMINAR)
          0.0000                     0.000                    0.240                     24.000

     FLOW LENGTH,INCHES              PO/P3                    GAMMA                     N(LAMINAR)
          304.0000                   1.250                    1.400                       1.00

     FLOW WIDTH,INCHES              TO,DEG F             VISCOSITY,LB-SEC/IN2      UPPER LIMIT RE (LAMINAR)
          4.7100                     70.0                   0.0000                      2300.0

                                   LOSS COEF.                SPEED,RPM                 K(TURBULENT)
                                     0.50                     0.0000                   0.7900E-01

                                                            V,FT/SEC                  N(TURBULENT)
                                                              0.00                     0.2500

                                                                                LOWER LIMIT RE (TURBULENT)
                                                                                        3000.0

OUTPUT DATA -

         R1,INCHES                  PO,PSIA                MOLECULAR WEIGHT             CALCULATE
          1.0000                    20.000                    28.966                    *********

         R2,INCHES                  P3,PSIA              CP,BTU/LBM-DEG F
          305.0000                  14.700                    0.000

     FLOW LENGTH,INCHES              PO/P3                    GAMMA
          304.0000                   1.361                    1.400

     FLOW WIDTH,INCHES              TO,DEG F             VISCOSITY,LB-SEC/IN2              PLOT
          4.7100                     70.000                 0.2680E-08           **********************

          AREA,IN2          GAS CONSTANT,LB-FT/LBM-F         SPEED,RPM
        292243.4375                53.35222                 0.0000

                                   LOSS COEF.                 V,FT/SEC
                                     0.50                      0.00

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

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ITERATION 2

PATH NO. 1 P(INLET)=300. P(OUTLET)=70.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1215
1.050	0.2668
1.100	0.3638
1.500	0.6132
2.000	0.6681
3.000	0.6736
4.000	0.6707

PATH NO. 2 P(INLET)=70.0 P(OUTLET)=25.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1099
1.050	0.2431
1.100	0.3323
1.500	0.5661
2.000	0.6219
3.000	0.6346
4.000	0.6344

PATH NO. 3 P(INLET)=70.0 P(OUTLET)=25.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.2530E-01
1.050	0.5564E-01
1.100	0.7639E-01
1.500	0.1306
2.000	0.1439
3.000	0.1473
4.000	0.1474

PATH NO. 4 P(INLET)=25.0 P(OUTLET)=15.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1680E-01
1.050	0.4190E-01
1.100	0.5745E-01
1.500	0.9889E-01
2.000	0.1095
3.000	0.1128
4.000	0.1131

PATH NO. 5 P(INLET)=25.0 P(OUTLET)=15.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.5906E-02
1.050	0.1642E-01
1.100	0.2526E-01
1.500	0.4357E-01
2.000	0.4839E-01
3.000	0.5000E-01
4.000	0.5014E-01

PATH NO. 6 P(INLET)=15.0 P(OUTLET)=10.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1051E-01
1.050	0.2343E-01
1.100	0.3213E-01
1.500	0.5533E-01
2.000	0.6130E-01
3.000	0.6316E-01
4.000	0.6330E-01

PATH NO. 7 P(INLET)=15.0 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.3607E-01
1.050	0.7952E-01
1.100	0.1065
1.500	0.1638
2.000	0.2011
3.000	0.2039
4.000	0.2034

PATH NO. 8 P(INLET)=15.0 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.4829E-01
1.050	0.1084
1.100	0.1492
1.500	0.2599
2.000	0.2902
3.000	0.3015
4.000	0.3026

PATH NO. 9 P(INLET)=25.0 P(OUTLET)=20.0

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1839
1.050	0.3954
1.100	0.5331
1.500	0.8648
2.000	0.9056
3.000	0.8378
4.000	0.7629

PATH NO. 10 P(INLET)=20.0 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.2794
1.050	0.6190
1.100	0.8468
1.500	1.447
2.000	1.594
3.000	1.631
4.000	1.632

FINAL RESULTS

R= 5.372823E-06

PHI= 5.996709E 01
2.232632E 01
1.462184E 01
1.881750E 01
1.563185E 01
1.506396E 01

MASS FLOW BALANCE INFORMATION AT NODES 1 TO 6
****

NODE NO.	MD(NET)	MD(MIN)	MD(NET)/MD(MIN)
1	-3.326E-05	1.268E-01	-2.632E-04
2	-4.161E-05	3.906E-02	-1.070E-03
3	1.992E-05	8.811E-03	2.260E-03
4	5.662E-06	5.443E-01	1.040E-05
5	-6.026E-05	5.444E-01	-1.107E-04
6	-2.164E-04	8.732E-02	-2.478E-03

ITERATION 3

PATH NO. 1 P(INLET)=300. P(OUTLET)=60.0

PRATIO	MASS FLOW
1.000	0.0000
1.050	0.2668
1.100	0.3638
1.500	0.6132
2.000	0.6681
3.000	0.6736
4.000	0.6707
5.003	0.6707

PATH NO. 2 P(INLET)=60.0 P(OUTLET)=18.8

PRATIO	MASS FLOW
1.000	0.0000
1.050	0.2073
1.100	0.2834
1.500	0.4835
2.000	0.5319
3.000	0.5435
3.187	0.5436
4.000	0.5436

PATH NO. 3 P(INLET)=60.0 P(OUTLET)=22.3

PRATIO	MASS FLOW
1.000	0.0000
1.050	0.4758E-01
1.100	0.6514E-01
1.500	0.1115
2.000	0.1230
2.686	0.1259
3.000	0.1261
4.000	0.1262

PATH NO. 4 P(INLET)=22.3 P(OUTLET)=15.1

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1673E-01
1.050	0.3726E-01
1.100	0.5110E-01
1.482	0.6738E-01
1.500	0.8607E-01
2.000	0.9763E-01
3.000	0.1007

PATH NO. 5 P(INLET)=22.3 P(OUTLET)=18.8

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.5891E-02
1.050	0.1610E-01
1.100	0.2260E-01
1.500	0.3680E-01
1.506	0.3890E-01
2.000	0.4312E-01
3.000	0.4459E-01

PATH NO. 6 P(INLET)=14.6 P(OUTLET)=18.7

PRATIO	MASS FLOW
1.000	0.0000
1.008	0.9426E-02
1.010	0.1038E-01
1.050	0.2314E-01
1.100	0.3174E-01
1.500	0.5466E-01
2.000	0.6056E-01
3.000	0.6241E-01

PATH NO. 7 P(INLET)=14.8 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.008	0.3284E-01
1.010	0.3563E-01
1.050	0.7855E-01
1.100	0.1072
1.500	0.1816
2.000	0.1986
3.000	0.2014

PATH NO. 8 P(INLET)=15.1 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.4850E-01
1.025	0.7709E-01
1.050	0.1090
1.100	0.1459
1.500	0.2610
2.000	0.2914
3.000	0.3028

PATH NO. 9 P(INLET)=18.8 P(OUTLET)=15.6

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.1394
1.050	0.2975
1.100	0.4012
1.204	0.5219
1.500	0.6508
2.000	0.6817
3.000	0.6311

PATH NO. 10 P(INLET)=15.6 P(OUTLET)=14.7

PRATIO	MASS FLOW
1.000	0.0000
1.010	0.2159
1.050	0.4799
1.063	0.5360
1.100	0.6569
1.500	1.123
2.000	1.242
3.000	1.274

FINAL RESULTS

F= 1.802602E-08

```
PHI= 6.007884E 01
     2.234119E 01
     1.480633E 01
     1.909761E 01
     1.566009E 01
     1.515520E 01
```

MASS FLOW BALANCE INFORMATION AT NODES 1 TO 6
****

NODE NO.	MD(NET)	MD(MIN)	MD(NET)/MD(MIN)
1	-1.281E-05	1.261E-01	-1.016E-04
2	1.194E-05	3.897E-02	3.064E-04
3	-5.729E-06	8.766E-03	-6.536E-04
4	1.318E-04	5.445E-01	2.420E-04
5	1.591E-05	5.445E-01	2.923E-05
6	-6.497E-06	8.712E-02	-7.457E-05

THE NETWORK SOLUTION IS
****

PATH NO.	INNODE	OUTNODE	P(INLET)	P(OUTLET)	MASS FLOW
1	8	1	300.0	60.09	0.6707
2	1	4	60.09	19.10	0.5446
3	1	2	60.08	22.30	0.1261
4	2	6	22.34	15.19	0.5712E-01
5	2	3	22.34	14.81	0.3397E-01
6	3	9	14.81	14.70	0.8766E-02
7	3	9	14.81	14.70	0.3021E-01
8	6	10	15.16	14.70	0.5713E-01
9	4	5	19.10	15.66	0.5446
10	5	7	15.66	14.70	0.5446

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1. Zuk, John; and Smith, Patricia J.: Quasi-one-dimensional flow across face seals and narrow slots. II - Computer Program. NASA TN D-6787, 1972.

2. Jones, A.: Spiral - A New Algorithm for Non-Linear Parameter Estimation Using Least Squares. The Comput. J., vol. 13, no. 3, Aug. 1970, pp. 301-308.

3. Fessler, Theodore E.; and Ford, William F.: USER'S GUIDE FOR SFTRAN/360. NASA TP-1006, 1977.

4. Zuk, John; Ludwig, Lawrence P.; and Johnson, Robert L.: Quasi-one-dimensional compressible flow across face seals and narrow slots. I - Analysis. NASA TN D-6668, 1972.

5. IBM Systems Reference Library - IBM Time Sharing System-Command System User's Guide. GC28-2001-9, 10th ed., Aug. 1976. International Business Machines Corp., 1976.

TABLE I - Variables in NAMELIST/PATHSP/

Variable Name	Description	Dimension
INLET	Integer array. Integers associated with the inlet nodes. INLET(J) is the integer associated with the inlet node of the Jth path.	(25)
OUTLET	Integer array. Integers associated with the outlet nodes. OUTLET(J) is the integer associated with the outlet node of the Jth path.	(25)
FLOTYP	Integer array. Integers associated with the type of flow through each path. If FLOTYP(I)=1, the flow through path I is described by subroutine QUASC. If FLOTYP(I)=2, then the flow through path I is described by a user supplied flow module.	(50)
NTPATH	Integer. Total number of flow paths in the network. (Identical paths at a node are counted as one path.)	
SAME	Two dimensional integer array. Contains the number of equivalent paths at the <u>inlet</u> node of these paths. SAME(J,I)=L means that path number I consists of L equivalent paths and their inlet node number is J. (SAME does not have to be specified if there are no equivalent paths.)	(25,50)
SAMEPR	Logical. If set .TRUE., then only the pressure ratios for the first flow path must be input and these values are used for all flow paths in the network. If set .FALSE., then a set of pressure ratios for each flow path in the network must be input.	

TABLE II - Variables in NAMELIST/NODESP/

Variable Name	Description	Dimension
NTNODE	Integer. Total number of nodes in the network.	
TO	Real array. Total temperature of the gas at each node. TO(J) is the temperature at node J.	(25)
FIXED	Logical array. If FIXED(J)=.TRUE., the pressure at node J is specified. If FIXED(J)=.FALSE., the pressure at node J is an unknown.	(25)
MDNET	Real array. Net mass flow at node J. If MDNET(J)≠0., then node J is a source or a sink. If MDNET(J)=0., then no mass is taken from the network at node J. (MDNET(J) must be positive if mass is taken from the network at node J and negative if mass is added to the network at node J.)	(25)
PRESS	Real array. Contains the values of the pressures at each node in the network. If there are NN unknown (non-fixed) pressures then the first NN values in the PRESS array <u>must</u> be the user supplied, initial estimates of these NN unknown pressures.	(25)

TABLE III - Variables In NAMELIST/PARAM/

Variable Name	Description	Dimension
NPRAT	Integer array. Contains the number of pressure ratios to be used, at a given inlet pressure, to generate the mass flow functions for each flow path. If NPRAT(I)=N, then the descrete mass flow function for path I is generated from N values of the pressure ratio.	(50)
PRAT	Two dimensional real array. Contains the values of the pressure ratios that will be used to calculate the mass flow functions for each flow path. PRAT(L,J) is the Lth value of the pressure ratio for the Jth path. For each flow path, the first value in the pressure ratio array must be 1.0, and the pressure ratio values must be monotonic increasing.	(10,50)
DELPMX	Used as a convergence criterion. If the scaled pressue at each non-fixed node changes by less than the value of DELPMX from one outer iteration to the next then the solution is considered converged.	
NPX	Integer. The number of unknown pressures in the flow network. (This is calculated by FLOWNET)	

PWRSKP	Logical variable. If .TRUE., calculations involving power are skipped	.TRUE.
NRMSKP	Logical variable. If .TRUE., normalized values of sealing dam force and center of pressure are skipped.	.TRUE.
PRSSKP	Logical variable. If set .TRUE. printout of distributions across face of seal will be omitted.	.TRUE.
PLTSKP	Array of eight logical variables. If all eight are set .TRUE. no plots are made.	8*.TRUE.
SKPH	Logical variable. If .TRUE. no film thickness data will be read.	.FALSE.
NOSI	Logical variable. If set .TRUE., input, internal calculations and output are in U.S. units. If set .FALSE., input, internal calculations, and output are in SI units.	
LOSS	Entrance velocity loss coefficient	
IPATH	Integer assigned to the flow path. (Used only to identify the data)	

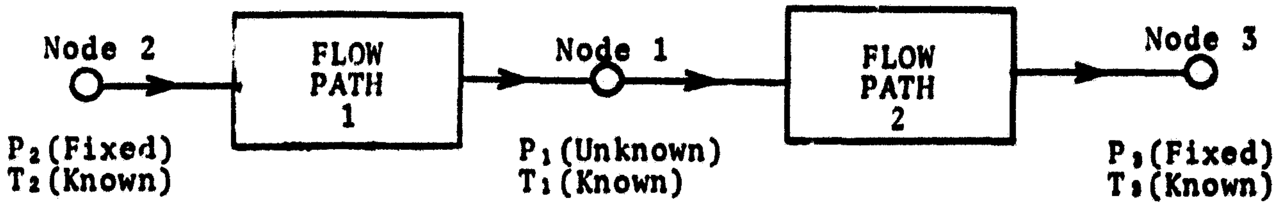
TABLE IV - Variables in NAMELIST/SDATA/

Variable Name	Description	Value to Use For Flow Network
R1IN	Inner radius of seal	
R2IN	Outer radius of seal	
RDIFIN	Flow length	
WIDTH	Mean flow width	
MOLWT	Molecular weight	
CP	Specific heat	
MU	Reservoir viscosity. The program will calculate MU for air but not for other gases	
GAMMA	Ratio of specific heats	
SPEED	Rotational velocity	
CAPV	Seal face speed	
XLAM	Exponent in friction factor - Reynolds number relation for laminar flow (eq. 10 of ref 1)	
CONLAM	Constant in friction factor - Reynolds number relation for laminar flow	
XTURB	Exponent in friction factor - Reynolds number relation for turbulent flow	
CONTRB	Constant in friction factor - Reynolds number relation for turbulent flow	
RELAM	Maximum Reynolds number for laminar flow	
RETURB	Minimum Reynolds number for turbulent flow	

TABLE V - Data for Sample Network of Figure 3

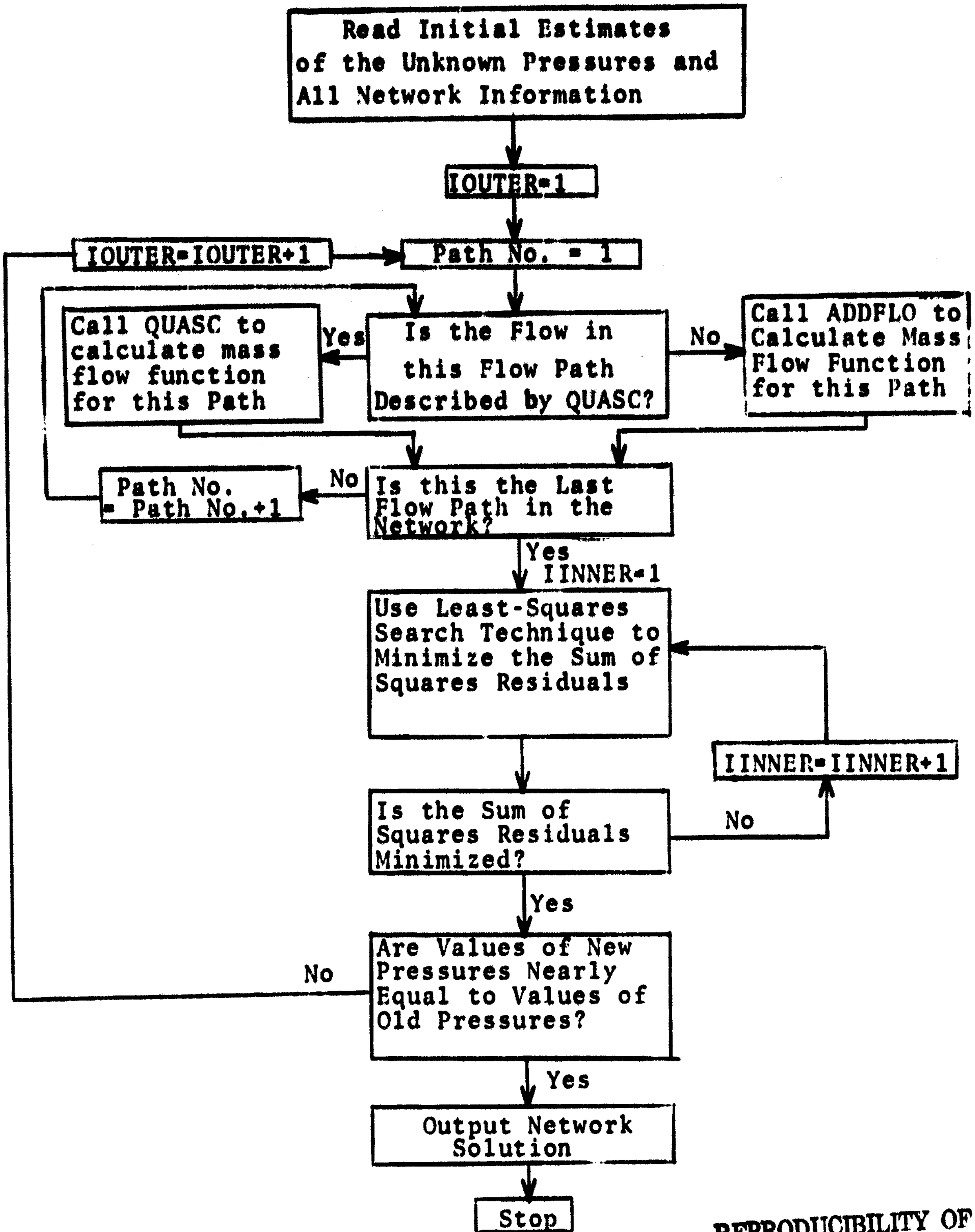
```
Sample Network - U.S. Customary Units
&PATHSP NTPATH=3, INLET(1)=2, INLET(2)=1, INLET(3)=1,
        OUTLET(1)=1, OUTLET(2)=3, OUTLET(3)=4,
        FLOTYP(1)=1, FLOTYP(2)=1, FLOTYP(3)=1               &END
        SAME(1,2)=2
&NODESP NTNODE=4, T0=4*250.0,
        FIXED=.FALSE., 3*.TRUE.,                            &END
        PRESS=50.0, 100.0, 14.7, 14.7
&PARAM  NPPAT=3*8, SAMEPF=.TRUE.,                           &END
        PRAT=1.0, 1.1, 1.5, 2.0, 3.0, 4.0, 6.0, 8.0
```

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



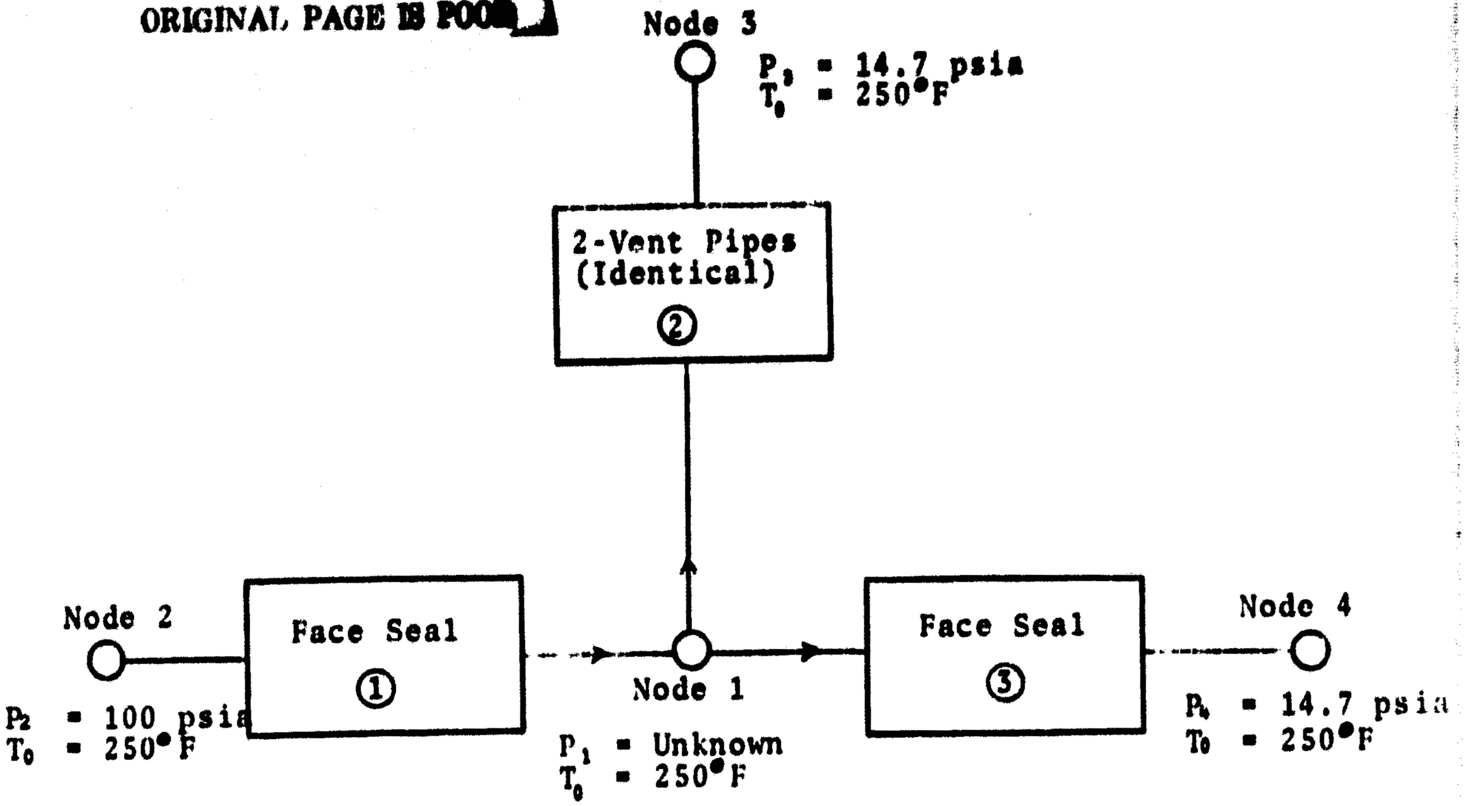
Sample Flow Network

FIGURE 1



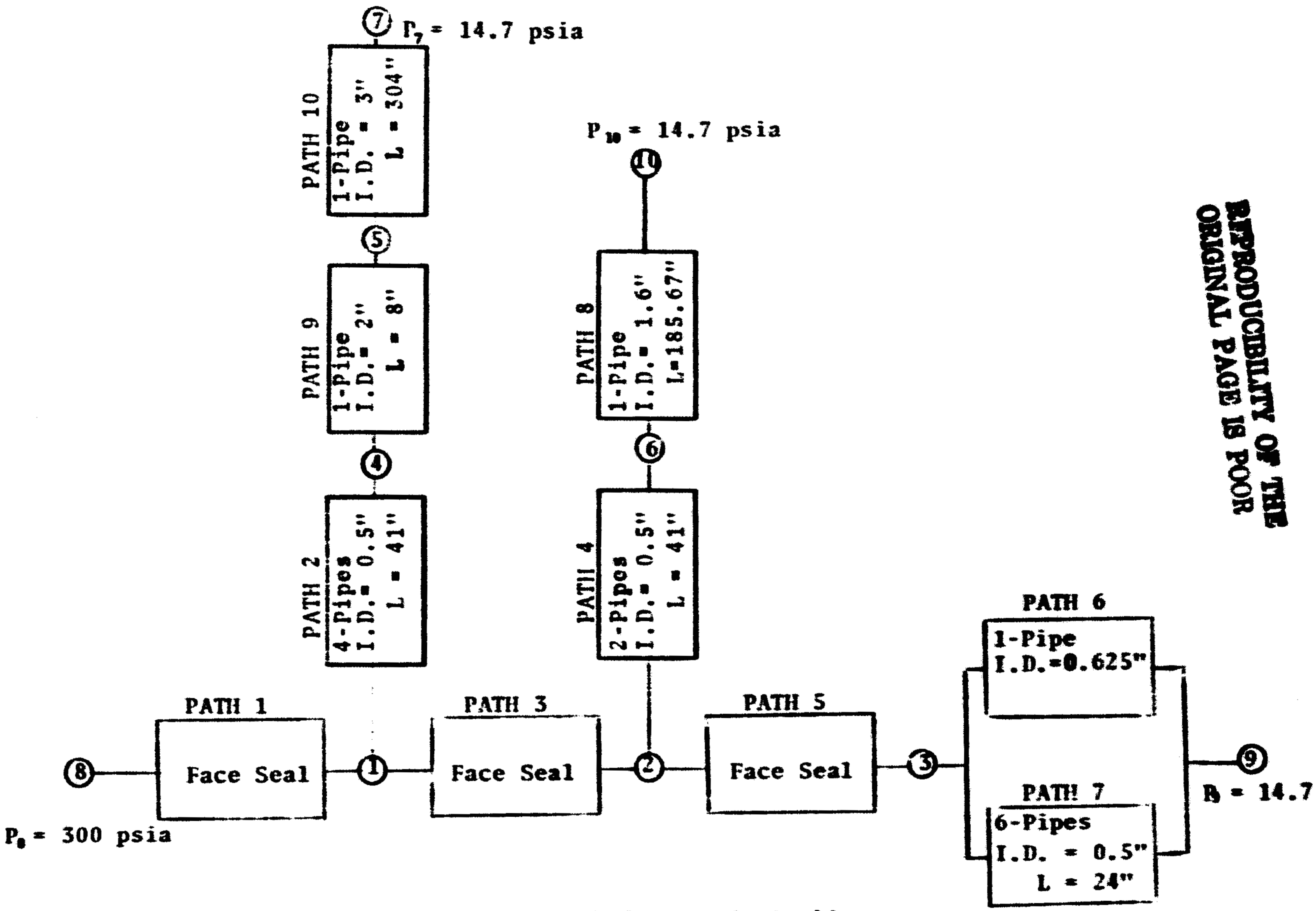
Functional Flow Chart for the Program Flownet

FIGURE 2



Example Flow Network

FIGURE 3



Flow Network for Sample Problem

FIGURE 4