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A prototype expert system for diffuser performance evaluation of blowdown type wind tunnels

Gary W. Jarrell

To the Graduate Council:

I am submitting herewith a thesis written by Gary W. Jarrell entitled "A prototype expert system for diffuser performance evaluation of blowdown type wind tunnels." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

Ching F. Lo, Major Professor

We have read this thesis and recommend its acceptance:

R. J. Schulz, A. D. Vakili

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Date 4/12/91

A PROTOTYPE EXPERT SYSTEM FOR DIFFUSER PERFORMANCE EVALUATION OF BLOWDOWN TYPE WIND TUNNELS

A Thesis
Presented for the
Master of Science
Degree
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Gary W. Jarrell

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ABSTRACT

The purpose of this research was to develop a prototype expert system built around the Diffuser Performance Program written by Mr. Bob Bauer of Calspan Corporation. The Diffuser Performance Program predicts the performance of the diffuser section of a blowdown type wind tunnel. The expert system was intended to have two main capabilities; assist the user in understanding the program inputs and assigning correct values to them, then execute the Diffuser Program and provide an interpretation of the diffuser's performance in text and graphical formats.

This thesis describes the components, structure and capabilities of the Diffuser Expert System. A brief synopsis of the Diffuser Performance Program is included with complete charts of the variables and equations. The structure of the expert system is described with each of the component program's function identified. And finally, the results of the expert system and their potential value to a user are discussed.

A final section of this thesis outlines future work that would be necessary to bring the expert system from the prototype level to an actual operating system.

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LIST OF SYMBOLS

A	area
Alt	altitude
C	Crocco number
C_D	wall drag coefficient
C_P	specific heat at constant pressure
C_V	specific heat at constant temperature
D	diameter
DF	differential force (thrust)
F	force (momentum plus pressure)
h	nondimensional heat released
k	normalized mass flow
L	diffuser gap
m	mass flow
M	Mach number
P	pressure
r	radial dimension
T	temperature
X	axial dimension
δ	boundary layer thickness
γ	ratio of specific heats

Superscripts

*	throat area

Subscripts

A	engine fuel afterburning
B	free jet diffuser region
BE	free jet diffuser minimum area region
B1	jet pump diffuser region
B1E	jet pump diffuser minimum area region
b1	engine base
b2	jet stretcher base
b4	jet pump base
C	chamber region
E	external region
i	engine inlet on test body
j	radial gap between nozzle exit and jet stretcher inlet
N	nozzle
N1	nozzle parameter solution for diffuser exhausting to atmosphere
P	jet stretcher porous wall

Subscripts Continued

S	model, support structure and free jet diffuser surface
S1	jet pump region surface
S2	jet pump diffuser surface
t	total or stagnation condition
W	water cooling spray
WS	water saturated
1	test body engine exit
2	region between test body and jet stretcher
3	gap between jet stretcher and free jet diffuser
4	jet pump
5	jet pump region

I. INTRODUCTION

Background

A FORTRAN computer program was developed by Mr. Bob Bauer of Calspan Corporation for analyzing the general performance and starting conditions of the diffuser section of blowdown type aerodynamic test units. The Diffuser Performance Program is used for predicting the performance of an existing diffuser section with a proposed test article. It can also be used in the design of a new diffuser. The program is complex and requires an extensive set of inputs that include geometric, thermodynamic and fluid mechanical parameters. Execution of the program results in another large set of output variables. The large amount of numerical information produced and required by the program makes it difficult and tedious to use. A user of the program must fully understand the theory behind the program and acquire a lot of background knowledge before he can use the program effectively. Artificial Intelligence (AI) techniques was used to provide some of the knowledge required to use the Diffuser Program.

Artificial Intelligence is defined as behavior by a machine, that if performed by a human being, would be called intelligent [1]. The branch of AI applied in this project is Expert Systems. Expert systems are defined as a computerized advisory program that attempts to imitate or substitute the reasoning processes and knowledge of human experts in solving specific types of problems [1]. It was believed that developing an expert system to substitute for the knowledge base required to use the Diffuser Program would be beneficial. Such an expert system would allow persons not familiar with the Diffuser Program to use it without extensive consultation with human experts. The consultation is time consuming and an expert is not always available. The expert system could also be used as a training tool for a user not familiar with diffuser characteristics. A final benefit in building a Diffuser Expert System would be to preserve the human expertise so that it would not be lost.

Objective

To better understand the requirements for a Diffuser Expert System, a description of a typical session using the Diffuser Performance Program was obtained. The user assembles a list of the input parameter values and enters them into the program. If the program is being used to check the performance of an existing test unit and test article, the input values are those for the existing equipment. If the program is being used to help design a test unit, the input parameter values are picked as per the test unit specifications. The program is run and the output parameters are interpreted and evaluated. If necessary, the inputs are altered according to the output evaluation and the program rerun. The process is repeated until usable answers are obtained.

Figure 1.[1] shows the proposed data path through the Diffuser Expert System. The data path closely resembles the path presently being used when the Diffuser Program is run. Expert system programs are inserted at the steps where a human expert would normally be. The expert system to assemble the inputs would have the following functions:

- Ask the user for the necessary inputs.
- Ask questions and make decisions about the initial diffuser configuration.
- Set reasonable default values to input parameters not needed from the user.
- Set limits to input parameters where required.
- Explain each input parameter when requested.
- Suggest reasonable values for parameters when requested.
- Assemble input data in data files.

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1 All figures may be found in Appendix A

The expert system to interpret the outputs would have the following functions:

- Check that the inputs make sense with respect to the outputs.
- Provide a general interpretation of the diffusers performance.
- Identify diffuser flow irregularities and suggest remedies.

Approach

To develop a Diffuser Expert System, it was first necessary to gain a working knowledge of the Diffuser Performance Program. Most of the literature found on the program dealt only with the development of the equations that describe the diffuser. There is very little written information on the variable definitions or the program's usage. A majority of the knowledge was gained through interviews with the program's developer, Mr. Bauer. Condensing a small part of the many years of Mr. Bauer's experience into the expert system proved to be the major task of this research.

The second aspect to the expert system was the transformation of the knowledge gained into software. The expert shell was the key to this transformation and it's selection was important. An expert shell was needed with a flexible programming language and with the ability to call and share data with external programs. The expert shell's flexibility would be important in developing the user interface. The user interface was desired to be menu driven, with all functions of the expert system accessible from a central main menu. The expert shell would have to interact with external programs easily because all interaction with the Diffuser Program would be done through external programs. The external programs would read the Diffuser Program's input and output data files. This was necessary because it was desired that no modifications would be made to the Diffuser Program. The Diffuser Program is mature and has been used for many years by people who have gained confidence in it's outputs. Any changes to the program would shake that confidence.

II. DIFFUSER PERFORMANCE PROGRAM

Diffuser Flow Development

A blowdown type wind tunnel is defined for this thesis as one that exhausts to atmosphere, either directly or through an exhauster plant. Blowdown wind tunnels are used primarily to allow testing of larger models than is possible in a closed loop wind tunnel and in testing of engines where products of combustion must be exhausted. Figure 2. shows a sketch of a representative blowdown wind tunnel. The major components include: the free jet nozzle where the process flow is accelerated to supersonic speeds, the test chamber where the model is mounted, and the diffuser section where deceleration of the process gas and pressure recovery is performed. Other components can include: a jet pump which provides an extra stage of compression in the process flow and a jet stretcher which is an aerodynamically tailored device which replaces a known streamline with a boundary layer corrected wall and provides interference free flow at the engine inlets [2]. A jet stretcher is typically used with a model where the engine inlet is far downstream of the nose.

Blowdown type wind tunnels are used to simulate high altitude conditions at supersonic speeds. The wind tunnel achieves these conditions by accelerating the process gas from stagnation conditions to supersonic flow through the converging/diverging nozzle. The resulting free jet entrains surrounding gas in the test chamber through turbulent mixing along the boundary layer, and transports it to the diffuser exit. The action of removing gas from the test chamber causes the chamber pressure to decrease, thereby simulating a higher altitude. The amount of chamber gas entrainment is a function of the momentum of the free jet which is also directly related to the pressure ratio across the test unit.

Figure 3. illustrates the flow development in a blowdown wind tunnel. The curve shown in the illustration is a standard format for representing a diffuser's performance. The performance curve is typically on a log-log scale of P_C/P_{tN} vs. P_B/P_{tN}, where P_{tN} is the nozzle total pressure, P_C is the test unit chamber pressure, and P_B is the diffuser discharge pressure. The performance curve shows the relationship of the overall test unit pressure ratio with the nondimensional chamber pressure. The curve shown is representative of a diffuser with good performance. The curve initially lies along the line where $P_C = P_B$, showing very little pump down of the test chamber. As test unit pressure ratio increases the curve acquires a near vertical slope, showing large drops in chamber pressure for small changes in test unit pressure ratio.

To discuss the flow development of a blowdown test unit, four operating points were selected on the performance curve for illustration in Fig. 3. For simplification, a basic test unit was used with only a nozzle, a test chamber and a diffuser. A pressure profile is also shown in Fig. 3. for each operating point. The pressure profile was produced by assuming no friction in the diffuser, adiabatic flow, and P_B is held constant while P_{tN} is increased to move down the performance curve.

Point A was selected high on the curve at P_C/P_{tN} equal to .528 and where the chamber pressure is essentially equal to the diffuser discharge pressure. At this point the the flow has reached sonic velocity in the throat, but the chamber pressure is high enough to cause the flow to separate from the nozzle wall as shown in Fig. 3. Since the sonic flow is not expanding, supersonic flow is not achieved and pressure in the diffuser is equal to the exit pressure. As P_{tN} is increased and the diffuser operating point moves down the curve, the flow begins to attach to the nozzle wall and shocks form in the nozzle.

Point B is selected at the labeled Diffuser Started region of the curve. Diffuser Started is defined as the point where there are no disturbances from the nozzle exit which influence the test body flow field of interest [3]. At this operating point the flow reaches supersonic speeds but the chamber pressure is still greater than the nozzle exit pressure. Oblique shocks form at the nozzle exit to compress the flow. Pressure recovery in the diffuser section is achieved by the free jet "shocking down" to reach subsonic speeds and match pressure at the exit. Model aerodynamic testing can be performed with the diffuser operating near the labeled starting point. In this region the test rhombus is shortened by the oblique shocks originating at the nozzle exit, but the diffuser will operate with the smallest value of nozzle total pressure for a given constant diffuser exit pressure. Increasing P_{tN} moves the diffuser operating point further down the curve, lengthens the test rhombus and moves the "shocking down" process further down the duct.

The sketch for Point C illustrates the flow at the nozzle design point where the chamber pressure and nozzle exit pressure are equal. At this point, the free jet comes straight out of the nozzle and there are no shocks at the nozzle exit. Again, the free jet "shocks down" further down in the diffuser to match pressures at the exit.

Point D illustrates an operating point where the chamber pressure is less than the nozzle exit pressure. Expansion waves form to expand the flow and match the static and chamber pressures. Increasing P_{tN} moves the diffuser operating point down the performance curve until the labeled Base Pressure Limit is reached. This pressure limit is the lowest theoretical value for the chamber pressure and is found by assuming an isentropic expansion of the flow from the nozzle throat area to the diffuser area. Typically rocket testing is performed near this operating point because it represents the highest altitude simulation possible for a given diffuser configuration.

Diffuser Performance Program Overview

The equations describing the performance of a diffuser was developed by Mr. R.C. Bauer by applying fluid mechanics conservation laws to the control volumes shown in Figure 2. The Diffuser Performance Program is based on these equations and is programmed in Fortran for use on IBM compatible personal computers. The diffuser analysis is divided into two parts 1) general performance and 2) diffuser starting conditions. The general performance analysis determines the relationship between the nozzle total pressure P_{tN}, the chamber pressure P_C, and the exhaust pressure P_B. The starting conditions analysis relates the nozzle total pressure to the maximum chamber pressure at which the system will operate in a steady state started condition [3].

The calculations of diffuser performance can be made with the diffuser in a variety of configurations. A sketch of a diffuser system with the major configuration components is shown in Figure 2. The basic diffuser modeled consists of a nozzle, a test chamber and a diffuser ducting section. A test article can be inserted into the test chamber and the effects of drag and blockage can be simulated. An engine can be added to the test article and the effects of thermal and momentum additions to the flow can be simulated. Another configuration is the addition of a jet pump and jet pump diffuser that are used to increase the performance of a diffuser. A jet stretcher can also be added to provide an interference free flow field over the model [2]. Miscellaneous additions to the diffuser simulation can be included, such as a cooling water spray, a test chamber leak from atmosphere, and cooler coils between the free jet diffuser and jet pump regions. The possible configurations of the diffuser are specified by the values of the Diffuser Program inputs. The inputs are set to default values to simulate the absence of a configuration structure, or specified a value depending on the configuration desired.

The diffuser performance equations were developed in the early seventies to model a jet stretcher system. The analysis was subsequently expanded to model Control Volume I shown in Fig. 2. The equations were first transformed into FORTRAN code to run on IBM mainframe computers by Wilbur Armstrong, formerly of Calspan Corp. The equations and computer code for Control Volumes II and III (Fig. 2) were added in later years . Other minor additions, such as fuel afterburning, were also added. The resulting Diffuser Performance Program was then converted to run on a desktop personal computer during the middle 1980's, also by Wilbur Armstrong. A menu driven interface to enter the input variables was also added by John Felderman of Calspan Corp.

in 1988. The evolution of the equations and computer code over many years is mostly responsible for the sometimes confusing nomenclature. As a reference aid the Diffuser Program variables and their definitions are included in Appendix B and a complete listing of the equations are in Appendix C.

Definition of Diffuser Starting Conditions

A definition and method for calculating the diffuser starting condition can be found in Reference 4. A diffuser and jet stretcher system is defined to be operating in a started condition when there are no disturbances from the nozzle and jet stretcher exits which influence the test body flow field of interest. These disturbances are produced by a chamber pressure, P_C, that is different from either the nozzle or jet stretcher exit static pressure, excessive blockage in the diffuser preventing the establishment of supersonic flow, or a nozzle exit boundary layer thickness that exceeds the radial distance between the nozzle exit and the jet stretcher inlet. The later two disturbances can be eliminated by properly designing the jet stretcher for blockage and the range of test Reynolds numbers. The first disturbance is eliminated by reducing the chamber pressure to a sufficiently low level for starting.

An unstarted flowfield exists when the chamber pressure is greater than the maximum allowable chamber pressure required for the boundary layer to be attached at the nozzle exit. At some point in the steady-state starting process the chamber pressure will become equal to this maximum allowable chamber pressure. At this point, both the nozzle and jet stretcher are flowing full. However, the system is unstarted because of the upstream feedback of the chamber pressure in the nozzle boundary layer caused by an adverse pressure gradient. For the system to be started, all of the compression waves produced by the high-pressure feedback must be intercepted by the jet stretcher. This will occur at a chamber pressure that is less than that for boundary layer separation.

To quantitatively determine the chamber pressure for starting, $(P_C)_{Start}$, it is necessary to analytically represent; 1)boundary layer separation pressure ratio, 2)high-pressure feedback in a boundary layer at the nozzle and jet stretcher exits, and 3)allowable feedback distance in the nozzle boundary layer where disturbances can originate and still be intercepted by the jet stretcher . The above analytical relations are produced with experimental data, nozzle geometry, and linear relationships. Their combination produces the following equation [4] for starting chamber to nozzle exit pressure ratio:

$$\left(\frac{P_C}{P_N}\right)_S = 1 + \frac{(M_N - 1)}{5\left(\frac{\delta_N}{r_N}\right)}\left[\left(1 - \frac{r_j}{r_N} - \frac{\delta_N^*}{r_N}\right)\left(M_N^2 - 1\right)^{1/2} - \frac{X_j}{r_N}\right] \tag{1}$$

Which applies in the following range: $M_N \geq \left(\frac{P_C}{P_N}\right)_S \geq 1.0$

For $\left(\frac{P_C}{P_N}\right)_S > M_N$, the starting value is $\left(\frac{P_C}{P_N}\right)_S = M_N$

For $\left(\frac{P_C}{P_N}\right)_S < 1.0$, the system will not start since the allowable feedback distance is less than zero.

A diffuser without a jet stretcher is a simplified subset of the starting analysis. If no jet stretcher is needed, default values are picked for the geometry variables so that the right side of the starting pressure equation is equal to M_N.

Diffuser General Performance

The Diffuser Performance Program can be used to predict problems with a diffuser's performance. The overriding concern is if the minimum attainable chamber pressure is reached before the diffuser has reached the chamber pressure for starting. The minimum chamber pressure is determined by either diffuser choking, free jet pluming or base flow phenomena [4]. Diffuser choking can occur on control volume surfaces 3, 5, B, and B1 as shown in Fig. 2. and can be caused by excess drag of the model and support surfaces, excessive chamber inleakage, area restrictions in the diffuser, etc. The jet plume limit is reached at a chamber pressure, less than the nozzle exit pressure, where the nozzle free jet plumes to a diameter larger than the diffuser diameter and pump down of the test chamber has stopped. The base flow limit occurs when a nozzle plume is attaching to the inside of the diffuser sufficiently downstream of the diffuser entrance so as not to interfere with the recompression process. Of the above limits, only diffuser choking is predictable by the control volume analysis used to develop the performance equations.

Data Files

Inputs for the Diffuser Performance Program are stored in a data file called BAUER.DOC. A BASIC program MENU.BAS was provided with the Diffuser Program to allow for changes to the input data file BAUER.DOC. The program divides the inputs into six categories such as engine variables, jet pump variables, etc. The variables are accessed through a menu driven user interface. The variables are displayed on the screen along with a definition and a field on the same line for accepting keyboard value inputs. An example of a MENU.BAS input screen is provided in Figure 4.

Several problems were seen with the MENU.BAS program. The definitions are very sketchy and even omitted in some cases. Many of the variables were not placed under the correct categories. All variables were left in the non-dimensional form used by Mr. Bauer during development of the equations. In some cases, such as a ratio of chamber pressure to nozzle total pressure, non-dimensional variables makes sense. However, it was felt that the non-dimensional variables caused some unnecessary calculations on the program users part. Also, the number of decimal places accepted and saved by MENU.BAS were not appropriate in many cases to the type of variable. Another problem is caused by limitations in the BASIC program language. The limitation will not allow zero to be entered as a variable value. Entering zero will cause the variable to be left unchanged. This problem can be circumvented by entering a very small number, on the order of 1×10^{-6}.

The Diffuser Program outputs are saved in two ASCII data files; PRIN6.DOC and PRIN8.DOC. PRIN6.DOC contains the results for the test chamber and free jet diffuser regions. PRIN8.DOC contains the results for the jet pump and jet pump diffuser region. PRIN8.DOC is only created if a jet pump has been included in the diffuser configuration. Examples of the PRIN6.DOC and PRIN8.DOC files are included in Figures 5. and 6. The output data files are divided into three sections. The input variable names and values are relisted in the first section. The second section contains miscellaneous calculated parameters such as mass flows, Mach numbers etc. for different regions in the diffuser. The third section is a tabulated listing of selected parameters calculated for ten user input values of P_C/P_{tN}. It is possible for the Bauer calculations to be stopped short of the full ten P_C/P_{tN} values. This happens when a value of unity is calculated for Mach number at region 3, 5 , B, or B1, (Fig. 2.) signifying that the region has reached sonic velocity and is choked. Referring to Figure 5, the last value at the bottom of the P_C/P_{tN} tabulation is the point where nozzle starting occurs based on the criteria set forth in the definition of diffuser starting section in this thesis. The program sets P_C/P_N starting to M_N and works backward to calculate a corresponding P_C/P_{tN}. Miscellaneous messages may be printed after the end of the P_C/P_{tN} tabulation. The data line after the STARTED heading contains the value of P_C/P_{tN} where the complete diffuser will start. The program calculates a P_C/P_N starting point from Equation 1. and uses it to work backward and calculate a corresponding P_C/P_{tN}. If a jet stretcher is not included in the configuration, the two started points will be equal. Also listed in the third section under the heading STARTED WHEN EXHAUSTING TO ATMOSPHERE is the point where the diffuser will operate started if exhausting to atmosphere which is typical of the majority of blowdown type test units. The section of data printout after the atmospheric start in PRIN6.DOC was a late add-on for when the Diffuser Program was used to simulate a jet engine, not a test facility, and is beyond the scope of this project.

III. THE DIFFUSER EXPERT SYSTEM

Expert System Construction Tools

The Diffuser Expert System was developed using IBM personnel computer compatible software. VP-Expert version 2.0, a rule-based expert shell developed by Paperback Software, was used to represent the knowledge base. VP-Expert was chosen for it's low cost, flexibility and ability to interact with external programs. External programs, which were necessary to supplement the capabilities of VP-Expert, were developed using the Basic language because the MENU.BAS program, supplied with the Diffuser Performance Program for modifying the inputs, was written in Basic. Microsoft QuickBasic, a Basic language editor and compiler was selected for it's low cost, availability and it's ability to compile BASIC code for quicker execution as compared to using a BASIC interpreter.

Expert System Architecture

Six major VP-Expert programs control the various aspects of the Diffuser Expert System. The program DIFFUSER.KBS is the main controller and presents the user the available options such as, build an input data file, run the Diffuser Program and printout the expert system analysis results. The option selected branches the user to one of the other five VP-Expert programs. A chart of the expert system structure is shown in Fig. 7. The chart shows the program interaction with each other and the data files. Definitions for all the programs shown on the chart are included in Figure 8. Execution of DIFFUSER.KBS will produce the menu shown in Figure 9. To select the required option, press the arrow keys to move the cursor to the number and press ENTER.

Selecting Option 1, Create New Data File For Inputs, will build a new input data file by modifying the existing BAUER.DOC file. As shown in Fig. 7, the major program run with this option is the VP-Expert program INPUTS.KBS. INPUTS first prompts the user for the basic inputs needed for any consultation. The program then asks the user a string of questions on the diffuser configuration. For an explanation about a question being asked, the backslash key can be pressed and "WHY?" selected from the VP-Expert function key choices. Depending on the users answers, INPUTS.KBS either calls external programs to set default values to variables, or calls external programs to prompt the user for more inputs. The changes are then saved to the BAUER.DOC input file. The external programs were modeled after the supplied MENU.BAS program to save development time. However, major changes where made. The majority of the variables were made dimensional to reduce the number of calculations required from the user. Also, a partial definition of each variable is given. Care should be taken not to run this option twice on the same

BAUER.DOC input data file. Answering the configuration questions differently can completely change the input variable values.

Selecting Option 2, Use Old Data File for Inputs, lists all data files in the present directory with a .DAT extension and asks for a selection. The selection is then copied onto BAUER.DOC and will be used in the next execution of the Diffuser Program. This allows a built input file that has been saved with a .DAT extension to be used at a later time.

Entering Option 3, Quick Change of Input File, will execute the VP-Expert file MENU.KBS that calls the original MENU.BAS program. The program is very useful when only one variable is to be changed. It allows "what if" analysis without going through the lengthy configuration question process of Option 1. No improvements have been made to the MENU.BAS program used in this option.

Option 4, Run Diffuser Program, will execute the OUTPUTS.KBS VP-Expert file that runs the Diffuser Program and contains the inference engine for analysis of the outputs. A copy of OUTPUTS.KBS is included in Appendix D. This option takes the longest to execute because it calls many external programs. OUTPUTS runs the Diffuser Program, corrects several input variables based on the outputs, and evaluates the diffuser performance. Passing data back and forth between the Diffuser Program output data files and OUTPUTS.KBS is accomplished using the VP-Expert commands SAVEFACTS and LOADFACTS [5].

SAVEFACTS and LOADFACTS read and produce data files that are built with one variable per line in the format Variable=Value CNF n. The confidence factor n, is always set to one hundred, or complete certainty, since numeric variables are being dealt with. The communication loop between the output and input data files and OUTPUTS can be seen in Fig. 7. Getting data from the Diffuser Program output files PRIN6.DOC is accomplished by the external program P6READ. P6READ reads selected variables from the data file, and copies the data into the file P6OUT in the required LOADFACTS format. The VP-Expert command LOADFACTS is used to read P6OUT into the VP-Expert file OUTPUTS. To get input changes made by OUTPUTS into the Diffuser Program input data file, SAVEFACTS is used to produce the file OUTDAT. The external program OUTREAD is called to read the few variable values that are needed from OUTDAT, and makes the changes to the Diffuser Program input data file. Interaction between PRIN8.DOC and the VP-Expert programs are not provided, therefore no analysis of the outputs for the jet pump and jet pump diffuser regions are possible.

In summary, a typical sequence of communications between the OUTPUTS VP-Expert file and the Diffuser Program data file PRIN6.DOC would execute like the following. A rule in the OUTPUTS file compares the Mach number at the nozzle exit, M_N, to the Mach number at region 2, M_2, and finds them unequal. The rule then sets M_N equal to M_2 and executes the command SAVEFACTS.

The external program OUTREAD is then called to read the new value of M_N from the file OUTDAT created by the SAVEFACTS command. OUTREAD then modifies the value of M_N in the Bauer input data file. The Diffuser Program is then executed by the VP-Expert rule, and a new output data file PRIN6.DOC is created. The external program P6READ is called to read in data from PRIN6 and the data loaded into the data file P6OUT. The Rule then executes the LOADFACTS command to load the file P6OUT into the OUTPUTS file for evaluation to continue.

Once all needed corrections are made to the inputs, OUTPUTS.KBS then selects twenty values for P_C/P_{tN}. The Diffuser Program is called and P_B/P_{tN} values are calculated for each of the twenty points. The data is saved in PLOT.DOC and used by the external program PERCRV.EXE to produce a plot of P_C/P_{tN} vs. P_B/P_{tN}. An example of the plot is shown in Fig. 10.

After the plot is produced, OUTPUTS.KBS then analysis the outputs. Presently, OUTPUTS is looking for these things:

- does the free jet diffuser choke, if so, then why?
- does the free jet diffuser choke before the it has started and flowing full?
- how is the diffuser performance, i.e. how well is the chamber pressure pumped down?

The text file RESULTS is generated providing a written analysis of the diffuser's performance based on the answers to the above questions.

Options 5, 6 and 7 allow a review of the resultant files created by the last execution of Option 4. As shown in Fig. 7, these options either rerun the PERCRV program to display the performance curve, or run the shareware program LIST which allows a user to display and search an ASCII data file.

Option 8, Printout of Results, will printout the resultant files created by the latest execution of Option 4. The files include; the plot of P_C/P_{tN} vs. P_B/P_{tN}, the analysis file RESULTS that contains the interpretation of outputs, and the PRIN6.DOC file produced by the Diffuser Program.

IV. EXPERT SYSTEM RESULTS

A cornerstone of the Diffuser Expert System analysis is the plot generated of P_C/P_{tN} vs. P_B/P_{tN} an example of which is in Figure 10. The plot is generated from twenty points calculated by two calls of the Diffuser Program from OUTPUT.KBS. Much information about the diffuser's performance can be obtained by analysis of the plot. Labeled on the plot are the points where the diffuser is started and where the nozzle is operating at it's design point.

A choked diffuser system can also be seen from the performance curve. A choked diffuser is represented by an abrupt horizontal line from the minimum point on the performance curve to the P_C axis where P_B is zero. A performance curve for a choked diffuser is included in Figure 11. Of interest if a diffuser has choked is whether the performance curve has reached the nozzle starting level. If it does not, measures should be taken to improve the minimum P_C level that can be reached.

An evaluation of a diffuser's efficiency can be determined from the performance curve. An efficient diffuser that provides good pumping action on the chamber pressure will have a near vertical performance curve in the diffuser started and nozzle design regions. A poorly performing diffuser will have a performance curve that lies on a P_C equals P_B line (45° slope), signifying that little pumping action is being done on the chamber pressure.

The evaluation of the Diffuser Program outputs is produced in text form by the program OUTPUTS.KBS in the file RESULTS. An example of the RESULTS is shown in Figure 12. The first few lines of RESULTS are miscellaneous messages placed there by OUTPUTS showing when iteration was necessary, values of certain calculated variables, etc. The RESULTS file then contains an evaluation of the diffusers performance, i.e. whether or not the diffuser has choked before starting, the operating point when exhausting to atmosphere, etc. The last part of RESULTS gives reasons for the diffusers choking in the order of probability. Some steps are also given that might alleviate the diffuser choking problem.

V. CONCLUDING REMARKS

Most of the original objectives for the part of the Diffuser Expert System that assists in assembling the inputs were met. The expert system will ask the user for all inputs that are absolutely required by the Diffuser Program. The expert system will then ask questions on the diffuser configuration and give an explanation of the choices when needed. Depending on the configuration, the expert system will set variable defaults or ask values for parameters as required. When input variable values are asked, they have been logically grouped and an on-screen definition is provided for each one. Also, the input variables are entered in dimensional form, the expert system does the calculations to put the variables in the non-dimensional format required by the Diffuser Program.

The objectives for the expert system that analyzes the Diffuser Program outputs were basically met. The expert system checks several of the inputs and will change them based on output parameter values. Diffuser performance knowledge is then represented in graphical and text form. Much of the knowledge is contained in the diffuser performance curve now produced by the expert system instead of hand plotted. It shows diffuser efficiency, the diffuser starting region, and diffuser choking. The same knowledge is recorded in text format in the RESULTS file.

Also included in the RESULTS file is a heirarchical list of diffuser choke reasons and possible remedies. Much expansion of the knowledge base must be accomplished; however, for the expert system to reach it's potential. Particularly an expansion of the knowledge base to include performance analysis for diffusers with a jet pump.

Some other benefits to a user of the Diffuser Expert System were not originally part of the objectives. Using the expert system is much more interactive than using the original Diffuser Program. The user can create or change the input file, run the Diffuser Program and review the results all without leaving the expert system. After satisfactory results have been obtained, the user can then request a printout of the output files. Also, past input files can be saved to create a library of diffuser configurations and these files can be recalled from inside the expert system.

Some of the expert system requirements remain to be refined. To assist the user, an input parameter definition is displayed on the input screens; however, the size of the screen limits the extent of the definition possible. A suggestion of reasonable values and limits for each parameter are also not show because of the same size limitation. Using the MENU.BAS program as a model for entering input values, while cutting front end development time, restricted programming options. No simple method for displaying variable limits or suggesting reasonable values could be found. It is felt that the best way to address the problems would be to provide parameter information in "pop up" form that would only be available when the user needs it. A possible method for displaying this information would be to use the VP-Expert command HYPERTEXT. HYPERTEXT allows text to be dynamically linked to a word or object displayed on the computer screen [6]. The text is displayed in a window when the word or object is selected by a mouse. To use this feature, screens would have to be built inside VP-Expert for keyboard input of the variables. The executable files used for this function would be eliminated. The variable names displayed in the input screens would be linked with text that gives a complete description, limits and suggested values for the variable.

Some other suggestions have been made to improve the present Diffuser Expert System prototype to a more useful product. An upgraded expert system should provide out-of-range checking on input variables as values are assigned to them. The system would interactively recognize unrealistic variable values and notify the user to change them. Another upgrade would be to link the expert system to an intelligent hypertext system. The hypertext system would provide to the user a tutorial on the gas dynamics and fluid mechanics of the diffuser. The tutorial could be coupled with illustrations, similar to Fig. 3, to convey to the user the diffuser operating regions and the testing performance expected.

All discussed upgrades to the Diffuser Expert System can be done using VP-Expert capabilities. However, newer and more capable software products have been brought to market and the possibility of using them should be investigated. One additional hardware requirement to using hypertext would be that computer systems that can run the expert system would be limited to those with a mouse.

LIST OF REFERENCES

LIST OF REFERENCES

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APPENDIXES

APPENDIX A

FIGURES

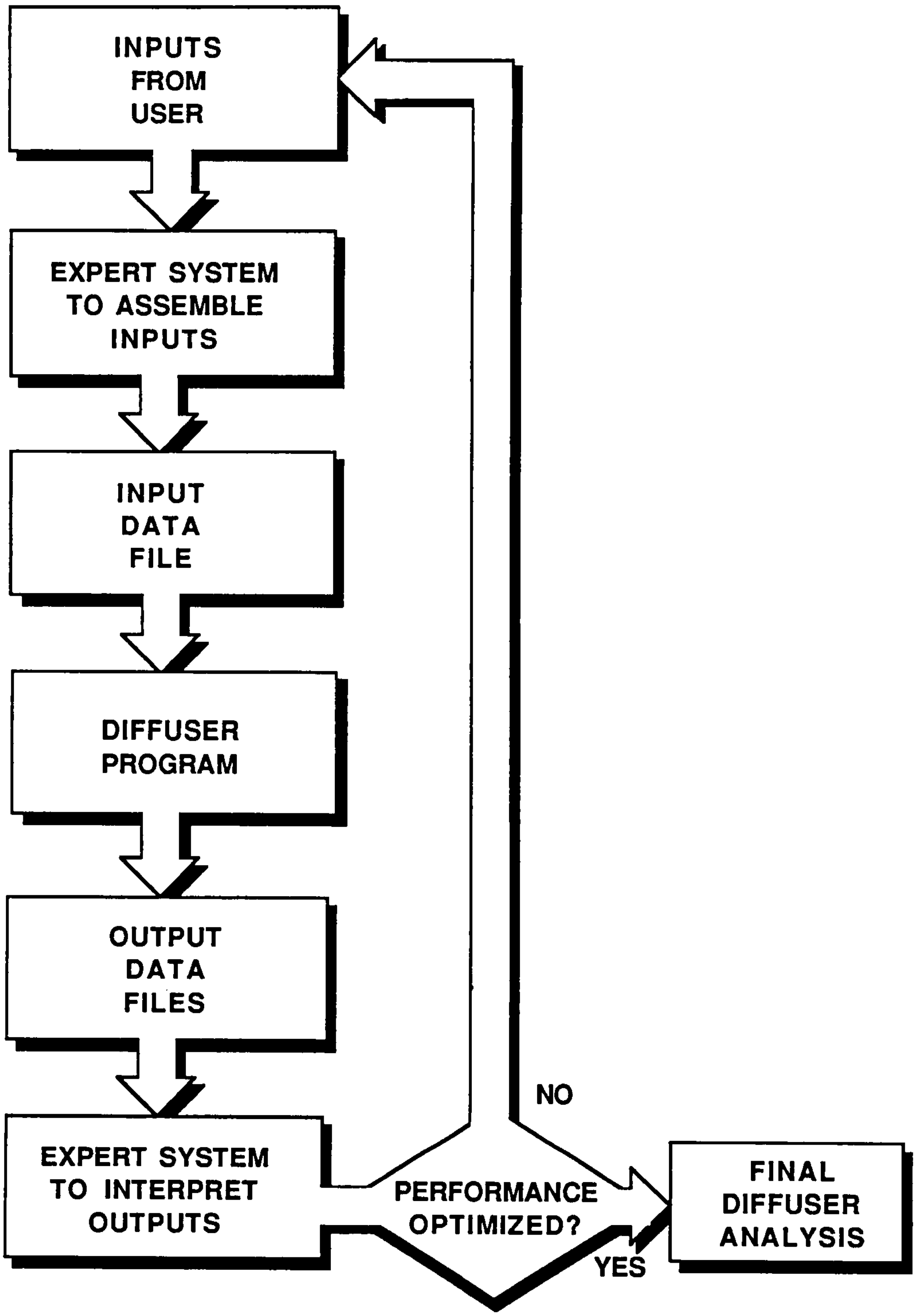

Figure1. Flow of Data Through the Diffuser Expert System

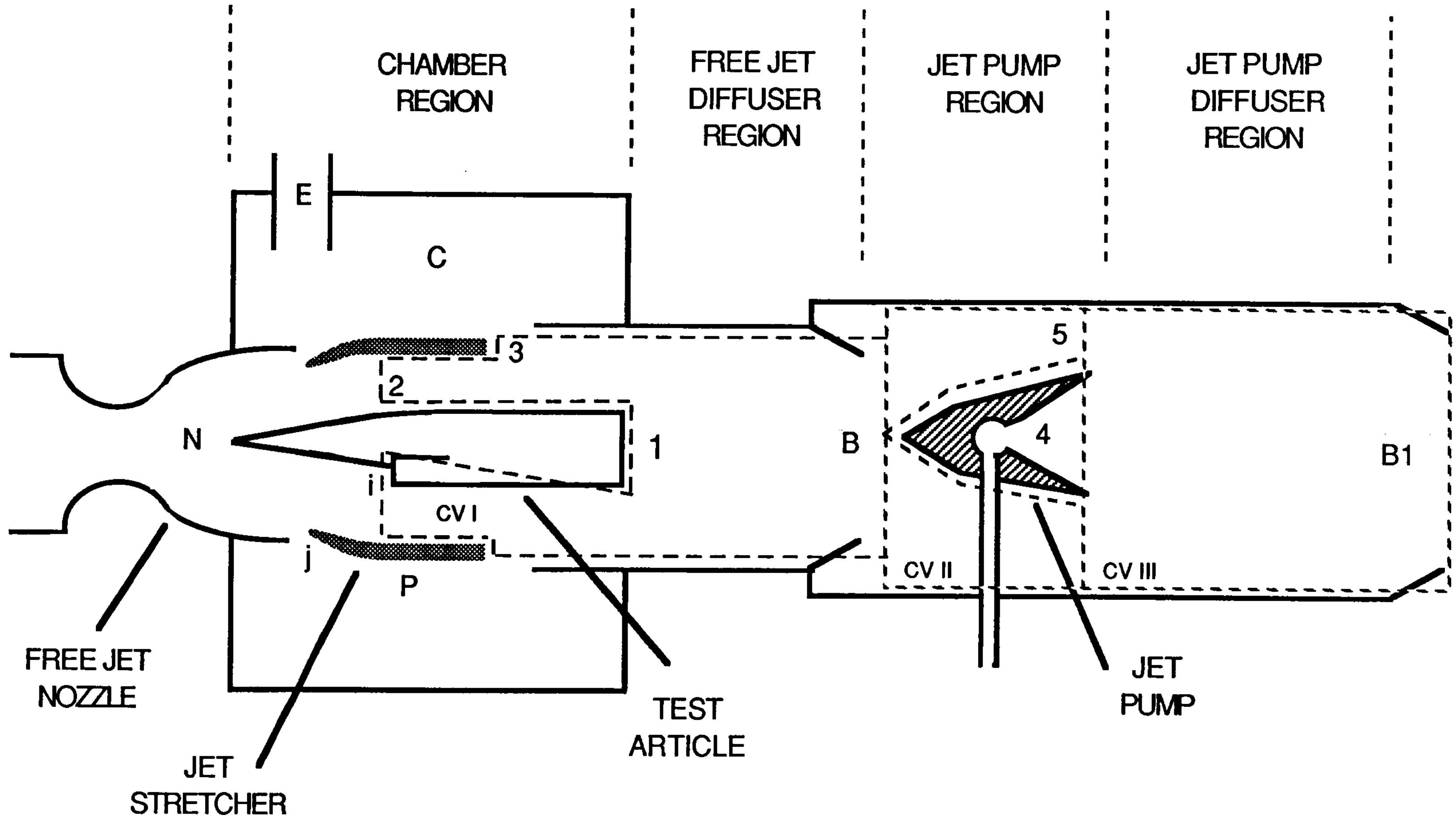

FIGURE 2. Representative Blowdown Test Unit

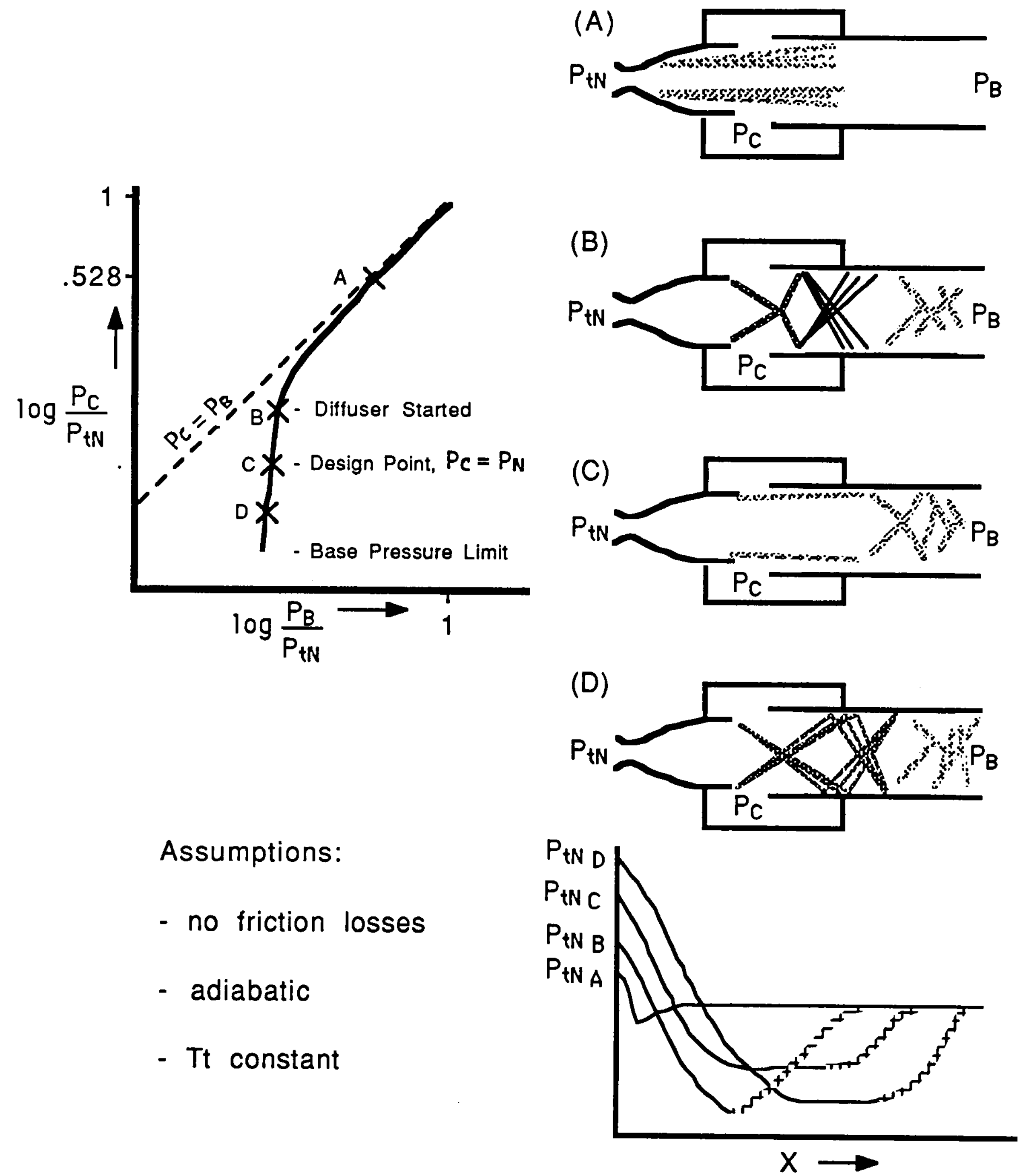

Figure 3. Diffuser Flow Development

```
RESERVOIR & GEOMETRY CONDITIONS

RESERVOIR TOTAL PRESSURE    (PTN)       PSIA, DEFAULT: 100        ?
RESERVOIR TOTAL TEMPERATURE (TTN)      DEG R, DEFAULT: 1500       ?
RESERVOIR SPECIFIC HEAT    (CPN) FT#/SLUG-R, DEFAULT: 6479       ?
RESERVOIR GAMMA             (GAM-N)          , DEFAULT: 1.4         1.36

NOZZLE EXIT MACH NUMBER     (MN)             , DEFAULT: 4          ?
NOZZLE EXIT:  GAMMA         (GAMMA 2)        , DEFAULT: 1.4        ?
NOZZLE EXIT:  SPECIFIC HEAT (CP2/CPN)        , DEFAULT: 1
NOZZLE EXIT:  TEMPERATURE   (TT2/TTN)        , DEFAULT: 1

NOZZLE THROAT AREA          (AN*)      SQ FT, DEFAULT: .024
NOZZLE EXIT AREA            (A2/AN*)         , DEFAULT: 12.5

DIFFUSER THROAT AREA        (AB/AN*)         , DEFAULT: 20.37
DISTANCE BTWN NOZZLE & DIFFUSER (L/DB)       , DEFAULT: .4
(AB/AN)* - (A2/AN*)   =     (A3/AN*)         , DEFAULT: 7.87
ENTER '1' TO ACCEPT DEFAULTS; '0' TO MAKE CHANGESO
```

Figure 4. Sample MENU.EXE Screen for Accepting Input Parameter Changes to the File BAUER.DOC

```
1                                DIFFUSER PROGRAM NO. 2

APTU-II M=4.0 Dn=32°

  INPUT
     PT1/PTN=  .0000E+00     TT1/TTN= 1.0000E+00     CP1/CPN= 1.0000E+00     GAMMA1= 1.3400E+00     A1/AN*= 1.0000E+00
      A1/A1*= 1.0000E+00          KJ= 1.0000E-15          KE=  .0000E+00         KP=  .0000E+00    PT2/PTN= 1.0000E+00
      GAMMA2= 1.3400E+00     A2/AN*= 1.0710E+01      CP2/CPN= 1.0000E+00        CDS=  .0000E+00      L/DB= 1.0000E+00
      AB/AN*= 4.7060E+01     AI/AN*= 1.0000E+00       AS/AN*= 2.4000E+00     GAMMAN= 1.3400E+00    AB1/AN*=  .0000E+00
      PB1/P2= 1.0000E+00    AB2/AN*=  .0000E+00           MN= 3.7800E+00    TT2/TTN= 1.0000E+00    CPP/CPN= 1.0000E+00
     TTP/TTN= 1.0000E+00    CPE/CPN= 1.0000E+00      TTE/TTN= 1.0000E+00     GAMMAP= 1.3400E+00     GAMMAE= 1.3400E+00
     CPJ/CPN= 1.0000E+00    TTJ/TTN= 1.0000E+00       A3/AN*= 3.6350E+01     GAMMAJ= 1.3400E+00    ABE/AN*= 4.7050E+01
       RJ/RN= 8.0000E-01      XJ/RN=-1.0000E+00        DN/RN= 2.0000E-01        PTN= 1.0000E+03     DN*/RN= 2.0000E-01
     AS1/AN*= 1.0000E+00    AB1/AN*= 8.7900E+01       A4/AN*= 3.5642E+01    AB4/AN*= 5.2013E+00     A4/A4*= 2.5000E+01
     AS2/AN*= 1.0000E+00    CP5/CPB= 1.0000E+00        G5/GB= 1.0000E+00    TT5/TTB= 1.0000E+00         G4= 1.3300E+00
     CP4/CPN= 1.0300E+00    TT4/TTN= 1.1800E+00         CDS1=  .0000E+00       CDS2=  .0000E+00    PT4/PTN=-1.0000E+00
         AN*= 4.1720E-01        CPN= 6.7550E+03          TTN= 1.7000E+03         HA=  .0000E+00        HAM=  .0000E+00
          KW= 1.0000E-01        KWS=  .0000E+00           KA= 2.0000E+00    TBA/TTN= 2.0000E+00         KI=  .0000E+00
     A1E/AN*= 8.7900E+01         MT=-1.0000E+00
0 CONSTANT OUTPUT
          C1= 3.8118E-01         C2= 8.4169E-01      CT3/CTN= 1.0000E+00      G3/GN= 1.0000E+00         G3= 1.3400E+00
     CP3/CPN= 1.0000E+00    TT3/TTN= 1.0000E+00        M1/MN=  .0000E+00      M2/MN= 1.0000E+00      M3/MN= 1.0000E-15
       MI/MN= 9.3371E-02          H= 1.0066E+00      CTB/CTN= 7.2133E-01    CPB/CPN= 1.0683E+00    TTB/TTN= 6.7520E-01
       GB/GN= 9.9529E-01         GB= 1.3337E+00      F1/PAN*=  .0000E+00    F2/PAN*= 1.6768E+00    FI/PAN*= 1.5657E-01
     FS/PAN*=  .0000E+00    P2/PT2= 7.7686E-03            M1= 1.0000E+00         M2= 3.7807E+00     PN/PTN= 7.7767E-03
     CP5/CPN= 1.0683E+00         G5= 1.3337E+00      TT5/TTN= 6.7520E-01         C4= 8.8084E-01     P4/PT4= 2.4110E-03
          M4= 4.5806E+00

     PC/PTN       PEX/PTN       P3/P2        PB/PTN       PC/PN        PB/PC         M3           MB

     8.8900E-03   3.7135E-02   1.1443E+00   3.5004E-02   1.1432E+00   3.9376E+00   2.9179E-16   2.9884E-01
     7.7800E-03   3.6224E-02   1.0015E+00   3.4031E-02   1.0004E+00   4.3743E+00   3.3342E-16   3.0722E-01
     6.9250E-03   3.5520E-02   8.9141E-01   3.3277E-02   8.9048E-01   4.8054E+00   3.7458E-16   3.1408E-01
     6.0730E-03   3.4817E-02   7.8174E-01   3.2520E-02   7.8092E-01   5.3550E+00   4.2714E-16   3.2127E-01
     5.2210E-03   3.4111E-02   6.7206E-01   3.1758E-02   6.7136E-01   6.0830E+00   4.9684E-16   3.2884E-01
     4.3690E-03   3.3403E-02   5.6239E-01   3.0991E-02   5.6180E-01   7.0936E+00   5.9373E-16   3.3684E-01
     3.5170E-03   3.2692E-02   4.5272E-01   3.0217E-02   4.5225E-01   8.5921E+00   7.3756E-16   3.4531E-01
     2.6650E-03   3.1979E-02   3.4305E-01   2.9437E-02   3.4269E-01   1.1046E+01   9.7336E-16   3.5428E-01
     1.8130E-03   3.1262E-02   2.3337E-01   2.8649E-02   2.3313E-01   1.5803E+01   1.4308E-15   3.6383E-01
     9.6100E-04   3.0543E-02   1.2370E-01   2.7852E-02   1.2357E-01   2.8984E+01   2.6993E-15   3.7401E-01
     2.9371E-02   5.3596E-02   3.7807E+00   5.2172E-02   3.7768E+00   1.7764E+00   8.8319E-17   2.0131E-01
0  P3/P2 GREATER THAN M2
0 STARTED
     2.9371E-02   5.3596E-02   3.7807E+00   5.2172E-02   3.7768E+00   1.7764E+00   8.8319E-17   2.0131E-01
     PC = 2.9371E+01          PEX = 5.3596E+01          PB = 5.2172E+01
0  STARTING WHEN EXHAUSTING TO ATMOSPHERE
   PC/PTN= 2.9396E-02  PTN1= 2.8739E+02  PN1= 2.2350E+00  ALT= 4.4180E+04  LMN= 2.1944E+02  MB= 2.0116E-01  LMW= 2.1944E+01

0  FAILED TO START WHEN EXHAUSTING TO ATMOSPHERE

0     FOR MBE= 2.75555E-01     PTB/PC= 3.23425E+00     WSC=  .00000E+00
     1.2356E-02   3.9962E-02   1.5905E+00   3.8001E-02   1.5888E+00   3.0756E+00   2.0994E-16   2.7555E-01
```

Figure 5. Sample PRIN6.DOC Output File for the Free Jet Diffuser Produced by BAUER.EXE

```
1                        JET PUMP ADDITIONS TO DIFFUSER PROGRAM NO. 2

APTU-II M=4.0 Dn=32"

  INPUT
      PT1/PTN=  .0000E+00     TT1/TTN= 1.0000E+00     CP1/CPN= 1.0000E+00      GAMMA1= 1.3400E+00      A1/AN*= 1.0000E+00
       A1/A1*= 1.0000E+00          KJ= 1.0000E-15          KE=  .0000E+00          KP=  .0000E+00     PT2/PTN= 1.0000E+00
       GAMMA2= 1.3400E+00      A2/AN*= 1.0710E+01     CP2/CPN= 1.0000E+00         CDS=  .0000E+00        L/DB= 1.0000E+00
       AB/AN*= 4.7060E+01      AI/AN*= 1.0000E+00      AS/AN*= 2.4000E+00      GAMMAN= 1.3400E+00     AB1/AN*=  .0000E+00
       PB1/P2= 1.0000E+00     AB2/AN*=  .0000E+00          MN= 3.7800E+00     TT2/TTN= 1.0000E+00     CPP/CPN= 1.0000E+00
      TTP/TTN= 1.0000E+00     CPE/CPN= 1.0000E+00     TTE/TTN= 1.0000E+00      GAMMAP= 1.3400E+00      GAMMAE= 1.3400E+00
      CPJ/CPN= 1.0000E+00     TTJ/TTN= 1.0000E+00      A3/AN*= 3.6350E+01      GAMMAJ= 1.3400E+00     ABE/AN*= 4.7050E+01
        RJ/RN= 8.0000E-01       XJ/RN=-1.0000E+00       DN/RN= 2.0000E-01         PTN= 1.0000E+03      DN*/RN= 2.0000E-01
      AS1/AN*= 1.0000E+00     AB1/AN*= 8.7900E+01      A4/AN*= 3.5642E+01     AB4/AN*= 5.2013E+00      A4/A4*= 2.5000E+01
      AS2/AN*= 1.0000E+00     CP5/CPB= 1.0000E+00       G5/GB= 1.0000E+00     TT5/TTB= 1.0000E+00          G4= 1.3300E+00
      CP4/CPN= 1.0300E+00     TT4/TTN= 1.1800E+00        CDS1=  .0000E+00        CDS2=  .0000E+00     PT4/PTN=-1.0000E+00
          AN*= 4.1720E-01         CPN= 6.7550E+03         TTN= 1.7000E+03          HA=  .0000E+00         HAM=  .0000E+00
           KW= 1.0000E-01         KWS=  .0000E+00          KA= 2.0000E+00     TBA/TTN= 2.0000E+00          KI=  .0000E+00
      A1E/AN*= 8.7900E+01          MT=-1.0000E+00
0 CONSTANT OUTPUT
           C1= 3.8118E-01          C2= 8.4169E-01     CT3/CTN= 1.0000E+00       G3/GN= 1.0000E+00          G3= 1.3400E+00
      CP3/CPN= 1.0000E+00     TT3/TTN= 1.0000E+00       M1/MN=  .0000E+00       M2/MN= 1.0000E+00       M3/MN= 1.0000E-15
        MI/MN= 9.3371E-02           H= 1.0066E+00     CTB/CTN= 7.2133E-01     CPB/CPN= 1.0683E+00     TTB/TTN= 6.7520E-01
        GB/GN= 9.9529E-01          GB= 1.3337E+00     F1/PAN*=  .0000E+00     F2/PAN*= 1.6768E+00     FI/PAN*= 1.5657E-01
      FS/PAN*=  .0000E+00     P2/PT2= 7.7686E-03           M1= 1.0000E+00          M2= 3.7807E+00      PN/PTN= 7.7767E-03
      CP5/CPN= 1.0683E+00          G5= 1.3337E+00     TT5/TTN= 6.7520E-01          C4= 8.8084E-01      P4/PT4= 2.4110E-03
           M4= 4.5806E+00

  PC/PTN     PB1/PTN    PTB1/PTN   PT4/PTN      K4        M5      MB1     PB1/PB     TTB1/TTN   GB1    PT5/PTB    CB1/CPN   M5S


  8.8900E-03 3.5942E-01 3.9789E-01 1.4522E+01 1.8942E+01  .2987  .3934 1.0268E+01 1.1536E+00 1.3302 1.0002E+00 1.0319E+00  .1558
  7.7800E-03 3.4938E-01 3.8687E-01 1.4119E+01 1.8415E+01  .3071  .3939 1.0266E+01 1.1529E+00 1.3302 1.0002E+00 1.0320E+00  .1598
  6.9250E-03 3.4160E-01 3.7833E-01 1.3806E+01 1.8007E+01  .3140  .3944 1.0265E+01 1.1523E+00 1.3302 1.0002E+00 1.0320E+00  .1631
  6.0730E-03 3.3380E-01 3.6977E-01 1.3492E+01 1.7598E+01  .3211  .3948 1.0264E+01 1.1517E+00 1.3302 1.0002E+00 1.0321E+00  .1665
  5.2210E-03 3.2595E-01 3.6116E-01 1.3176E+01 1.7186E+01  .3287  .3952 1.0263E+01 1.1511E+00 1.3302 1.0002E+00 1.0321E+00  .1701
  4.3690E-03 3.1804E-01 3.5248E-01 1.2858E+01 1.6770E+01  .3367  .3957 1.0262E+01 1.1504E+00 1.3302 1.0002E+00 1.0322E+00  .1738
  3.5170E-03 3.1008E-01 3.4374E-01 1.2537E+01 1.6352E+01  .3452  .3962 1.0261E+01 1.1497E+00 1.3302 1.0002E+00 1.0322E+00  .1777
  2.6650E-03 3.0204E-01 3.3492E-01 1.2213E+01 1.5930E+01  .3541  .3967 1.0260E+01 1.1489E+00 1.3302 1.0002E+00 1.0323E+00  .1818
  1.8130E-03 2.9394E-01 3.2602E-01 1.1886E+01 1.5503E+01  .3637  .3972 1.0260E+01 1.1481E+00 1.3302 1.0002E+00 1.0323E+00  .1862
  9.6100E-04 2.8575E-01 3.1704E-01 1.1556E+01 1.5072E+01  .3738  .3978 1.0259E+01 1.1473E+00 1.3302 1.0002E+00 1.0324E+00  .1908
  2.9371E-02 5.3700E-01 5.9264E-01 2.1645E+01 2.8231E+01  .2012  .3874 1.0293E+01 1.1620E+00 1.3301 1.0002E+00 1.0313E+00  .1071
0 STARTED
  2.9371E-02 5.3700E-01 5.9264E-01 2.1645E+01 2.8231E+01  .2012  .3874 1.0293E+01 1.1620E+00 1.3301 1.0002E+00 1.0313E+00  .1071
  2.9371E+01 5.3700E+02 5.9264E+02 2.1645E+04
0  STARTING WHEN EXHAUSTING TO ATMOSPHERE
  PC/PTN= 2.9396E-02    PTN1= 2.7922E+01     PN1= 2.1714E-01     ALT= 9.2497E+04     LMN= 2.1309E+01     LM4= 6.0182E+02
     LMT= 6.2313E+02   V5/V4= 7.1612E-02     PT4= 6.0460E+02      K4= 2.8243E+01     MB1= 3.8739E-01     M5S= 1.0710E-01
     LMW= 2.1309E+00     FB1= 1.2003E+05      DF= 1.1721E+05      FN= 2.8128E+03
```

Figure 6. Sample PRIN8.DOC Output File for the Jet Pump Addition Produced by BAUER.EXE

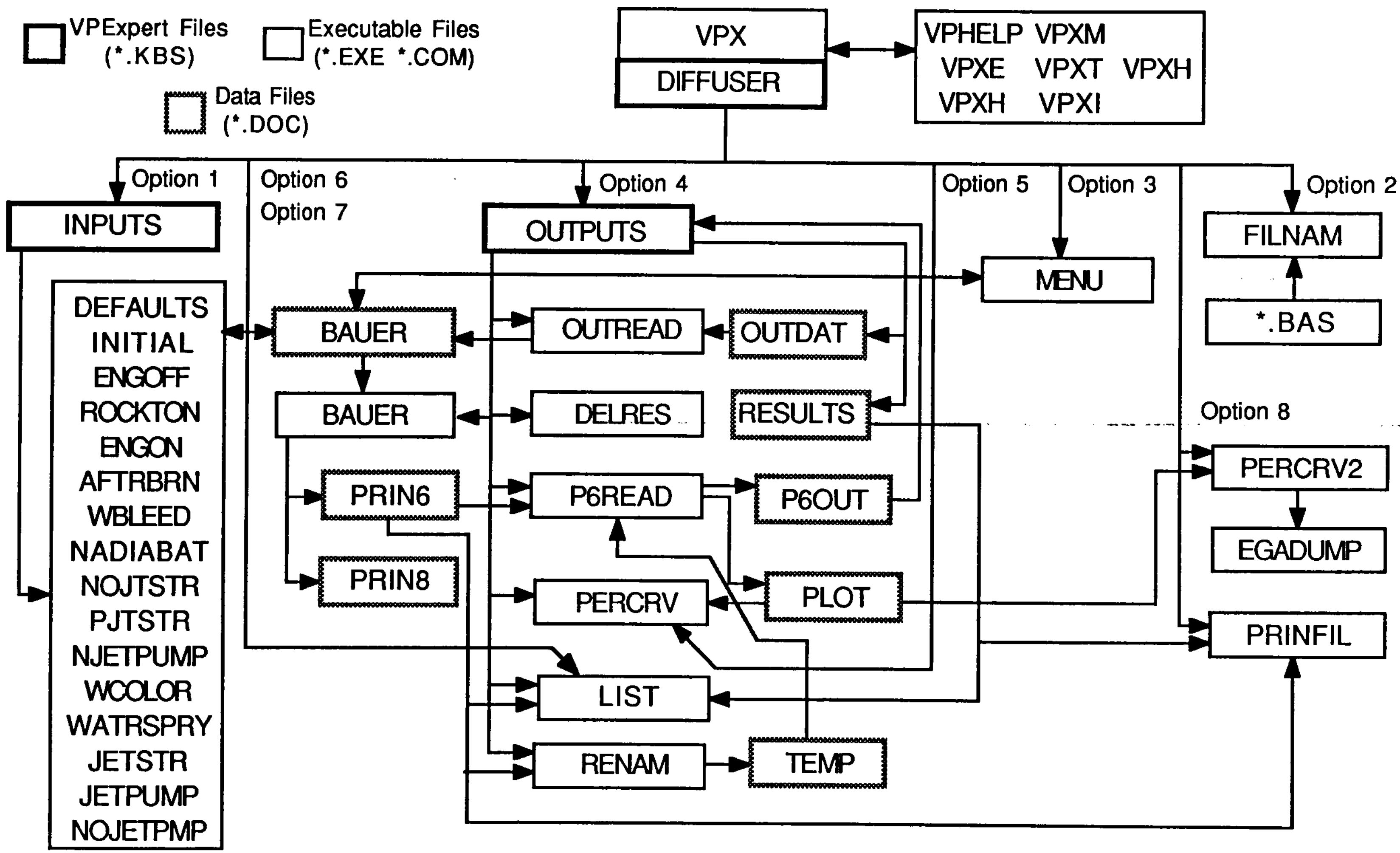

Figure 7. Diffuser Expert System Program Call Chart

VP-Expert Programs

DIFFUSER.KBS	Driver program, displays main menu.
INPUTS.KBS	Assembles inputs.
OUTPUTS.KBS	Interprets outputs.

Executable Programs

AFTRBRN.EXE	Accepts variables for simulating engine afterburn.
BAUER.EXE	Diffuser math model.
BRUN45.EXE	QuickBasic library routines.
DEFAULTS.EXE	Sets variable default values.
DELRES.EXE	Deletes file RESULTS to allow a new one to be built.
EGADUMP.EXE	Library routine that dumps EGA graphics to printer.
ENGOFF.EXE	Sets variable default values for engine not running.
ENGON.EXE	Accepts variables for engine running.
FILNAM.EXE	Renames PRIN6.DOC to TEMP.DOC for retention.
INITIAL.EXE	Accepts values for required input variables.
JETPUMP.EXE	Accepts variables for a jet pump simulation.
JETSTR.EXE	Accepts variables for simulating a jet stretcher.
LIST.COM	Displays ASCII data files on computer screen
MENU.EXE	Original variable input routine provided with BAUER.EXE.
NADIABATIC.EXE	Accepts variables for non-adiabatic flow.
NJETPUMP.EXE	Sets variable defaults for no jet pump.
NOJETPMP.EXE	Sets variable defaults for a non-optimum jet pump.
NOJTSTR.EXE	Sets variable defaults for no jet stretcher.
OUTREAD.EXE	Reads input modifications by OUTPUTS.KBS and corrects BAUER.DOC.

Figure 8. Diffuser Expert System Files

PERCRV.EXE	Produces diffuser performance plot.
PERCRV2.EXE	Produces diffuser performance plot and prints it.
PJTSTR.EXE	Accepts defaults for simulating a porous jetstretcher.
PRINFIL.EXE	Prints RESULTS and PRIN6.DOC.
P6READ.EXE	Reads PRIN6.DOC and reforms for use by OUTPUTS.KBS.
RENAM.EXE	Renames PRIN6.DOC to TEMP.DOC for holding.
ROCKTON.EXE	Accepts variables for when engine is a rocket.
WATRSPRY.EXE	Accepts variables for simulating a cooling waterspray.
WBLEED.EXE	Accepts variables for simulating chamber leaks.
WCOLER.EXE	Accepts variables for simulating a cooler before the jet pump diffuser region.
VPX.EXE	VP-Expert development tool, VPXE, VPXH, VPXM, VPXT, VPXI are supporting files.

Data Files

BAUER.DOC	Input file for BAUER.EXE.
OUTDAT	Output file from OUTPUTS.KBS for modifying BAUER.DOC with OUTREAD.EXE.
PLOT.DOC	Contains data for diffuser performance curve.
PRIN6.DOC	Output file from BAUER.EXE.
PRIN8.DOC	Jet pump output file from BAUER.EXE.
P6OUT	Output file from P6READ.EXE to form readable by OUTPUTS.KBS.
RESULTS	Contains OUTPUTS.KBS analysis results.
TEMP.DOC	Holding file for one copy of PRIN6.DOC.

Figure 8 (con't). Diffuser Expert System Files

```
MENU OPTIONS ARE

                    1 - CREATE NEW DATA FILE FOR INPUTS
                    2 - USE OLD DATA FILE FOR INPUTS
                    3 - QUICK CHANGE OF INPUT DATA
                    4 - RUN DIFFUSER PROGRAM
                    5 - REVIEW PERFORMANCE CURVE
                    6 - REVIEW OUTPUT DATA FILE
                    7 - REVIEW DIFFUSER ANALYSIS
                    8 - PRINT REPORT
                    X - EXIT CONSULTATION

                  PICK AN OPTION
1                        2                        3
4                        5                        6
7                        8                        X
```

Figure 9. Sample of the Main Menu for the Diffuser Expert System

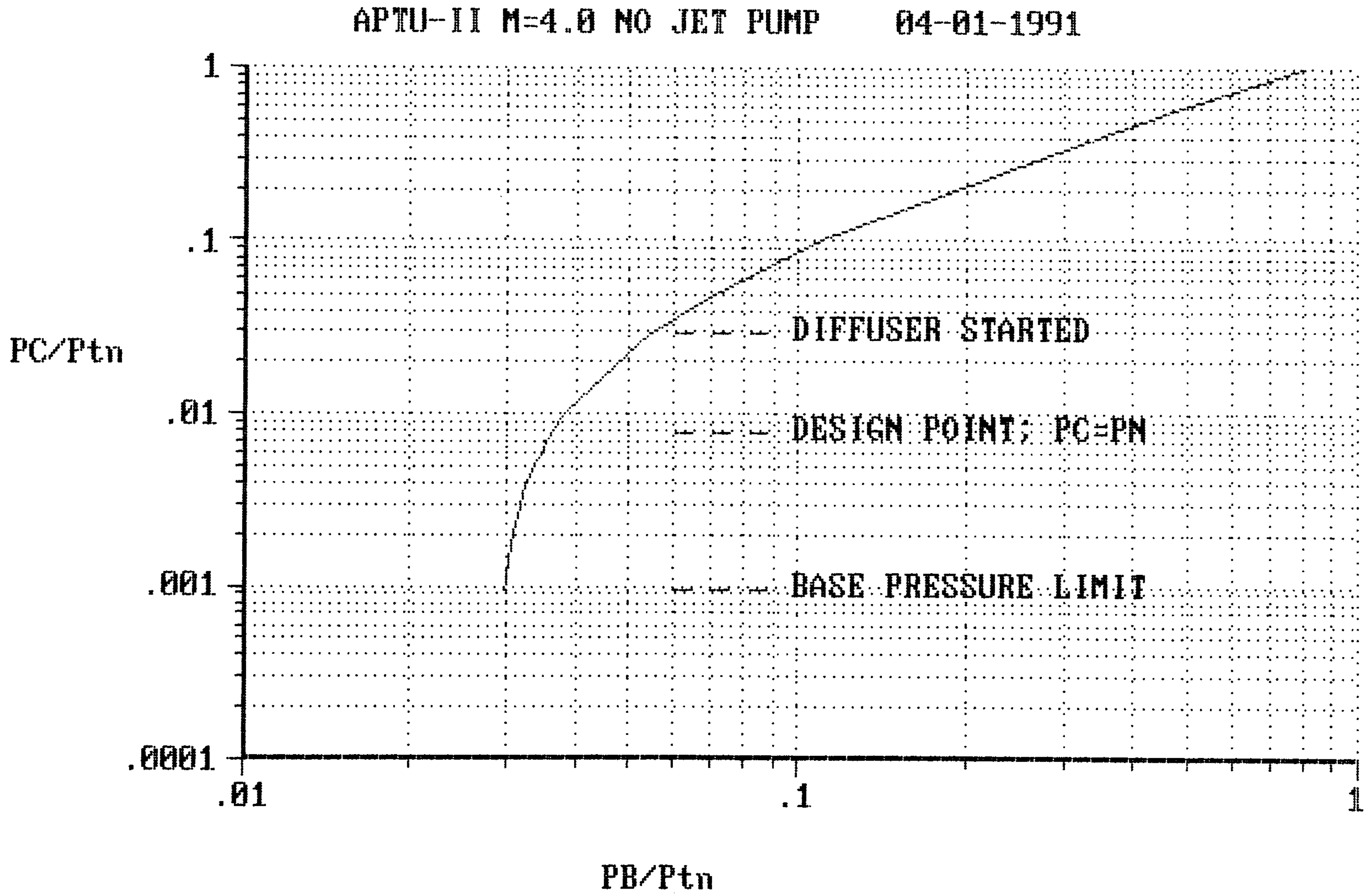

Figure 10. Sample of a Diffuser Performance Curve

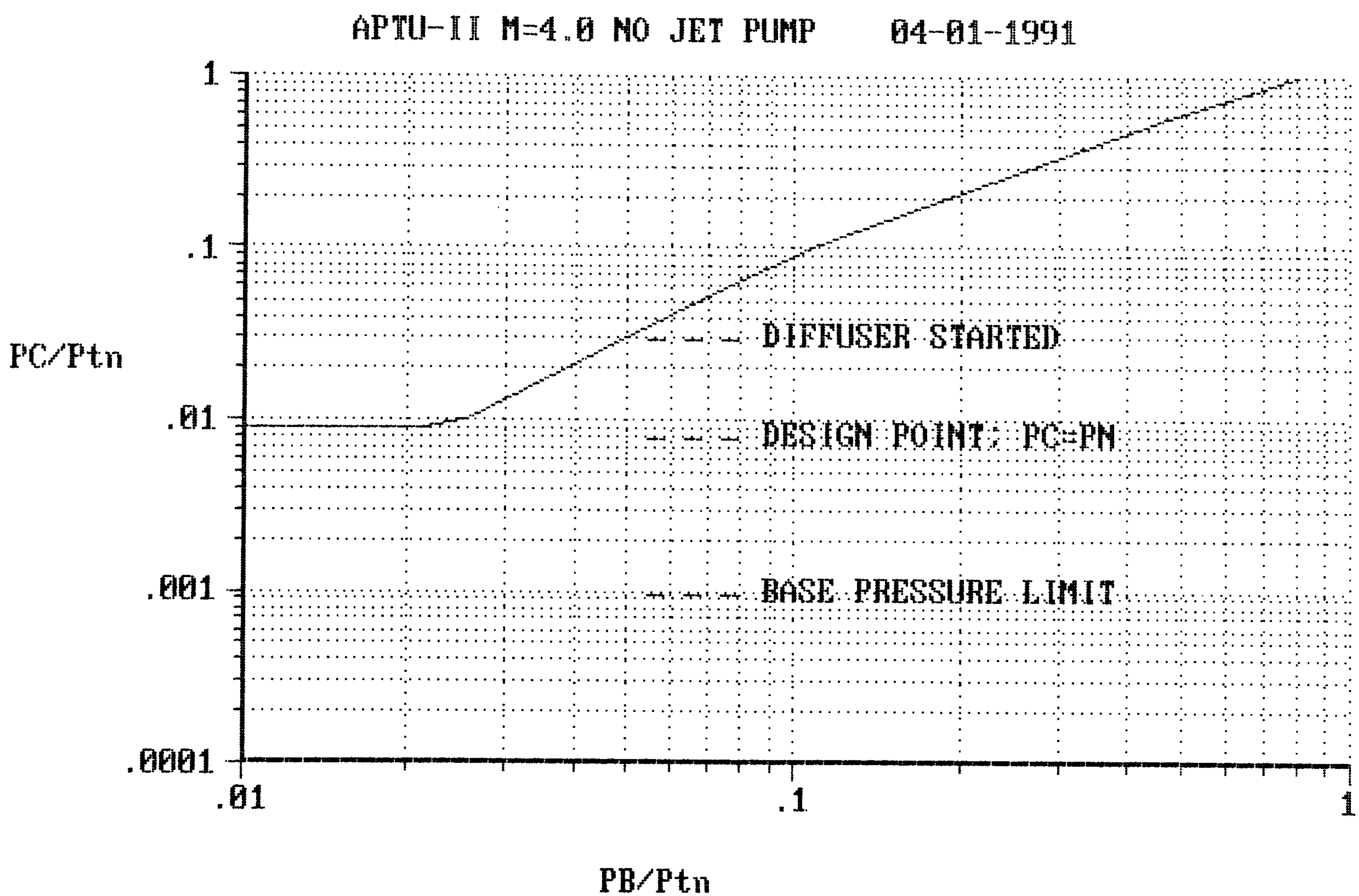

Figure 11. Sample of a Diffuser Performance Curve Showing a Choked Diffuser

THE SATURATED WATER SPRAY FLOW; ZKWS=0.299010
THE SUGGESTED CHAMBER PRESSURE RATIOS ARE
PC/PTN[1]=1
PC/PTN[2]=0.775000
PC/PTN[3]=0.550000
PC/PTN[4]=0.325000
PC/PTN[5]=.1
PC/PTN[6]=0.082000
PC/PTN[7]=0.064000
PC/PTN[8]=0.046000
PC/PTN[9]=0.028000
PC/PTN[10]=.01"
PC/PTN[11]=0.008888
PC/PTN[12]=0.007777
PC/PTN[13]=0.006925
PC/PTN[14]=0.006073
PC/PTN[15]=0.005221
PC/PTN[16]=0.004369
PC/PTN[17]=0.003517
PC/PTN[18]=0.002665
PC/PTN[19]=0.001813
PC/PTN[20]=0.000961
AN/AN* = 47.131207, ZRATIO=1.001513"

DIFFUSER ANALYSIS

The diffuser performance curve is along the PC=PB line in the
diffuser started region. This shows a diffuser with a poor
pumpdown of the chamber. SLOPE = 0.525586
The diffuser flow has started and is flowing full

Most testing should be done around the diffuser started chamber pressure of
PC/PTN= 0.0293. In this region of the performance curve the test rhombus
is shortened, but the diffuser will operate with the smallest value of PTN
for a constant PB.

The diffuser will operate in the started conditions while exhausting
to atmousphere at:

PTN = 278.83 psia PB = 15 psia MB = 0.229 PN = 2.168 psia
Simulated Altitude = 44811 Ft

The Nozzle will operate at it's design point (PC=PN) at: PC/PTN=0.007777

The diffuser has choked for the following reasons:
- Diffuser choking at exit (MB=1.0), diffuser minimum area
ABE/AN* = 26.00 is less than the diffuser area AB/AN* = 47.06.
The reduction in area can cause the diffuser to choke.
- Diffuser choking at exit (MB=1.0), the model drag is too large;
Either the diffuser area must be increased or the model size decreased.
Either the diffuser area must be increased or the model size decreased.

Figure 12. Sample of the RESULTS File Produced by the Diffuser Expert System

APPENDIX B

DIFFUSER PERFORMANCE PROGRAM

VARIABLE DEFINITIONS

Variable	Definition	Program Name	Units
A_1/A_1^*	Area ratio test body engine nozzle	A1/A1*	
A_1/A_N^*	Nondimensional area of test body engine exit	A1/AN*	
A_{B1E}/A_N^*	Nondimensional minimum area of the jet pump diffuser exit	A1E/AN*	
A_2/A_N^*	Nondimensional area between test body and jet stretcher at the engine inlet. Nozzle exit area if there is no jet stretcher.	A2/AN*	
A_3/A_N^*	Nondimensional area of gap between jet stretcher and diffuser	A3/AN*	
A_4/A_4^*	Area ratio jet pump nozzle	A4/A4*	
A_4/A_N^*	Nondimensional area of jet pump nozzle exit	A4/AN*	

Variable	Definition	Program Name	Units
A_B / A_N^*	Nondimensional area of free jet diffuser exit	AB/AN*	
A_{B1} / A_N^*	Nondimensional area of the jet pump diffuser exit	AB1/AN*	
A_{b1} / A_N^*	Nondimensional area of test article base	AB1/AN* (repeated)	
A_{b2} / A_N^*	Nondimensional area of jet stretcher base	AB2/AN*	
A_{b4} / A_N^*	Nondimensional area of jet pump nozzle base	AB4/AN*	
A_{BE} / A_N^*	Nondimensional minimum area of the free jet diffuser exit	ABE/AN*	
A_i / A_N^*	Nondimensional area of test article engine inlet	AI/AN*	

Variable	Definition	Program Name	Units
ALT	Altitude simulated in test cell based on the Standard Atmosphere and using PN1	ALT	ft
A_{N^*}	Free jet nozzle throat area	AN*	ft^2
A_S / A_N^*	Nondimensional reference area of free jet diffuser surface, model, and support	AS/AN*	
A_{S1} / A_N^*	Nondimensional reference area of jet pump region surface	AS1/AN*	
A_{S2} / A_N^*	Nondimensional reference area of jet pump diffuser surface	AS2/AN*	
C_1	Crocco number at test article engine exit (Egn. 2. Appendix C)	C1	
C_2	Crocco number at region 2 between model and jet stretcher (Eqn. 3 App. C)	C2	

Variable	Definition	Program Name	Units
C_4	Crocco number of jet pump flow (Eqn. 44 App. C)	C4	
C_{PB1}/C_{PN}	Nondimensional specific heat at the jet pump diffuser exit (Eqn. 64 App. C)	CB1/CPN	
C_{DS}	Drag coefficient of free jet diffuser surface, model, and support	CDS	
C_{DS1}	Drag coefficent of jet pump region	CDS1	
C_{DS2}	Drag coefficient of jet pump diffuser surface	CDS2	
C_{P1}/C_{PN}	Nondimensional specific heat at test article engine exit	CP1/CPN	
C_{P2}/C_{PN}	Nondimensional specific heat region between test article body and jet stretcher	CP2/CPN	

Variable	Definition	Program Name	Units
C_{P3}/C_{PN}	Nondimensional specific heat at jet stretcher gap (Eqn. 7 App. C)	CP3/CPN	
C_{P4}/C_{PN}	Nondimensional specific heat jet pump reservoir	CP4/CPN	
C_{P5}/C_{PB}	Specific heat jet pump diffuser divided by Specific heat free jet diff. exit (set to zero for no jet pump printout)	CP5/CPB	
C_{P5}/C_{PN}	Nondimensional specific heat jet pump region (Eqn. 43 App. C)	CP5/CPN	
C_{PB}/C_{PN}	Nondimensional specific heat at the free jet diffuser exit (Eqn. 16 App. C)	CPB/CPN	
C_{PE}/C_{PN}	Nondimensional specific heat of the external bleed flow	CPE/CPN	
C_{Pj}/C_{PN}	Nondimensional specific heat at radial gap between nozzle exit and jet stretcher inlet	CPJ/CPN	

Variable	Definition	Program Name	Units
C_{PN}	Nozzle reservoir specific heat at constant pressure	CPN	ft-lb/slug-°R
C_{PP}/C_{PN}	Nondimensional specific heat of flow through the jet stretcher porous wall	CPP/CPN	
$\frac{C_{P3}\,T_{t3}}{C_{PN}\,T_{tN}}$	Nondimensional total enthalpy at the diffuser gap (Eqn. 4 App. C)	CT3/CTN	
$\frac{C_{PB}\,T_{tB}}{C_{PN}\,T_{tN}}$	Nondimensional total enthalpy at the free jet diffuser exit (Eqn. 15 App. C)	CTB/CTN	
D_B	Free jet diffuser exit diameter	DB	ft
DF	Thrust difference between jet pump diffuser exit and free jet nozzle (Eqn. 78 App. C)	DF	lbf
δ^*_N/r_N	Boundary layer displacement thickness of free jet nozzle/ radius free jet nozzle exit	DN*/RN	

Variable	Definition	Program Name	Units
δ_N / r_N	Total boundary layer thickness at free jet nozzle exit/ radius free jet nozzle exit	DN/RN	
$F_1 / P_{tN} A_N^*$	Nondimensional flow momentum at test article engine exit (Eqn. 20 App. C)	F1/PAN*	
$F_2 / P_{tN} A_N^*$	Nondimensional flow momentum in the region between the test article and jet stretcher (Eqn. 21 App. C)	F2/PAN*	
F_{B1}	Flow momentum at jet pump diffuser exit for the case where the diffuser is exhausting to atmosphere (Eqn. 76 App. C)	FB1	lbf
$F_i / P_{tN} A_N^*$	Nondimensional flow momentum at the test article engine inlet (Eqn. 23 App. C)	FI/PAN*	
F_N	Flow momentum at free jet nozzle exit for the case where the diffuser is exhausting to atmosphere (Eqn. 77 App. C)	FN	lbf
$F_S / P_{tN} A_N^*$	Nondimensional friction momentum (drag) for the free jet diffuser (Eqn. 24 App. C)	FS/PAN*	

Variable	Definition	Program Name	Units
γ_3	Specific heat ratio at the gap between the jet stretcher exit and the free jet diffuser inlet (Eqn. 6 App. C)	G3	
γ_3/γ_N	Specific heat ratio at the jet stretcher gap divided by the nozzle specific heat ratio (Eqn. 5 App. C)	G3/GN	
γ_4	Specific heat ratio of jet pump reservoir	G4	
γ_5	Specific heat ratio in the jet pump region (Eqn. 44 App. C)	G5	
γ_5/γ_B	Specific heat ratio for the jet pump region flow/ specific heat ratio for the free jet diffuser exit region	G5/GB	
γ_1	Specific heat ratio at test article engine exit	GAMMA1	
γ_2	Specific heat ratio for the region between test body and jet stretcher	GAMMA2	

Variable	Definition	Program Name	Units
γ_E	Specific heat ratio of external bleed flow	GAMMAE	
γ_j	Specific heat ratio for the gap between nozzle exit and jet stretcher inlet	GAMMAJ	
γ_N	Specific heat ratio for the free jet nozzle reservoir	GAMMAN	
γ_P	Specific heat ratio for jet stretcher porous wall flow	GAMMAP	
γ_B	Specific heat ratio for the free jet diffuser exit region (Eqn. 19 App. C)	GB	
γ_{B1}	Specific heat ratio at jet pump diffuser exit (Eqn. 66 App. C)	GB1	
γ_B/γ_N	Specific heat ratio for the free jet diffuser exit divided by the free jet nozzle reservoir specific heat (Eqn. 18 App. C)	GBOGN	

Variable	Definition	Program Name	Units
H	Nondimensional mass flow sum of control volume 1 (Eqn. 14 App. C)	H	
h_A	Afterburning energy released per slug of engine exhaust divided by Cp and Tt of the nozzle reservoir.	HA	
h_{AM}	Nondimensional maximum heat released for fuel afterburning limited by amount of oxygen available	HAM	
$\frac{m_4}{m_N}$	Mass flow from jet pump divided by free jet nozzle mass flow (Eqn. 61 App. C)	K4	
k_A	Value of M1/MN at which all oxygen in MN (nozzle flow) is consumed by afterburn of the fuel in M1 (engine flow)	KA	
k_E	Ratio of mass flow external bleed to nozzle mass flow	KE	
k_i	Fraction of engine mass flow bled from engine inlet before entering combustion chamber	KI	

Variable	Definition	Program Name	Units
k_j	Ratio of jet stretcher gap mass flow (reintroduced at area 3) to free jet nozzle mass flow (Eqn. 1 App. C)	KJ	
k_P	Ratio of jet stretcher porous wall mass flow to free jet nozzle mass flow	KP	
k_W	Ratio of water spray mass flow to free jet nozzle mass flow (if set to -1 KWS is calculated by program)	KW	
k_{WS}	Saturated ratio of water spray mass flow to free jet nozzle mass flow (Eqn. 17 App. C)	KWS	
L/D_B	Distance from jet strecher to free jet diffuser/Diameter of free jet diffuser	L/DB	
m_4	Mass flow leaving the jet pump nozzle for the case of the diffuser exhausting to atmosphere (Eqn. 82 App. B)	LM4	lbm/sec
m_N	Mass flow leaving the free jet nozzle for the case of the diffuser exhausting to atmosphere (Eqn. 81 App. C)	LMN	lbm/sec

Variable	Definition	Program Name	Units
m_T	Total mass flow through diffuser calculated by Diffuser Performance Program (Eqn. 84 App. C)	LMT	lbm/sec
m_W	Water spray mass flow for the case of the diffuser exhausting to atmosphere (Eqn. 83 App. C)	LMW	lbm/sec
M_1	Mach number engine exit (Eqn. 30 App. C)	M1	
m_1/m_N	Nondimensional mass flow at the test article engine exit (Eqn. 10 App. C)	M1/MN	
M_2	Mach number at area A2 between test article and jet stretcher or nozzle exit Mach number if there is no jet stretcher (Equation 31 App. C)	M2	
m_2/m_N	Mass flow area between test article and jet stretcher/ free jet nozzle mass flow (Eqn. 11 App. C)	M2/MN	
M_3	Mach number at gap between jet stretcher and free jet diffuser (Eqn. 32 App. C)	M3	

Variable	Definition	Program Name	Units
m_3/m_N	Mass flow jet stretcher gap/ free jet nozzle mass flow (Eqn. 12 App. C)	M3/MN	
M_4	Mach number of flow leaving jet pump (Eqn. 48 App. C)	M4	
M_5	Mach number of flow in jet pump region (Eqn. 74 App. C)	M5	
M_{5S}	Drag area (AS1) corrected Mach number at region 5 in the jet pump diffuser (Eqn. 89 App. C)	M5S	
M_B	Mach number free jet diffuser exit (Eqn. 34 App. C)	MB	
M_{B1}	Mach number jet pump diffuser exit (Eqn. 75 App. C)	MB1	
m_i/m_N	Mass flow test article engine inlet/ free jet nozzle mass flow (Eqn. 13 App. C)	MI/MN	

Variable	Definition	Program Name	Units
M_N	Free jet nozzle exit Mach number	MN	
m_{TOTAL}	Total mass flow (set to -1 forces Diffuser Performance Program to calculate)	MT	lbm/sec
P_2/P_{t2}	Pressure area between test article and jet stretcher / total pressure of same (Eqn. 25 App. C)	P2/PT2	
P_3/P_2	Jet stretcher gap pressure/ Pressure area between test article and jet stretcher (Eqn. 41 App. C)	P3/P2	
P_4/P_{t4}	Pressure at jet pump exit/total pressure of same (Eqn. 47 App. C)	P4/PT4	
P_B/P_C	Pressure free jet diffuser exit/ Pressure chamber (Eqn. 42 App. C)	PB/PC	
P_B/P_{tN}	Nondimensional pressure free jet diffuser exit (Eqn. 36 App. C)	PB/PTN	

Variable	Definition	Program Name	Units
P_{b1}/P_2	Pressure test article engine base/Pressure region between test body and jet stretcher	PB1/P2	
P_{B1}/P_B	Pressure jet pump diffuser exit/ Pressure free jet diffuser exit (Eqn. 73 App. C)	PB1/PB	
P_{B1}/P_{tN}	Pressure jet pump diffuser exit/ Free jet nozzle reservoir total pressure (Eqn. 72 App. C)	PB1/PTN	
P_C/P_N	Pressure chamber/ Pressure free jet nozzle exit (Eqn. 38 App. C)	PC/PN	
P_C/P_{tN}	Non-dimensional test cell pressures	PC/PTN	
P_{tB}/P_{tN}	Nondimensional total pressure free jet diffuser exit (Eqn. 35, 36 App. C)	PEX/PTN	
P_N/P_{tN}	Free jet nozzle pressure ratio (Eqn. 37 App. C)	PN/PTN	

Variable	Definition	Program Name	Units
P_{N1}	Free jet nozzle exit pressure for solution where diffuser is exhausting to atmospheres (Eqn. 80 App. C)	PN1	psia
P_{t1}/P_{tN}	Nondimensional total pressure engine exit	PT1/PTN	
P_{t2}/P_{tN}	Nondimensional total pressure between test body and jet stretcher	PT2/PTN	
P_{t4}	Total pressure of the jet pump reservoir for the case where the diffuser is exhausting to atmosphere (Eqn. 86 App. C)	PT4	psia
P_{t4}/P_{tN}	Nondimensional total pressure of jet pump reservoir (if set to -1 program will calculate optimum, P5=P4) (Eqn. 55, 56 App. C)	PT4/PTN	
P_{t5}/P_{tB}	Total pressure jet pump region/ Total pressure free jet diffuser exit (Eqn. 57 App. C)	PT5/PTB	
P_{tB1}/P_{tN}	Nondimensional total prssure jet pump diffuser exit (Eqn. 70 App. C)	PTB1/PTN	

Variable	Definition	Program Name	Units
P_{tN}	Free jet nozzle reservoir total pressure	PTN	psia
P_{tN1}	Free jet nozzle reservoir total pressure (PtN) for case where diffuser is exhausting to atmosphere (Eqn. 79 App. C)	PTNI	psia
r_j/r_N	Radius of jet stretcher inlet/Radius of free jet nozzle exit	RJ/RN	
r_N	Radius free jet nozzle exit	RN	
T_{tBA}/T_{tN}	Nondimensional maximum temperature due to fuel afterburning	TBA/TTN	
T_{t1}/T_{tN}	Nondimensional total temperature at test article engine exit	TT1/TTN	
T_{t2}/T_{tN}	Nondimensional total temperature between test body and jet stretcher	TT2/TTN	

Variable	Definition	Program Name	Units
T_{t3}/T_{tN}	Nondimensional total temperature gap between jet stretcher and free jet diffuser (Eqn. 8 App. C)	TT3/TTN	
T_{t4}/T_{tN}	Nondimensional jet pump reservoir total temperature	TT4/TTN	
T_{t5}/T_{tB}	Total temperature jet pump region/total temperature free jet diffuser exit	TT5/TTB	
T_{t5}/T_{tN}	Nondimensional total temperature jet pump region (Eqn. 45 App. C)	TT5/TTN	
T_{tB}/T_{tN}	Nondimensional total temperature at free jet diffuser exit (Eqn. 17 App. C)	TTB/TTN	
T_{tB1}/T_{tN}	Nondimensional total temperature jet pump diffuser exit (Eqn. 68 App. C)	TTB1/TTN	
T_{tE}/T_{tN}	Nondimensional total temperature external bleed flow	TTE/TTN	

Variable	Definition	Program Name	Units
T_{tj}/T_{tN}	Nondimensional total temperature radial gap between free jet nozzle exit and jet strecher inlet	TTJ/TTN	
T_{tN}	Free jet nozzle reservoir total temperature	TTN	°R
T_{tP}/T_{tN}	Nondimensional total temperature of flow through jet strecher porous wall	TTP/TTN	
V_5/V_4	Flow velocity in jet pump region/flow velocity of jet pump plume (Needs to be small for jet pump to work) (Eqn. 85 App. C)	V5/V4	
X_j/r_N	Linear distance from free jet nozzle exit to jet stretcher inlet/ radius free jet nozzle exit	XJ/RN	

APPENDIX C

DIFFUSER PERFORMANCE PROGRAM

EQUATIONS

The conservation laws were applied based on the following assumptions (References 2, 3 and 4):

- The test body is at zero angle of attack.
- The test facility nozzle provides one-dimensional supersonic flow approaching the test vehicle.
- The test body engine inlets are located at least 5 body diameters from the nose, therefore, the flow conditions on the control volume surface 2 are one-dimensional.
- The bow shock wave from the test vehicle falls outside the facility nozzle exit, therefore, the total stream thrust on surface 2 equals the total stream thrust that would exist at the nozzle exit plane without the presence of the test vehicle.
- The test body engine exhaust is one-dimensional.
- For a typical test body, the jet stretcher is cylindrical beyond the engine inlets.
- The flow conditions over surface 3 of the control volume are one-dimensional.
- The cylindrical diffuser is of sufficient length to allow complete mixing; therefore, the flow conditions at the diffuser exit (surface B of the control volume) are one-dimensional.
- All the gases are perfect.
- The flow field within the chamber is the low velocity recirculating type; therefore, the chamber pressure, P_C,

is the total pressure of the flow on surface 3 of the control volume.

- There are no regions of flow separation in the nozzle or jet stretcher.

The diffuser performance equations are developed in terms of Crocco number (C) instead of Mach number. Crocco number is defined by:

$$C^2 = \frac{V^2}{2\, C_P\, T_t}$$

and is related to the Mach number by:

$$M = \left(\frac{2}{\gamma - 1}\right)^{1/2} \frac{C}{\left(1 - C^2\right)^{1/2}}$$

The Crocco number has an upper limit of one. It was used as an equation basis because it is based on stagnation temperature, not static temperature as is Mach number. Stagnation temperature is easier to calculate than static temperature, and it does not change unless the flow is nonadiabatic.

Determine k_j from:

$$K_j = 1 - \frac{\left(\frac{r_j}{r_N}\right)^2}{\left(1 - \frac{\delta_N^*}{r_N}\right)^2} \tag{1}$$

Determine the maximum positive value of C_1 from:

$$\left(1 - C_1^2\right)^{\frac{1}{\gamma_1 - 1}} C_1 = \frac{A_1^*}{A_1}\left(\frac{2}{\gamma_1 + 1}\right)^{\frac{1}{\gamma_1 - 1}} \left[\frac{\gamma_1 - 1}{\gamma_1 + 1}\right]^{1/2} \tag{2}$$

Determine the maximum positive value of C_2 from:

$$\left(1 - C_2^2\right)^{\frac{1}{\gamma_2 - 1}} C_2 = \left(\frac{P_{tN}}{P_{t2}}\right)\left(\frac{A_N^*}{A_2}\right)\sqrt{\left(\frac{C_{p2}}{C_{pN}}\right)\left(\frac{T_{t2}}{T_{tN}}\right)} \left(\frac{\gamma_2 - 1}{\gamma_2}\right) \cdots$$

$$\left[\frac{\gamma_N}{\left(\gamma_N^2 - 1\right)^{1/2}}\right]\left(\frac{2}{\gamma_N + 1}\right)^{\frac{1}{\gamma_N - 1}} \left[1 - k_j - k_P\right] \tag{3}$$

Determine $\left(\frac{C_{P3}\, T_{t3}}{C_{PN}\, T_{tN}}\right)$ from:

$$\left(\frac{C_{P3}\, T_{t3}}{C_{PN}\, T_{tN}}\right) = \frac{k_j\left(\frac{C_{Pj}}{C_{PN}}\right)\left(\frac{T_{tj}}{T_{tN}}\right) + \left(\frac{C_{PP}}{C_{PN}}\right)\left(\frac{T_{tP}}{T_{tN}}\right)\left[\frac{k_P + |k_P|}{2}\right] + \left(\frac{C_{PE}}{C_{PN}}\right)\left(\frac{T_{tE}}{T_{tN}}\right)\left[\frac{k_E + |k_E|}{2}\right]}{k_j + \left[\frac{k_P + |k_P|}{2}\right] + \left[\frac{k_E + |k_E|}{2}\right]} \tag{4}$$

Determine $\left(\frac{\gamma_3}{\gamma_N}\right)$ from:

$$\left(\frac{\gamma_3}{\gamma_N}\right) = \frac{k_j\left(\frac{C_{Pj}}{C_{PN}}\right) + \left(\frac{C_{PP}}{C_{PN}}\right)\left[\frac{k_P + |k_P|}{2}\right] + \left(\frac{C_{PE}}{C_{PN}}\right)\left[\frac{k_E + |k_E|}{2}\right]}{k_j\left(\frac{C_{Pj}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_j}\right) + \left(\frac{C_{PP}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_P}\right)\left[\frac{k_P + |k_P|}{2}\right] + \left(\frac{C_{PE}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_E}\right)\left[\frac{k_E + |k_E|}{2}\right]} \quad (5)$$

Determine γ_3 from:

$$\gamma_3 = \left(\frac{\gamma_3}{\gamma_N}\right)\gamma_N \quad (6)$$

Determine $\frac{C_{P3}}{C_{PN}}$ from:

$$\frac{C_{P3}}{C_{PN}} = \frac{k_j\left(\frac{C_{Pj}}{C_{PN}}\right) + \left(\frac{C_{PP}}{C_{PN}}\right)\left[\frac{k_P + |k_P|}{2}\right] + \left(\frac{C_{PE}}{C_{PN}}\right)\left[\frac{k_E + |k_E|}{2}\right]}{k_j + \left[\frac{k_P + |k_P|}{2}\right] + \left[\frac{k_E + |k_E|}{2}\right]} \quad (7)$$

Determine $\frac{T_{t3}}{T_{tN}}$ from:

$$\frac{T_{t3}}{T_{tN}} = \frac{\left(\frac{C_{P3}\,T_{t3}}{C_{PN}\,T_{tN}}\right)}{\left(\frac{C_{P3}}{C_{PN}}\right)} \quad (8)$$

Determine the maximum positive value of C_3 from:

$$\left(1-C_3^2\right)^{\frac{1}{\gamma_3-1}} C_3 = \left(\frac{P_{tN}}{P_C}\right)\left[\frac{A_N^*}{A_3+4\left(\frac{L}{D_B}\right)A_B}\right]\sqrt{\left(\frac{C_{p3}}{C_{pN}}\right)\left(\frac{T_{t3}}{T_{tN}}\right)} \ \ldots$$

$$\left(\frac{\gamma_3-1}{\gamma_3}\right)\left[\frac{\gamma_N}{\left(\gamma_N^2-1\right)^{1/2}}\right]\left(\frac{2}{\gamma_N+1}\right)^{\frac{1}{\gamma_N-1}}\left[k_j+k_E+k_P\right] \quad (9)$$

Determine $\frac{m_1}{m_N}$ from:

$$\frac{m_1}{m_N} = \frac{\left(\frac{P_{t1}}{P_{tN}}\right)\left(\frac{A_1^*}{A_N^*}\right)}{\sqrt{\left(\frac{C_{p1}}{C_{pN}}\right)\left(\frac{T_{t1}}{T_{tN}}\right)}}\left(\frac{\gamma_N+1}{2}\right)^{\frac{1}{\gamma_N-1}}\left(\frac{2}{\gamma_1+1}\right)^{\frac{1}{\gamma_1-1}}\left[\frac{\gamma_N^2-1}{\gamma_1^2-1}\right]^{1/2}\left(\frac{\gamma_1}{\gamma_N}\right) \quad (10)$$

Determine $\frac{m_2}{m_N}$ from:

$$\frac{m_2}{m_N} = 1 - k_j - k_P \quad (11)$$

Determine $\frac{m_3}{m_N}$ from:

$$\frac{m_3}{m_N} = k_j + k_E + k_P \quad (12)$$

Determine $\frac{m_i}{m_N}$ from:

$$\frac{m_i}{m_N} = \left(1-k_j-k_P\right)\left(\frac{A_i}{A_N^*}\right)\left(\frac{A_N^*}{A_2}\right) \quad (13)$$

Determine H from:

$$\mathbf{H} = \frac{m_1}{m_N} - \frac{m_i}{m_N} + \frac{m_2}{m_N} + \frac{m_3}{m_N} + k_W + k_i \frac{m_i}{m_N} \tag{14}$$

Determine h_{AM} by:

For $\frac{m_1}{m_N} \geq k_A$ (lack of oxygen)

$$h_{AM} = \frac{K_A \, h_A}{\left(\frac{m_1}{m_N}\right)}$$

For $\frac{m_1}{m_N} < k_A$ (excess oxygen)

$$h_{AM} = h_A$$

If calculated $\frac{T_{tB}}{T_{tN}} \leq \frac{T_{tBA}}{T_{tN}}$ then use h_{AM}

If calculated $\frac{T_{tB}}{T_{tN}} > \frac{T_{tBA}}{T_{tN}}$ then determine

h_{AM} for $\frac{T_{tB}}{T_{tN}} = \frac{T_{tBA}}{T_{tN}}$

Determine $\left(\frac{C_{PB}\, T_{tB}}{C_{PN}\, T_{tN}}\right)$ from:

$$\left(\frac{C_{PB}\, T_{tB}}{C_{PN}\, T_{tN}}\right) = \frac{\frac{m_1}{m_N}\left(\frac{C_{P1} T_{t1}}{C_{PN} T_{tN}}\right) + \left[\frac{m_2}{m_N} - \frac{m_i}{m_N}\right]\left(\frac{C_{P2} T_{t2}}{C_{PN} T_{tN}}\right) + \left(\frac{C_{P3} T_{t3}}{C_{PN} T_{tN}}\right)\left(\frac{m_3}{m_N}\right)}{\mathrm{H}}$$

$$+ \frac{\frac{m_1}{m_N} h_{AM} + \left(\frac{m_i}{m_N}\right) k_i \left(\frac{C_{P2} T_{t2}}{C_{PN} T_{tN}}\right) + k_W \left[\frac{2.073 \times 10^7}{C_{PN} T_{tN}}\right]}{\mathrm{H}} \tag{15}$$

Determine $\frac{C_{PB}}{C_{PN}}$ from:

$$\frac{C_{PB}}{C_{PN}} = \frac{\frac{m_1}{m_N}\left(\frac{C_{P1}}{C_{PN}}\right) + \left[\frac{m_2}{m_N} - \frac{m_i}{m_N}\right]\left(\frac{C_{P2}}{C_{PN}}\right) + \left(\frac{C_{P3}}{C_{PN}}\right)\left(\frac{m_3}{m_N}\right)}{H}$$

$$+ \frac{k_i\left(\frac{m_i}{m_N}\right)\left(\frac{C_{P2}}{C_{PN}}\right) + k_W\left[\frac{1.14 \times 10^4}{C_{PN}}\right]}{H} \qquad (16)$$

Determine $\frac{T_{tB}}{T_{tN}}$ from:

$$\frac{T_{tB}}{T_{tN}} = \frac{\left(\frac{C_{PB}\,T_{tB}}{C_{PN}\,T_{tN}}\right)}{\left(\frac{C_{PB}}{C_{PN}}\right)} \qquad (17)$$

condition:

1. for $k_W > 0.0$ and $T_{tB} < 520$ °R

   make $T_{tB} = 520$ °R and solve equations 15 ,16 and 17 for a $k_W = k_{WS}$ (saturated condition) and printout

2. for $k_W < 0.0$

   determine k_{WS} as in condition 1 and use in calculations

Determine $\frac{\gamma_B}{\gamma_N}$ from:

$$\frac{\gamma_B}{\gamma_N} = \frac{\frac{m_1}{m_N}\left(\frac{C_{P1}}{C_{PN}}\right) + \left[\frac{m_2}{m_N} - \frac{m_i}{m_N}\right]\left(\frac{C_{P2}}{C_{PN}}\right) + \left(\frac{C_{P3}}{C_{PN}}\right)\left(\frac{m_3}{m_N}\right)}{\frac{m_1}{m_N}\left(\frac{C_{P1}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_1}\right) + \left[\frac{m_2}{m_N} - \frac{m_i}{m_N}\right]\left(\frac{C_{P2}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_2}\right) + \left(\frac{C_{P3}}{C_{PN}}\right)\left(\frac{m_3}{m_N}\right)\left(\frac{\gamma_N}{\gamma_3}\right)} \cdots$$

$$\frac{+ k_i\left(\frac{m_i}{m_N}\right)\left(\frac{C_{P2}}{C_{PN}}\right) + k_W\left[\frac{1.14 \times 10^4}{C_{PN}}\right]}{+ k_i\left(\frac{m_i}{m_N}\right)\left(\frac{C_{P2}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_2}\right) + k_W\, 8.764 \times 10^8\left(\frac{\gamma_N}{C_{PN}}\right)} \qquad (18)$$

Determine γ_B from:

$$\gamma_B = \left(\frac{\gamma_B}{\gamma_N}\right)\gamma_N \qquad (19)$$

Determine $\frac{F_1}{P_{tN}\,A_N^*}$ from:

$$\frac{F_1}{P_{tN}\,A_N^*} = \left(\frac{P_{t1}}{P_{tN}}\right)\left(\frac{A_1}{A_N^*}\right)\left(1 - C_1^2\right)^{\frac{1}{\gamma_1 - 1}}\left[1 + \left(\frac{\gamma_1 + 1}{\gamma_1 - 1}\right)C_1^2\right] \qquad (20)$$

Determine $\frac{F_2}{P_{tN}\,A_N^*}$ from:

$$\frac{F_2}{P_{tN}\,A_N^*} = \left(\frac{P_{t2}}{P_{tN}}\right)\left(\frac{A_2}{A_N^*}\right)\left(1 - C_2^2\right)^{\frac{1}{\gamma_2 - 1}}\left[1 + \left(\frac{\gamma_2 + 1}{\gamma_2 - 1}\right)C_2^2\right] \qquad (21)$$

Determine $\frac{F_3}{P_{tN}\,A_N^*}$ from:

$$\frac{F_3}{P_{tN}\,A_N^*} = \left(\frac{P_C}{P_{tN}}\right)\left(\frac{A_3}{A_N^*}\right)\left(1 - C_3^2\right)^{\frac{1}{\gamma_3 - 1}}\left[1 + \left(\frac{\gamma_3 + 1}{\gamma_3 - 1}\right)C_3^2\right] \qquad (22)$$

Determine $\dfrac{F_i}{P_{tN}\, A_N^*}$ from:

$$\frac{F_i}{P_{tN}\, A_N^*} = \frac{F_2}{P_{tN}\, A_N^*}\left(\frac{A_i}{A_N^*}\right)\left(\frac{A_N^*}{A_2}\right) \tag{23}$$

Determine $\dfrac{F_S}{P_{tN}\, A_N^*}$ from:

$$\frac{F_S}{P_{tN}\, A_N^*} = C_{DS}\left(\frac{P_{t2}}{P_{tN}}\right)\left(\frac{A_S}{A_N^*}\right)\left(\frac{\gamma_2}{\gamma_2 -1}\right)\left(1- C_2^2\right)^{\frac{1}{\gamma_2 -1}} C_2^2 \tag{24}$$

Determine $\dfrac{P_2}{P_{t2}}$ from:

$$\frac{P_2}{P_{t2}} = \left(1- C_2^2\right)^{\frac{\gamma_2}{\gamma_2 -1}} \tag{25}$$

Determine $\dfrac{P_3}{P_C}$ from:

$$\frac{P_3}{P_C} = \left(1- C_3^2\right)^{\frac{\gamma_3}{\gamma_3 -1}} \tag{26}$$

Determine G from:

$$G = \frac{F_1}{P_{tN}\, A_N^*} + \left(\frac{P_{b1}}{P_2}\right)\left(\frac{P_2}{P_{t2}}\right)\left(\frac{P_{t2}}{P_{tN}}\right)\left(\frac{A_{b1}}{A_N^*}\right) - \frac{F_i}{P_{tN}\, A_N^*} + \frac{F_2}{P_{tN}\, A_N^*} + \left(\frac{P_3}{P_C}\right)\left(\frac{P_C}{P_{tN}}\right)\left(\frac{A_{b2}}{A_N^*}\right) + \frac{F_3}{P_{tN}\, A_N^*} - \frac{F_S}{P_{tN}\, A_N^*} \tag{27}$$

Determine the subsonic solution for C_B from:

$$C_B = \frac{1}{2}\left(\frac{\mathbf{G}}{\mathbf{H}}\right)\sqrt{\left(\frac{C_{PN}}{C_{PB}}\right)\left(\frac{T_{tN}}{T_{tB}}\right)}\left(\frac{\gamma_B}{\gamma_B+1}\right)\left[\frac{\left(\gamma_N^2-1\right)^{1/2}}{\gamma_N}\right]\left(\frac{\gamma_N+1}{2}\right)^{\frac{1}{\gamma_N-1}}$$
$$-\frac{1}{2}\sqrt{\left(\frac{\mathbf{G}}{\mathbf{H}}\right)^2\left(\frac{C_{PN}}{C_{PB}}\right)\left(\frac{T_{tN}}{T_{tB}}\right)\left(\frac{\gamma_B}{\gamma_B+1}\right)^2\left[\frac{\left(\gamma_N^2-1\right)}{\gamma_N^2}\right]\left(\frac{\gamma_N+1}{2}\right)^{\frac{2}{\gamma_N-1}}-4\left(\frac{\gamma_B-1}{\gamma_B+1}\right)}$$

(28)

Determine $\frac{P_{tB}}{P_{tN}}$ from:

$$\frac{P_{tB}}{P_{tN}} = \frac{\mathbf{G}}{\left(\frac{A_B}{A_N^*}\right)\left(1-C_B^2\right)^{\frac{1}{\gamma_B-1}}\left[1+\left(\frac{\gamma_B+1}{\gamma_B-1}\right)C_B^2\right]}$$

(29)

Determine M_1 from:

$$M_1 = \left(\frac{2}{\gamma_1-1}\right)^{1/2}\frac{C_1}{\left(1-C_1^2\right)^{1/2}}$$

(30)

Determine M_2 from:

$$M_2 = \left(\frac{2}{\gamma_2-1}\right)^{1/2}\frac{C_2}{\left(1-C_2^2\right)^{1/2}}$$

(31)

Determine M_3 from:

$$M_3 = \left(\frac{2}{\gamma_3-1}\right)^{1/2}\frac{C_3}{\left(1-C_3^2\right)^{1/2}}$$

(32)

Determine $\frac{P_3}{P_{tN}}$ from:

$$\frac{P_3}{P_{tN}} = \left(\frac{P_3}{P_C}\right)\left(\frac{P_C}{P_{tN}}\right)$$

(33)

Determine M_B from:

$$M_B = \left(\frac{2}{\gamma_B - 1}\right)^{1/2} \frac{C_B}{\left(1 - C_B^2\right)^{1/2}} \tag{34}$$

Condition: if $A_{BE} \neq A_B$ then assume an isentropic expansion/contraction and calculate a new M_B.

Determine $\frac{P_B}{P_{tB}}$ from:

$$\frac{P_B}{P_{tB}} = \left(1 - C_B^2\right)^{\gamma_B/\gamma_B - 1} \tag{35}$$

Determine $\frac{P_B}{P_{tN}}$ from:

$$\frac{P_B}{P_{tN}} = \left(\frac{P_B}{P_{tB}}\right)\left(\frac{P_{tB}}{P_{tN}}\right) \tag{36}$$

Determine $\frac{P_N}{P_{tN}}$ from:

$$\frac{P_N}{P_{tN}} = \left[1 + \left(\frac{\gamma_N - 1}{2}\right) M_N^2\right]^{-\frac{\gamma_N}{\gamma_N - 1}} \tag{37}$$

Determine $\frac{P_C}{P_N}$ from:

$$\frac{P_C}{P_N} = \left(\frac{P_C}{P_{tN}}\right)\left(\frac{P_{tN}}{P_N}\right) \tag{38}$$

Determine $\frac{P_C}{P_2}$ from:

$$\frac{P_C}{P_2} = \left(\frac{P_C}{P_{tN}}\right)\left(\frac{P_{t2}}{P_2}\right)\left(\frac{P_{tN}}{P_{t2}}\right) \tag{39}$$

Determine $\left(\frac{P_C}{P_N}\right)_{Start}$ from:

$$\left(\frac{P_C}{P_N}\right)_{Start} = \frac{(M_N-1)\left[\left(1-\frac{\delta_N^*}{r_N}-\frac{r_j}{r_N}\right)\left(M_N^2-1\right)^{1/2}-\frac{x_j}{r_N}\right]}{5\left(\frac{\delta_N}{r_N}\right)} + 1.0 \qquad (40)$$

after $\left(\frac{P_C}{P_N}\right)_{Start}$ is calculated all parameters which correspond to this value is determined. These will be the values for the system to start if the following conditions apply:

$$MB \leq 1.0$$

$$M3 \leq 1.0$$

$$\frac{P_3}{P_2} \geq 1.0$$

$$\left(\frac{P_C}{P_N}\right)_{Start} \geq 1.0$$

$$\frac{\delta_N}{r_N} \leq \left(1-\frac{r_j}{r_N}\right)$$

$\left(\frac{P_C}{P_N}\right)_{Start} > M_N$ then make $\left(\frac{P_C}{P_N}\right)_{Start} = M_N$

$$\frac{P_3}{P_2} \leq M_2$$

if the last condition is violated then determine the started conditions based on $\frac{P_3}{P_2} = M_2$.

Determine $\frac{P_3}{P_2}$ from:

$$\frac{P_3}{P_2} = \left(\frac{P_{t2}}{P_2}\right)\left(\frac{P_{tN}}{P_{t2}}\right)\left(\frac{P_C}{P_{tN}}\right)\left(\frac{P_3}{P_C}\right) \tag{41}$$

Determine $\frac{P_B}{P_C}$ from:

$$\frac{P_B}{P_C} = \left(\frac{P_{tN}}{P_C}\right)\left(\frac{P_B}{P_{tN}}\right) \tag{42}$$

Determine $\frac{C_{P5}}{C_{PN}}$ from:

$$\frac{C_{P5}}{C_{PN}} = \left(\frac{C_{P5}}{C_{PB}}\right)\left(\frac{C_{PB}}{C_{PN}}\right) \tag{43}$$

Determine γ_5 from:

$$\gamma_5 = \left(\frac{\gamma_5}{\gamma_B}\right)\gamma_B \tag{44}$$

Determine $\frac{T_{t5}}{T_{tN}}$ from:

$$\frac{T_{t5}}{T_{tN}} = \left(\frac{T_{t5}}{T_{tB}}\right)\left(\frac{T_{tB}}{T_{tN}}\right) \tag{45}$$

Determine C_4 from:

$$\left(1 - C_4^2\right)^{\frac{1}{\gamma_4 - 1}} C_4 = \frac{A_4^*}{A_4}\left(\frac{2}{\gamma_4 + 1}\right)^{\frac{1}{\gamma_4 - 1}}\left[\frac{\gamma_4 - 1}{\gamma_4 + 1}\right]^{1/2} \tag{46}$$

Determine $\frac{P_4}{P_{t4}}$ from:

$$\frac{P_4}{P_{t4}} = \left(1 - C_4^2\right)^{\frac{\gamma_4}{\gamma_4 - 1}} \tag{47}$$

Determine M_4 from:

$$M_4 = \left(\frac{2}{\gamma_4 - 1}\right)^{1/2} \frac{C_4}{\left(1 - C_4^2\right)^{1/2}} \tag{48}$$

Determine $\frac{F_{S1}}{P_{tN} A_N^*}$ from:

$$\frac{F_{S1}}{P_{tN} A_N^*} = C_{DS1} \left(\frac{P_{tB}}{P_{tN}}\right)\left(\frac{A_{S1}}{A_N^*}\right)\left(\frac{\gamma_B}{\gamma_B - 1}\right)\left(1 - C_B^2\right)^{\frac{1}{\gamma_B - 1}} C_B^2$$
$$+ \left(\frac{P_B}{P_{tN}}\right) P_{tN} A_N^* \left(\frac{A_4}{A_N^*} + \frac{A_{b4}}{A_N^*}\right) \tag{49}$$

Define G_1 as:

$$G_1 = G + \left(\frac{P_B}{P_{tB}}\right)\left(\frac{P_{tB}}{P_{tN}}\right)\left(\frac{A_{B1}}{A_N^*} - \frac{A_B}{A_N^*}\right) - \left(\frac{F_{S1}}{P_{tN} A_N^*}\right) \tag{50}$$

Determine the subsonic solution of C_5 from:

$$C_5 = \frac{1}{2}\left(\frac{G_1}{H}\right)\sqrt{\left(\frac{C_{PN}}{C_{P5}}\right)\left(\frac{T_{tN}}{T_{t5}}\right)} \left(\frac{\gamma_5}{\gamma_5 + 1}\right)\left[\frac{\left(\gamma_N^2 - 1\right)^{1/2}}{\gamma_N}\right]\left(\frac{\gamma_N + 1}{2}\right)^{\frac{1}{\gamma_N - 1}}$$
$$- \frac{1}{2}\sqrt{\left(\frac{G_1}{H}\right)^2 \left(\frac{C_{PN}}{C_{P5}}\right)\left(\frac{T_{tN}}{T_{t5}}\right)\left(\frac{\gamma_5}{\gamma_5 + 1}\right)^2 \left[\frac{\left(\gamma_N^2 - 1\right)}{\gamma_N^2}\right]\left(\frac{\gamma_N + 1}{2}\right)^{\frac{2}{\gamma_N - 1}} - 4\left(\frac{\gamma_5 - 1}{\gamma_5 + 1}\right)} \tag{51}$$

Determine $\frac{P_{t5}}{P_{tN}}$ from:

$$\frac{P_{t5}}{P_{tN}} = \frac{G_1}{\left(\frac{A_{B1}}{A_N^*} - \frac{A_4}{A_N^*} - \frac{A_{b4}}{A_N^*}\right)\left(1 - C_5^2\right)^{\frac{1}{\gamma_5 - 1}}\left[1 + \left(\frac{\gamma_5 + 1}{\gamma_5 - 1}\right) C_5^2\right]} \tag{52}$$

Determine $\frac{P_5}{P_{t5}}$ from:

$$\frac{P_5}{P_{t5}} = \left(1 - C_5^2\right)^{\frac{\gamma_5}{\gamma_5 - 1}} \tag{53}$$

Determine $\frac{P_5}{P_{tN}}$ from:

$$\frac{P_5}{P_{tN}} = \left(\frac{P_5}{P_{t5}}\right)\left(\frac{P_{t5}}{P_{tN}}\right) \tag{54}$$

If $\frac{P_{t4}}{P_{tN}} = -1$ calculate optimum jet pump option, assume $P_5 = P_4$

Determine $\frac{P_{t4}}{P_{tN}}$ from:

$$\frac{P_{t4}}{P_{tN}} = \frac{\left(\frac{P_5}{P_{t5}}\right)\left(\frac{P_{t5}}{P_{tN}}\right)}{\frac{P_4}{P_{t4}}} \tag{55}$$

If $\frac{P_{t4}}{P_{tN}} \neq -1$ then

Determine $\frac{P_5}{P_4}$ from:

$$\frac{P_5}{P_4} = \left(\frac{P_5}{P_{t5}}\right)\left(\frac{P_{t5}}{P_{tN}}\right)\left(\frac{P_{tN}}{P_{t4}}\right)\left(\frac{P_{t4}}{P_4}\right) \tag{56}$$

Determine $\frac{P_{t5}}{P_{tB}}$ from:

$$\frac{P_{t5}}{P_{tB}} = \left(\frac{P_{t5}}{P_{tN}}\right)\left(\frac{P_{tN}}{P_{tB}}\right) \tag{57}$$

Determine $\frac{F_{S2}}{P_{tN} A_N^*}$ from:

$$\frac{F_{S2}}{P_{tN} A_N^*} = C_{DS2} \left(\frac{P_{t5}}{P_{tN}}\right)\left(\frac{A_{S2}}{A_N^*}\right)\left(\frac{\gamma_5}{\gamma_5 - 1}\right)\left(1 - C_5^2\right)^{\frac{1}{\gamma_5 - 1}} C_5^2 \tag{58}$$

Determine $\frac{F_4}{P_{tN} A_N^*}$ from:

$$\frac{F_4}{P_{tN} A_N^*} = \left(\frac{P_{t4}}{P_{tN}}\right)\left(\frac{A_4}{A_N^*}\right)\left(1 - C_4^2\right)^{\frac{1}{\gamma_4 - 1}}\left[1 + \left(\frac{\gamma_4 + 1}{\gamma_4 - 1}\right) C_4^2\right] \tag{59}$$

Define G_2 as:

$$G_2 = G_1 + \frac{F_4}{P_{tN} A_N^*} + \frac{P_5 A_{b4}}{P_{tN} A_N^*} - \frac{F_{S2}}{P_{tN} A_N^*} \tag{60}$$

Determine $\frac{m_4}{m_N}$ from:

$$\frac{m_4}{m_N} = \frac{\left(\frac{P_{t4}}{P_{tN}}\right)\left(\frac{A_4^*}{A_4}\right)\left(\frac{A_4}{A_N^*}\right)}{\sqrt{\left(\frac{C_{p4}}{C_{pN}}\right)\left(\frac{T_{t4}}{T_{tN}}\right)}} \left(\frac{\gamma_N + 1}{2}\right)^{\frac{1}{\gamma_N - 1}} \left(\frac{2}{\gamma_4 + 1}\right)^{\frac{1}{\gamma_4 - 1}} \left[\frac{\gamma_N^2 - 1}{\gamma_4^2 - 1}\right]^{1/2} \left(\frac{\gamma_4}{\gamma_N}\right) \tag{61}$$

Define H_1 as:

$$H_1 = H + \frac{m_4}{m_N} \tag{62}$$

Define k_4 as $\frac{m_4}{m_N}$

Determine $\frac{C_{PB1}\,T_{tB1}}{C_{PN}\,T_{tN}}$ from:

$$\frac{C_{PB1}\,T_{tB1}}{C_{PN}\,T_{tN}} = \left(\frac{k_4}{H + k_4}\right)\left(\frac{C_{P4}T_{t4}}{C_{PN}T_{tN}}\right) + \left(\frac{H}{H + k_4}\right)\left(\frac{C_{P5}T_{t5}}{C_{PN}T_{tN}}\right) \quad (63)$$

Determine $\frac{C_{PB1}}{C_{PN}}$ from:

$$\frac{C_{PB1}}{C_{PN}} = \left(\frac{k_4}{H + k_4}\right)\left(\frac{C_{P4}}{C_{PN}}\right) + \left(\frac{H}{H + k_4}\right)\left(\frac{C_{P5}}{C_{PN}}\right) \quad (64)$$

Determine $\frac{C_{VB1}}{C_{VN}}$ from:

$$\frac{C_{VB1}}{C_{VN}} = \left(\frac{k_4}{H + k_4}\right)\left(\frac{C_{P4}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_4}\right) + \left(\frac{H}{H + k_4}\right)\left(\frac{C_{P5}}{C_{PN}}\right)\left(\frac{\gamma_N}{\gamma_5}\right) \quad (65)$$

Determine $\frac{\gamma_{B1}}{\gamma_N}$ from:

$$\frac{\gamma_{B1}}{\gamma_N} = \frac{\left(\frac{C_{PB1}}{C_{PN}}\right)}{\left(\frac{C_{VB1}}{C_{VN}}\right)} \quad (66)$$

Determine h_{AM1} as follows:

For $\frac{m_1}{m_N} \geq k_A\,k_4$ (lack of oxygen)

$$h_{AM1} = \frac{k_A\,k_4}{\left(\frac{m_1}{m_N}\right)}\,(h_A - h_{AM}) \quad (67)$$

For $\frac{m_1}{m_N} < k_A\,k_4$ (excess oxygen)

$$h_{AM1} = h_A - h_{AM}$$

If calculated $\frac{T_{tB1}}{T_{tN}} \leq \frac{T_{tBA}}{T_{tN}}$ then use h_{AM1}

If calculated $\frac{T_{tB1}}{T_{tN}} > \frac{T_{tBA}}{T_{tN}}$ then make $\frac{T_{tB1}}{T_{tN}} = \frac{T_{tBA}}{T_{tN}}$

Determine $\frac{T_{tB1}}{T_{tN}}$ from:

$$\frac{T_{tB1}}{T_{tN}} = \frac{k_4 \left(\frac{T_{t4}}{T_{tN}}\right)\left(\frac{C_{P4}}{C_{PN}}\right) + H \left(\frac{T_{t5}}{T_{tN}}\right)\left(\frac{C_{P5}}{C_{PN}}\right) + \left(\frac{m_1}{m_N}\right) h_{AM1}}{k_4 \left(\frac{C_{P4}}{C_{PN}}\right) + H \left(\frac{C_{P5}}{C_{PN}}\right)} \tag{68}$$

Determine the subsonic solution of C_{B1} from:

$$C_{B1} = \frac{1}{2}\left(\frac{\mathbf{G}_2}{\mathbf{H}_1}\right)\sqrt{\left(\frac{C_{PN}}{C_{PB1}}\right)\left(\frac{T_{tN}}{T_{tB1}}\right)} \left(\frac{\gamma_{B1}}{\gamma_{B1} -1}\right)\left[\frac{\left(\gamma_N^2 -1\right)^{1/2}}{\gamma_N}\right]\left(\frac{\gamma_N +1}{2}\right)^{\frac{1}{\gamma_N -1}}$$

$$- \frac{1}{2}\sqrt{\left(\frac{\mathbf{G}_2}{\mathbf{H}_1}\right)^2\left(\frac{C_{pN}}{C_{pB1}}\right)\left(\frac{T_{tN}}{T_{tB1}}\right)\left(\frac{\gamma_{B1}}{\gamma_{B1} -1}\right)^2\left[\frac{\left(\gamma_N^2 -1\right)}{\gamma_N^2}\right]\left(\frac{\gamma_N +1}{2}\right)^{\frac{2}{\gamma_N -1}} - 4\left(\frac{\gamma_{B1}+1}{\gamma_{B1}-1}\right)} \tag{69}$$

Determine $\frac{P_{tB1}}{P_{tN}}$ from:

$$\frac{P_{tB1}}{P_{tN}} = \frac{\mathbf{G}_2}{\left(\frac{A_{B1}}{A_N^*}\right)\left(1- C_{B1}^2\right)^{\frac{1}{\gamma_{B1}-1}}\left[1+\left(\frac{\gamma_{B1}+1}{\gamma_{B1}-1}\right)C_{B1}^2\right]} \tag{70}$$

Determine $\frac{P_{B1}}{P_{tB1}}$ from:

$$\frac{P_{B1}}{P_{tB1}} = \left(1- C_{B1}^2\right)^{\gamma_{B1}/\gamma_{B1}-1} \tag{71}$$

Determine $\frac{P_{B1}}{P_{tN}}$ from:

$$\frac{P_{B1}}{P_{tN}} = \left(\frac{P_{B1}}{P_{tB1}}\right)\left(\frac{P_{tB1}}{P_{tN}}\right) \tag{72}$$

Determine $\frac{P_{B1}}{P_B}$ from:

$$\frac{P_{B1}}{P_B} = \left(\frac{P_{B1}}{P_{tN}}\right)\left(\frac{P_{tN}}{P_B}\right) \tag{73}$$

Determine M_5 from:

$$M_5 = \left(\frac{2}{\gamma_5 - 1}\right)^{1/2} \frac{C_5}{\left(1 - C_5^2\right)^{1/2}} \tag{74}$$

Determine M_{B1} from:

$$M_{B1} = \left(\frac{2}{\gamma_{B1} - 1}\right)^{1/2} \frac{C_{B1}}{\left(1 - C_{B1}^2\right)^{1/2}} \tag{75}$$

Condition: if $A_{BE1} \neq A_{B1}$ then assume an isentropic expansion/contraction and calculate a new M_{B1}.

Determine F_{B1} from:

$$F_{B1} = P_{tN1}\left(\frac{P_{tB1}}{P_{tN}}\right) A_{B1}\left(1 - C_{B1}^2\right)^{\frac{1}{\gamma_{B1} - 1}}\left[1 + \left(\frac{\gamma_{B1} + 1}{\gamma_{B1} - 1}\right) C_{B1}^2\right] \tag{76}$$

Determine F_N from:

$$F_N = \frac{F_2}{P_{tN} A_N^*} P_{tN1} A_N^* \ (144) \tag{77}$$

Determine DF from:

$$DF = F_{B1} - F_N \tag{78}$$

Determine P_{tN1} from:

$$P_{tN1} = \frac{15}{\left(\frac{P_B}{P_{tN}}\right)} \qquad \text{(without jet pump)} \qquad (79)$$

$$P_{tN1} = \frac{15}{\left(\frac{P_{B1}}{P_{tN}}\right)} \qquad \text{(with jet pump)}$$

Determine P_{N1} from:

$$P_{N1} = \left(\frac{P_N}{P_{tN}}\right) P_{tN1} \qquad (80)$$

Determine m_N from:

$$m_N = \frac{(9265)\ P_{tN1}\ A_N^*}{\sqrt{2\ C_{PN}\ T_{tN}}} \left(\frac{2}{\gamma_N + 1}\right)^{\frac{1}{\gamma_N - 1}} \left[\frac{\gamma_N}{\left(\gamma_N^2 - 1\right)^{1/2}}\right] \qquad (81)$$

Determine m_4 from:

$$m_4 = m_N\ k_4 \qquad (82)$$

Determine m_W from:

$$m_W = m_N\ K_W$$

or if $k_W = -1$ (calculate saturated case)
then

$$m_W = m_N\ K_{WS} \qquad (83)$$

Determine m_T from:

$$m_T = m_N + m_4 \qquad (84)$$

Determine $\frac{V_5}{V_4}$ from:

$$\frac{V_5}{V_4} = \left(\frac{M_5}{M_4}\right)\left[\frac{\left(\frac{T_{t5}}{T_{tB}}\right)\left(\frac{T_{tB}}{T_{tN}}\right)}{\left(\frac{T_{t4}}{T_{tN}}\right)}\left[\frac{\gamma_B\left(\frac{\gamma_5}{\gamma_B}\right) - 1}{\gamma_4 - 1}\right]\left[\frac{\left(\frac{C_{P5}}{C_{PB}}\right)\left(\frac{C_{PB}}{C_{PN}}\right)}{\left(\frac{C_{P4}}{C_{PN}}\right)}\right]\left[\frac{1 + \left(\frac{\gamma_4 - 1}{2}\right)M_4^2}{1 + \left[\frac{\gamma_B\left(\frac{\gamma_5}{\gamma_B}\right) - 1}{2}\right]M_5^2}\right]\right]^{1/2} \tag{85}$$

Determine P_{t4} from:

$$P_{t4} = \left(\frac{P_{t4}}{P_{tN}}\right)P_{tN1} \tag{86}$$

Determine $\frac{A_5^*}{A_5}$ from:

$$\frac{A_5^*}{A_5} = \left(\frac{\gamma_5 + 1}{2}\right)^{\frac{\gamma_5 + 1}{2(\gamma_5 - 1)}} M_5\left[1 + \left(\frac{\gamma_5 + 1}{2}\right)M_5^2\right]^{-\left[\frac{\gamma_5 + 1}{2(\gamma_5 - 1)}\right]} \tag{87}$$

Determine $\frac{A_5^*}{A_{5S}}$ from:

$$\frac{A_5^*}{A_{5S}} = \left(\frac{A_5^*}{A_5}\right)\left(\frac{\frac{A_{B1}}{A_N^*} - \frac{A_4}{A_N^*} - \frac{A_{b4}}{A_N^*}}{\frac{A_{B1}}{A_N^*} - \frac{A_{S1}}{A_N^*}}\right) \tag{88}$$

Determine M_{5S} from:

$$\frac{A_5^*}{A_{5S}} = \left(\frac{\gamma_5 + 1}{2}\right)^{\frac{\gamma_5 + 1}{2(\gamma_5 - 1)}} M_{5S}\left[1 + \left(\frac{\gamma_5 + 1}{2}\right)M_{5S}^2\right]^{-\left[\frac{\gamma_5 + 1}{2(\gamma_5 - 1)}\right]} \tag{89}$$

APPENDIX D

DIFFUSER EXPERT SYSTEM

PROGRAM

OUTPUTS.KBS

```
!portion of the diffuser expert system that reads in outputs from Bauer.exe
!and makes decisions based on their values.



EXECUTE;
ENDOFF;
RUNTIME;

ACTIONS
     XDUM=1
     YDUM=1
     ZDUM=1
     ZCOUNT=1
     MACHC1=1            !put here to hold a place in outdat
     CLS
     CLROFF
     CALL DELRES,""      !deletes RESULTS and PLOT.DOC
     CLRON
     CALL BAUER,""
     CLROFF
     CALL P6READ,""
     CLRON
     LOADFACTS P6OUT

!    CALCULATE CONSTANTS FOR ISENTROPIC EXPANSION CLCULATIONS

     ZA=((YGAMMAN-1)/2)
     ZB=((YGAMMAN+1)/2)
     ZC=((YGAMMAN+1)/(2*(YGAMMAN-1)))
     ZD=(YGAMMAN/(YGAMMAN-1))

!    CORRECT INPUTS WHERE NEEDED

     RESET ZCORRECTMN
     FIND ZCORRECTMN

!    LOOP TO FIND THE CORRECT MASS FLOW IN AND OUT OF THE ENGINE

     ZCOUNT=20
     WHILETRUE ZCOUNT=20 THEN
       RESET ZCORRECTMASS1
       RESET ZDUMMY22
       RESET ZDUMMT23
       FIND ZCORRECTMASS1
     END
```

```
RESET ZMAXIMUMKW
FIND ZMAXIMUMKW
RESET ZCORRECTPRESS
FIND ZCORRECTPRESS

!    LOOP TO FIND THE BASE PRESSURE LIMIT

ZCOUNT = 20
ZMACH = (MN)
RESET ZBASEPRESS
WHILETRUE ZCOUNT = 20 THEN
  RESET ZBASEPRESS
  ZMACH=(ZMACH+.05)
  ZAOAN=(@EXP(@LOG(1/ZMACH)+ZC*(@LOG((1+ZA*ZMACH*ZMACH)/ZB))))
  ZRATIO=(ZAOAN/YABOAN)
  FIND ZBASEPRESS
END
FDISPLAY RESULTS,"AN/AN* = {ZAOAN}, ZRATIO={ZRATIO}~"

CLROFF
CALL P6READ,""
CLRON
LOADFACTS P6OUT
RESET ZCALCCHECK
FIND ZCALCCHECK
CALL PERCRV,""                          !displays performance curve
CCALL LIST,"PRIN6.DOC"                !displays output data file
RESET ANALYSIS
RESET FJDCHOKE
RESET FJDCHOKEREASON
RESET STARTED
RESET EFFICIENCY
FIND ANALYSIS
SORT FJDCHOKEREASON


CLS
WOPEN 1,0,0,22,79,7
ACTIVE 1
DISPLAY "                        DIFFUSER ANALYSIS"
FDISPLAY RESULTS,"
                        DIFFUSER ANALYSIS
"
RESET EFFICIENCYTEXT
FIND EFFICIENCYTEXT
RESET FFULLTEXT
FIND FFULLTEXT
```

```
    RESET CHOKETEXT
    FIND CHOKETEXT

!   loop to find choke reason text in order of probability

    WHILEKNOWN FJDCHOKEREASON1
      RESET FJDCHOKEREASON1
      POP FJDCHOKEREASON, FJDCHOKEREASON1
      RESET FJDCHOKEREASONTEXT
      FIND FJDCHOKEREASONTEXT
    END
    DISPLAY"
Analysis complete - strike any key to quit~"


    CHAIN DIFFUSER
;

!   RULE PORTION OF THE EXPERT SYSTEM THAT CORRECTS ERRORS IN THE INPUTS
!--------------------------------------------------------------------------

RULE 20
IF        YKP = 0.0       AND
          M2 < (.95*MN)  OR
          M2 > (1.05*MN)
THEN      MN = (M2)
          PC10 = 0.010000
          PC09 = 0.040000
          PC08 = 0.060000
          PC07 = 0.080000
          PC06 = 0.100000
          PC05 = 0.200000
          PC04 = 0.400000
          PC03 = 0.600000
          PC02 = 0.800000
          PC01 = 1.000000
          SAVEFACTS OUTDAT
          CLROFF
          CALL OUTREAD,""
          CLRON
          CALL BAUER,""
          CLROFF
          CALL P6READ,""
          CLRON
          LOADFACTS P6OUT
          FDISPLAY RESULTS,"IT WAS NECESSARY TO SET MN=M2={MN}"
          ZCORRECTMN = YES
```

```
ELSE      ZCORRECTMN = YES
;

RULE 22
IF        MIOMN > 0.0  AND
          M1OMN > 0.0  AND
          M1OMN < (.99*(MIOMN-XYKI*MIOMN)) OR
          M1OMN > (1.01*(MIOMN-XYKI*MIOMN))
THEN      XXPT1OPTN = (((MIOMN-XYKI*MIOMN)/M1OMN)*XXPT1OPTN)
          FDISPLAY RESULTS,"CALCULATED VALUE OF PT1/PTN= {XXPT1OPTN}~"
          ZDUMMY22=YES
ELSE      ZCORRECTMASS1=YES
          ZCOUNT=1
          ZDUMMY22=NO
          ZDUMMY23=NO
;

RULE 23
IF        ZDUMMY22=YES AND
          XXPT1OPTN>1.0
THEN      XXPT1OPTN=1.0
          XYKI = 0.000000
          PC10 = 0.010000
          PC09 = 0.040000
          PC08 = 0.060000
          PC07 = 0.080000
          PC06 = 0.100000
          PC05 = 0.200000
          PC04 = 0.400000
          PC03 = 0.600000
          PC02 = 0.800000
          PC01 = 1.000000
          SAVEFACTS OUTDAT
          CLROFF
          CALL OUTREAD,""
          CLRON
          CALL BAUER,""
          CLROFF
          CALL P6READ,""
          CLRON
          LOADFACTS P6OUT
          ZKI=((MIOMN-M1OMN)/MIOMN)
          XYKI=(XYKI+ZKI)
          WOPEN 2,0,0,11,79,7
          ACTIVE 2
          DISPLAY"While iterating on engine exit total pressure (PT1) to mass
balance the engine, PT1 reached the limiting case of being equal
```

```
to the nozzle total pressure (PTN).  To make up the mass difference,
a value of the engine bleed flow, KI={XYKI} was calculated."
        ZDUMMY23=YES
;

RULE 23A
IF      ZDUMMY23=YES AND
        ZPREFERENCE=CONTINUE
THEN    PC10 = 0.010000
        PC09 = 0.040000
        PC08 = 0.060000
        PC07 = 0.080000
        PC06 = 0.100000
        PC05 = 0.200000
        PC04 = 0.400000
        PC03 = 0.600000
        PC02 = 0.800000
        PC01 = 1.000000
        SAVEFACTS OUTDAT
        CLROFF
        CALL OUTREAD,""
        CLRON
        CALL BAUER,""
        CLROFF
        CALL P6READ,""
        CLRON
        LOADFACTS P6OUT
        FDISPLAY RESULTS,"IT WAS NECESSARY TO SET PT1/PTN=1.0 AND
CALCULATE A KI={XYKI} TO MASS BALANCE THE ENGINE"
        ZCORRECTMASS1 = YES
        ZCOUNT=1
;

RULE 23D
IF      ZPREFERENCE=STOP_ANALYSIS
THEN    CHAIN DIFFUSER
;

RULE 23C
IF      ZDUMMY22=YES AND
        XXPT1OPTN<=1.0
THEN    PC10 = 0.010000
        PC09 = 0.040000
        PC08 = 0.060000
        PC07 = 0.080000
        PC06 = 0.100000
        PC05 = 0.200000
```

```
        PC04 = 0.400000
        PC03 = 0.600000
        PC02 = 0.800000
        PC01 = 1.000000
        SAVEFACTS OUTDAT
        CLROFF
        CALL OUTREAD,""
        CLRON
        CALL BAUER,""
        CLROFF
        CALL P6READ,""
        CLRON
        LOADFACTS P6OUT
        FDISPLAY RESULTS,"IT WAS NECESSARY TO ITERATE ON PT1/PTN TO MAKE
M1/MN=MI/MN"
        ZDUMMY23=NO
        ZCORRECTMASS1=NO
;

RULE 25
IF      XKWS = 0.0
THEN    ZKWSAVE=(XXKW)
        XXKW=(-1.000000)
        PC10 = 0.010000
        PC09 = 0.040000
        PC08 = 0.060000
        PC07 = 0.080000
        PC06 = 0.100000
        PC05 = 0.200000
        PC04 = 0.400000
        PC03 = 0.600000
        PC02 = 0.800000
        PC01 = 1.000000
        SAVEFACTS OUTDAT
        CLROFF
        CALL OUTREAD,""
        CLRON
        CALL BAUER,""
        CLROFF
        CALL P6READ,""
        CLRON
        LOADFACTS P6OUT
        ZKWS=(XKWS)
        XXKW=(ZKWSAVE)
        SAVEFACTS OUTDAT
        CLROFF
        CALL OUTREAD,""
```

```
        CLRON
        FDISPLAY RESULTS,"THE SATURATED WATER SPRAY FLOW; ZKWS={ZKWS}"
        ZMAXIMUMKW=YES
ELSE    ZKWS=(XKWS)
        ZMAXIMUMKW=YES
;

RULE 28
IF      PNOPTN >.1
THEN    PC05=(PNOPTN)
        ZDUMMY28=FOUND
ELSE    PC05=.1
        ZDUMMY28 = FOUND
;

RULE 29
IF      PNOPTN >.01
THEN    PC10=(PNOPTN)
        ZDUMMY29=FOUND
ELSE    PC10=.01
        ZDUMMY29 = FOUND
;


RULE 30
IF      ZDUMMY28 = FOUND AND
        ZDUMMY29 = FOUND
THEN    PC01 = 1
        ZSTEP=((PC01-PC05)/4)
        PC02 = (PC01-ZSTEP)
        PC03 = (PC02-ZSTEP)
        PC04 = (PC03-ZSTEP)
        ZSTEP=((PC05-PC10)/5)
        PC09 = (PC10+ZSTEP)
        PC08 = (PC09+ZSTEP)
        PC07 = (PC08+ZSTEP)
        PC06 = (PC07+ZSTEP)
        FDISPLAY RESULTS,"THE SUGGESTED CHAMBER PRESSURE RATIOS ARE"
        FDISPLAY RESULTS,"PC/PTN[1]={PC01}"
        FDISPLAY RESULTS,"PC/PTN[2]={PC02}"
        FDISPLAY RESULTS,"PC/PTN[3]={PC03}"
        FDISPLAY RESULTS,"PC/PTN[4]={PC04}"
        FDISPLAY RESULTS,"PC/PTN[5]={PC05}"
        FDISPLAY RESULTS,"PC/PTN[6]={PC06}"
        FDISPLAY RESULTS,"PC/PTN[7]={PC07}"
        FDISPLAY RESULTS,"PC/PTN[8]={PC08}"
        FDISPLAY RESULTS,"PC/PTN[9]={PC09}"
```

```
          FDISPLAY RESULTS,"PC/PTN[10]={PC10}~"
          SAVEFACTS OUTDAT
          CLROFF
          CALL OUTREAD,""
          CLRON
          CALL BAUER,""
          CALL RENAM,""
          ZCORRECTPRESS=FOUND
ELSE      ZCORRECTPRESS=FOUND
;

RULE 35
IF        PC10>(PNOPTN) AND
          PNOPTN>.001
THEN      PC01=(PC10-((PC10-PNOPTN)/2))
          PC02=(PNOPTN)
          ZDUMMY35=YES
;

RULE 36
IF        PC10<(PNOPTN)
THEN      PC01=(PC10)
          PC02=.01
          ZDUMMY35=YES
;

RULE 37
IF        PNOPTN<.001
THEN      PC02=.001
          PC01=(PC10-((PC10-PC02)/2))
          ZDUMMY35=YES
;

RULE 38
IF        PC10=(PNOPTN)
THEN      PC01=.01
          PC02=.009
          ZDUMMY35=YES
;

RULE 40
IF        ZDUMMY35=YES AND
          ZRATIO >.98
THEN      PC10 = (@EXP(ZD*@LOG(1/(1+ZA*ZMACH*ZMACH))))
          ZSTEP= ((PC02-PC10)/8)
          PC03 = (PC02-ZSTEP)
          PC04 = (PC03-ZSTEP)
```

```
         PC05 = (PC04-ZSTEP)
         PC06 = (PC05-ZSTEP)
         PC07 = (PC06-ZSTEP)
         PC08 = (PC07-ZSTEP)
         PC09 = (PC08-ZSTEP)
         FDISPLAY RESULTS,"PC/PTN[11]={PC01}"
         FDISPLAY RESULTS,"PC/PTN[12]={PC02}"
         FDISPLAY RESULTS,"PC/PTN[13]={PC03}"
         FDISPLAY RESULTS,"PC/PTN[14]={PC04}"
         FDISPLAY RESULTS,"PC/PTN[15]={PC05}"
         FDISPLAY RESULTS,"PC/PTN[16]={PC06}"
         FDISPLAY RESULTS,"PC/PTN[17]={PC07}"
         FDISPLAY RESULTS,"PC/PTN[18]={PC08}"
         FDISPLAY RESULTS,"PC/PTN[19]={PC09}"
         FDISPLAY RESULTS,"PC/PTN[20]={PC10}"
         SAVEFACTS OUTDAT
         CLROFF
         CALL OUTREAD,""
         CLRON
         CALL BAUER,""
         ZCOUNT=1
         ZBASEPRESS = FOUND
ELSE     ZBASEPRESS = REDO
;

RULE 49
IF       YSTARTCALC = NO
THEN     WOPEN 3,0,0,11,79,7
         ACTIVE 3
         DISPLAY "The BAUER program was unable to calculate a diffuser
flow starting point.  Therefore no started region will be show on the
diffuser performance curve.

Strike any key to contnue.~"
         ZCALCCHECK = PROBLEM
ELSE     ZCALCCHECK = OK
;

!   RULE PORTION OF EXPERT SYSTEM THAT ANALYSIS RESULTS OF BAUER PROGRAM
!-----------------------------------------------------------------------

RULE 2000
IF       XJORN >= 0.0 AND
         M3>.98
THEN     FJDCHOKEREASON=INTERNAL CNF 50
;
```

```
RULE 2010
IF       MB>.98 AND
         XXKW>0.01 AND
         XXKW<(.8*ZKWS)
THEN     FJDCHOKEREASON=WATERSPRAY CNF 50
;

RULE 2011
IF       MB>.98 AND
         XXKW>=(.8*ZKWS)
THEN     FJDCHOKEREASON=WATERSPRAY CNF 80
;

RULE 2020
IF       MB>.98 AND
         XASDAN > 0.0 AND
         XCDS > 0.0
THEN     FJDCHOKEREASON=DRAG CNF 50
;

RULE 2030
IF       MB>.98 AND
         YABEDAN<(.9*YABOAN) AND
         YABEDAN>(.5*YABOAN)
THEN     FJDCHOKEREASON=AREA CNF 50
;

RULE 2031
IF       MB>.98 AND
         YABEDAN<=(.5*YABOAN)
THEN     FJDCHOKEREASON=AREA CNF 80
;
RULE 2100
IF       MB>.98 OR
         M3>.98
THEN     FJDCHOKE=YES
ELSE     FJDCHOKE=NO
;

RULE 2201
IF       FJDCHOKE = YES AND
         PCS < (1.5*PC)
THEN     STARTED = NO
ELSE     STARTED = YES
;
```

```
RULE 2210
IF        FJDCHOKE=NO
THEN      FJDCHOKEREASON=NONE
;

RULE 2220
IF        YKE>0.0 AND
          YKE<.3 AND
          M3>.98
THEN      FJDCHOKEREASON=INTERNAL_W_EXTERNALBLEED CNF 50
;

RULE 2221
IF        YKE>=.3 AND
          M3>.98
THEN      FJDCHOKEREASON=INTERNAL_W_EXTERNALBLEED CNF 90
;

RULE 2225
IF        YKP>0.0 AND
          YKP<.5 AND
          M3>.98
THEN      FJDCHOKEREASON=INTERNAL_W_POROUSJETSTR CNF 50
;

RULE 2228
IF        YKP>=.5 AND
          M3>.98
THEN      FJDCHOKEREASON=INTERNAL_W_POROUSJETSTR CNF 80
;

RULE 2230
IF        YKE>0.0 AND
          YKE<.5 AND
          MB>.98
THEN      FJDCHOKEREASON=EXTERNALBLEED CNF 50
;

RULE 2231
IF        YKE>=0.5 AND
          MB>.98
THEN      FJDCHOKEREASON=EXTERNALBLEED CNF 90
;

RULE 2240
IF        STARTED = NO
THEN      EFFICIENCY = NULL
```

```
;

RULE 2250
IF       STARTED = YES AND
         YSLOPE>45
THEN     EFFICIENCY = GOOD
;

RULE 2260
IF       STARTED = YES AND
         YSLOPE<6.3
THEN     EFFICIENCY = POOR
;

RULE 2270
IF       STARTED = YES AND
         YSLOPE>6.3 AND
         YSLOPE<45
THEN     EFFICIENCY=OK
;

RULE 2280
IF       MB>.98 AND
         M10MN> 0.0 AND
         XXKW<.04 AND
         YTT10TTN> 1.0
THEN     FJDCHOKEREASON=THERMAL CNF 50
;

RULE 2281
IF       MB>.98 AND
         M10MN> 0.0 AND
         XXKW>0.04 AND
         YTT10TTN> 1.0
THEN     FJDCHOKEREASON=THERMAL CNF 30
;

RULE 2290
IF       MB>.98 AND
         XYKI > 0.0 AND
         XYKI < 0.5
THEN     FJDCHOKEREASON=ENGINE_BLEED CNF 50
;

RULE 2291
IF       MB > .98 AND
         XYKI >= 0.5
```

```
THEN      FJDCHOKEREASON=ENGINE_BLEED CNF 80
;

RULE 2300
IF        MB>.98 AND
          M10MN>0.0 AND
          YHAM>0.0
THEN      FJDCHOKEREASON=AFTERBURN CNF 50
;

RULE 5000
IF        FJDCHOKE <> UNKNOWN AND
          FJDCHOKEREASON <> UNKNOWN AND
          STARTED <> UNKNOWN AND
          EFFICIENCY <> UNKNOWN
THEN      ANALYSIS = COMPLETE
;

! RULE PORTION OF THE EXPERT SYSTEM THAT SELECTS WORDING FOR DISPLAY
!-------------------------------------------------------------------------

RULE 6000
IF        FJDCHOKE = YES
THEN      ACTIVE 1
DISPLAY"
The diffuser has choked for the following reasons:"
FDISPLAY RESULTS,"
The diffuser has choked for the following reasons:"
          CHOKETEXT = ASSIGNED
ELSE      ACTIVE 1
          DISPLAY"
The diffuser did not choke"

          FDISPLAY RESULTS,"
The diffuser did not choke"
          CHOKETEXT = ASSIGNED
;

RULE 6010
IF        FJDCHOKE = NO
THEN      FJDCHOKEREASONTEXT = NONE
;

RULE 6100
IF        STARTED = NO
THEN      ACTIVE 1
          FORMAT PCS, 7.4
```

```
        FORMAT PC, 7.4
        FORMAT PBOPTNS, 7.4
        FORMAT PBOPTN, 7.4
        DISPLAY"The diffuser has choked before the nozzle flow can start
                and develope fully

    diffuser started at      PC/PTN={PCS}        PB/PTN={PBOPTNS}
    diffuser choked at       PC/PTN={PC}         PB/PTN={PBOPTN}


Strike any key to continue to choke analysis ...^"



    FDISPLAY RESULTS,"The diffuser has choked before the nozzle flow can start
                and develope fully

    Diffuser started at      PC/PTN={PCS}        PB/PTN={PBOPTNS}
    Diffuser choked at       PC/PTN={PC}         PB/PTN={PBOPTN}"

        FFULLTEXT = ASSIGNED
ELSE    FORMAT PTN1, 7.2
        FORMAT PN1, 8.3
        FORMAT YMBA, 6.3
        FORMAT ALT, 7.0
        FORMAT PCS, 7.4
        FORMAT PC, 7.4
        FORMAT PBOPTNS, 7.4
        FORMAT PBOPTN, 7.4
  DISPLAY"
The diffuser flow has started and is flowing full

Most testing should be done around the diffuser started chamber pressure of
PC/PTN={PCS}.  In this region of the performance curve the test rhombus
is shortened, but the diffuser will operate with the smallest value of PTN
for a given PB.

The diffuser will operate in the started conditions while exhausting
to atmousphere at:

    PTN = {PTN1} psia   PB = 15 psia  MB = {YMBA}  PN = {PN1} psia
                Simulated Altitude = {ALT} Ft

The Nozzle will operate at it's design point (PC=PN) at:   PC/PTN={PNOPTN}

Strike any key to continue to choke analysis...^"
```

```
 FDISPLAY RESULTS,"The diffuser flow has started and is flowing full

Most testing should be done around the diffuser started chamber pressure of
PC/PTN={PCS}.  In this region of the performance curve the test rhombus
is shortened, but the diffuser will operate with the smallest value of PTN
for a constant PB.

The diffuser will operate in the started conditions while exhausting
to atmousphere at:

    PTN = {PTN1} psia   PB = 15 psia  MB = {YMBA}  PN = {PN1} psia
                Simulated Altitude = {ALT} Ft

The Nozzle will operate at it's design point (PC=PN) at:   PC/PTN={PNOPTN}"

          FFULLTEXT = ASSIGNED
;

RULE 6110
IF        FJDCHOKEREASON1=INTERNAL
THEN      ACTIVE 1
          FORMAT XKJ, 8.4
DISPLAY"- Internal choking (M3=1.0) at Region 3 with a Jet Stretcher
bypass flow of KJ = {XKJ}.  To reduce choking and achieve a lower PC,
enlarge L, the distance between the Jet Stretcher exit and the diffuser
entrance, or increase A3, the radial area between the Jet Stretcher
and the diffuser."

FDISPLAY RESULTS,"- Internal choking (M3=1.0) at Region 3 with a Jet Stretcher
bypass flow of KJ = {XKJ}.  To reduce choking and achieve a lower PC,
enlarge L, the distance between the Jet Stretcher exit and the diffuser
entrance, or increase A3, the radial area between the Jet Stretcher
and the diffuser."
           FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6120
IF        FJDCHOKEREASON1=WATERSPRAY
THEN      ACTIVE 1
          FORMAT XXKW, 8.3
          FORMAT ZKWS, 8.3
DISPLAY" - Diffuser choking at exit (MB=1.0), waterspray mass flow to nozzle
mass flow ratio, KWN, is excessive.  KWN = {XXKW} should be 10% to 20%
of the flow saturation value of KWN = {ZKWS}."

FDISPLAY RESULTS," - Diffuser choking at exit (MB=1.0), waterspray mass flow to nozzle
mass flow ratio, KWN, is excessive.  KWN = {XXKW} should be 10% to 20%
```

```
of the flow saturation value of KWN = {ZKWS}."
          FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6130
IF        FJDCHOKEREASON1=AREA
THEN      ACTIVE 1
          FORMAT YABOAN, 6.2
          FORMAT YABEOAN, 6.2
DISPLAY" - Diffuser choking at exit (MB=1.0), diffuser minimum area
ABE/AN* = {YABEOAN} is less than the diffuser area AB/AN* = {YABOAN}.
The reduction in area can cause the diffuser to choke."

FDISPLAY RESULTS," - Diffuser choking at exit (MB=1.0), diffuser minimum area
ABE/AN* = {YABEOAN} is less than the diffuser area AB/AN* = {YABOAN}.
The reduction in area can cause the diffuser to choke."


          FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6140
IF        FJDCHOKEREASON1=DRAG
THEN      ACTIVE 1
          FORMAT XCDS, 7.3
          FORMAT XASOAN, 8.3
DISPLAY"- Diffuser choking at exit (MB=1.0), the model drag is too large;
Either the diffuser area must be increased or the model size decreased."

FDISPLAY RESULTS,"- Diffuser choking at exit (MB=1.0), the model drag is too large;
Either the diffuser area must be increased or the model size decreased."
          FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6150
IF        FJDCHOKEREASON1=EXTERNALBLEED
THEN      ACTIVE 1
          FORMAT YKE, 8.5
DISPLAY" - Diffuser choking at exit (MB=1.0), external bleed flow to nozzle
mass flow ratio, KE, is excessive.  The nozzle is having to pump too much
mass flow out of the test chamber.  KE = {YKE} should be reduced."

FDISPLAY RESULTS," - Diffuser choking at exit (MB=1.0), external bleed flow to nozzle
mass flow ratio, KE, is excessive.  The nozzle is having to pump too much
mass flow out of the test chamber.  KE = {YKE} should be reduced."
          FJDCHOKEREASONTEXT=ASSIGNED
;
```

```
RULE 6160
IF        FJDCHOKEREASON1=INTERNAL_W_EXTERNALBLEED
THEN      ACTIVE 1
          FORMAT YKE, 8.5
DISPLAY" - Diffuser choking at area between jet stretcher and diffuser (M3=1.0),
external bleed flow to nozzle mass flow ratio, KE, is excessive.
The nozzle is having to pump too much mass flow out of the test chamber.
KE = {YKE} should be reduced, or the area A3 increased by enlarging the diffuser."

FDISPLAY RESULTS,"- Diffuser choking at area between jet stretcher and diffuser (M3=1.0),
external bleed flow to nozzle mass flow ratio, KE, is excessive.
The nozzle is having to pump too much mass flow out of the test chamber.
KE = {YKE} should be reduced, or the area A3 increased by enlarging the diffuser."
             FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6161
IF        FJDCHOKEREASON1=INTERNAL_W_POROUSJETSTR
THEN      ACTIVE 1
          FORMAT YKP, 8.5
DISPLAY" - Diffuser choking at area between jet stretcher and diffuser (M3=1.0),
porous jet stretcher flow to nozzle mass flow ratio, KP, is excessive.
The nozzle is having to pump too much mass flow out of the test chamber.
KP = {YKP} should be reduced, or enlarge L, the distance between the jet
stretcher exit and the diffuser entrance, or increase AB to increase A3,
the radial area between the jet stretcher and the diffuser."

FDISPLAY RESULTS,"- Diffuser choking at area between jet stretcher and diffuser (M3=1.0),
external bleed flow to nozzle mass flow ratio, KE, is excessive.
The nozzle is having to pump too much mass flow out of the test chamber.
KE = {YKE} should be reduced,  or enlarge L, the distance between the jet
stretcher exit and the diffuser entrance, or increase AB to increase A3,
the radial area between the jet stretcher and the diffuser."
             FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6162
IF        FJDCHOKEREASON1=ENGINE_BLEED
THEN      ACTIVE 1
          FORMAT XYKI, 8.5
DISPLAY" - Diffuser choking at exit (MB=1.0),
engine bleed flow to engine mass flow ratio, KI, is excessive.
Too much momentum is being lost by mass spilling out of the engine inlet.
KI = {XYKI} should be reduced, or the diffuser area increased."

FDISPLAY RESULTS," - Diffuser choking at exit (MB=1.0),
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```
engine bleed flow to engine mass flow ratio, KI, is excessive.
Too much momentum is being lost by mass spilling out of the engine inlet.
KI = {XYKI} should be reduced, or the diffuser area increased."

             FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6170
IF        EFFICIENCY = NULL
THEN      EFFICIENCYTEXT = NONE
;

RULE 6180
IF        EFFICIENCY = GOOD
THEN      ACTIVE 1
DISPLAY "The diffuser performance curve is a near vertical line in the
diffuser started region.  This shows a diffuser with a good, efficient
pumpdown of the chamber.  SLOPE = {YSLOPE}"

FDISPLAY RESULTS,"The diffuser performance curve is a near vertical line in the
diffuser started region.  This shows a diffuser with a good, efficient
pumpdown of the chamber.  SLOPE = {YSLOPE}"
          EFFICIENCYTEXT=ASSIGNED
;

RULE 6190
IF        EFFICIENCY = POOR
THEN      ACTIVE 1
DISPLAY "The diffuser performance curve is along the PC=PB line in the
diffuser started region.  This shows a diffuser with a poor
pumpdown of the chamber.  The diffuser efficiency might be inproved by
decreasing the diffuser area, AB.  SLOPE = {YSLOPE}"

FDISPLAY RESULTS,"The diffuser performance curve is along the PC=PB line in the
diffuser started region.  This shows a diffuser with a poor
pumpdown of the chamber.  SLOPE = {YSLOPE}"
          EFFICIENCYTEXT=ASSIGNED
;

RULE 6200
IF        EFFICIENCY = OK
THEN      ACTIVE 1
DISPLAY "The diffuser performance curve is between the PC=PB line
and a near vertical line in the diffuser started region.  This shows
a diffuser with an OK pumpdown of the chamber.  SLOPE = {YSLOPE}"

FDISPLAY RESULTS,"The diffuser performance curve is between the PC=PB line
```

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and a near vertical line in the diffuser started region.  This shows a diffuser
with an OK pumpdown of the chamber.  SLOPE = {YSLOPE}"
          EFFICIENCYTEXT=ASSIGNED
;

RULE 6210
IF        FJDCHOKEREASON1=THERMAL
THEN      ACTIVE 1
          FORMAT XCDS, 7.3
          FORMAT XASOAN, 8.3
DISPLAY"- Diffuser choking at exit (MB=1.0), the model engine is
operating, introducing heat into the diffuser and possibly causing thermal
choking.  Possible solutions are; enlarge the diffuser area,
or add a small amount of water spray, KW, less than the saturated
value of KWS = {ZKWS}, for cooling."

FDISPLAY RESULTS,"- Diffuser choking at exit (MB=1.0), the model engine is
operating, introducing heat into the diffuser and possibly causing thermal
choking.  Possible solutions are; enlarge the diffuser area,
or add a small amount of water spray, KW, less than the saturated
value of KWS = {ZKWS}, for cooling."
          FJDCHOKEREASONTEXT=ASSIGNED
;

RULE 6210
IF        FJDCHOKEREASON1=AFTERBURN
THEN      ACTIVE 1
          FORMAT YHAM, 7.3
DISPLAY"- Diffuser choking at exit (MB=1.0), the model engine is
operating with afterburning downstream of the test article, introducing
heat energy into the diffuser of the value HA = {YHAM} and possibly causing
thermal choking.  Possible solutions are; enlarge the diffuser area, or add
a small amount of water spray, KW, less than the saturated value of
KWS = {ZKWS}, for cooling."

FDISPLAY RESULTS,"- Diffuser choking at exit (MB=1.0), the model engine is
operating with afterburning downstream of the test article, introducing
heat energy into the diffuser of the value HA = {YHAM} and possibly causing
thermal choking.  Possible solutions are; enlarge the diffuser area, or add
a small amount of water spray, KW, less than the saturated value of
KWS = {ZKWS}, for cooling."


          FJDCHOKEREASONTEXT=ASSIGNED
;

ASK       ZSUGGESTEDPC : "Do you wish to run the simulation with suggested values
```

```
of test cell and nozzle reservoir pressure ratios?";

CHOICES   ZSUGGESTEDPC : YES, NO;

ASK ZPREFERENCE: "Do you wish to continue with PT10PTN=1.0 and the
calculated KI, or stop the analysis?

   INDICATE PREFERENCE:";

CHOICES   ZPREFERENCE  : CONTINUE, STOP_ANALYSIS;


PLURAL: FJDCHOKEREASON;
PLURAL: FJDCHOKEREASONTEXT;
```

APPENDIX E

DIFFUSER PERFORMANCE PROGRAM

SETUP

Program Setup and System Requirements

The Diffuser Expert System will run on an IBM compatible PC with the following:

- MS-DOS Version 2.0 or higher
- 512k of RAM free of memory resident programs
- A hard disk
- EGA Graphics
- Epson command set compatible printer

To run the Diffuser Expert System, create a dedicated directory on the hard disk and copy the entire contents of the three program disks into it. Type VPX DIFFUSER to start the program. The menu shown in Fig. 9. will appear when the program executes. The menu reappears after successful completion of a selected option.

VITA

Gary W. Jarrell was born in Manchester, Tennessee, on April 29, 1962. He was educated in the Tullahoma school system, attending East Lincoln Elementary, East Middle, and Tullahoma High School, graduating in 1980. The same year he entered The University of Tennessee in Knoxville and in June of 1985 received a Bachelor of Science degree in Mechanical Engineering. While attending The University of Tennessee, he began the Co-Operative Program, working at Arvin/Calspan, an operating contractor for the Arnold Engineering Development Center, Aronld Air Force Station, Tennessee. After graduation from The University of Tennessee, he began working at Arvin/Calspan in July of 1985. He is currently working as a Plant Engineer with the Plant Operations Group.

The author began employer sponsored graduate study at The University of Tennessee Space Institute, Tullahoma, Tennessee, in 1985. He received a Master of Science degree with a major in Mechanical Engineering from The University of Tennessee, Knoxville in 1991.

Gary is currently living in Tullahoma, Tennessee, with his wife,the former Direnda Harrelson, and their son, Clay.