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**A Computer Program for Analysis of Tornado-Induced
Transients in Ventilation Systems**

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TVENT

A COMPUTER PROGRAM FOR ANALYSIS OF TORNADO-INDUCED TRANSIENTS IN VENTILATION SYSTEMS

by

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ABSTRACT

This report describes TVENT, a portable FORTRAN computer program for predicting flows and pressures in a ventilation system subject to a tornado. The pressure and flow values calculated by TVENT can be used as a basis for structural analysis. TVENT is a one-dimensional, lumped-parameter model with incompressible flow augmented by fluid storage. The theoretical basis for the mathematical modeling and analysis is presented, and a description of the input for the computer code is provided. Modeling techniques specific to ventilation systems are described. Sample problems illustrate the use of TVENT in analyzing ventilation systems. Other sample problems illustrate modeling techniques used in reducing complex systems.

I. INTRODUCTION

Ventilation systems are necessary within most structures to provide fresh, clean air for the occupants, and for safety. In nuclear facilities, these systems are especially important to control hazardous gases and to prevent the release of toxic or radioactive particulates. Maintenance of differential pressures between containment areas of nuclear fuel cycle facilities is required to prevent the spread of radioactive dust. Atmospheric pressure drops as large as 20.7 kPa (3 psi) may occur during a tornado with

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subsequent undesirable pressures and flows in a ventilation system. A digital computer code TVENT has been developed to predict the transient response of ventilation systems to tornado-induced pressure transients. Using the computer code, an analyst can identify points of excessive depressurization and areas of high flow.

TVENT is written in FORTRAN IV and is designed to be portable; that is, it can be easily transferred from one computer to another with a minimum of change. To demonstrate this capability, sample problems have been run on the CDC 7600 and IBM 360 computers. The portability requirements precluded free format input and film plotting options, which are not found on some computer installations.

Input is organized and formatted in a way that is natural to the designer or engineer who prepares the data for analysis. Input error diagnostic messages are printed to help find errors in data preparation. Checks are made and messages are supplied when possible modeling errors are detected. Output lists and summaries are formatted and organized in a way that is helpful in determining the effects of a transient on system components and the integrity of pressure differentials between containment areas. Line printer plots of selected pressures and flows are also generated.

TVENT solves steady-state and transient pressure distributions of complex ventilation networks and calculates system flows based on assumptions of

- One-dimensional, isothermal flow,
- Lumped parameters (neglecting spatial distribution of components), and
- Incompressible flow with fluid storage at nodes.

A problem can be stopped and subsequently restarted. This is advantageous when calculating ventilation systems with large time constants or analyzing complex systems requiring long computing times.

Appendix A provides supplemental information for installing the program as an overlay. Appendices B and C are useful summaries of input requirements and error messages. Appendix D supplies a theoretical basis for the computer code. Numerical representation of the equations developed in Appendix D is given in Appendix E. TVENT does not include inertia and shock. The justification for this omission is presented in Appendix F.

The computer code is available from the Argonne National Laboratory Code Center.

II. THE COMPUTER PROGRAM

A. General

The program is structured as a one-level overlay (Fig. II-1) to permit its use on medium-size computers and to allow expansion of the program. Appendix A shows the overlay structure. Five partitions perform the following functions.

Fig. II-1.
TVENT program structure.

B. Required Files

The standard input and output files (normally FORTRAN units 5 and 6, respectively) and the punch file are required. Two temporary read/write scratch files (units 10 and 17) are also required. The files mentioned above are Binary Coded Decimal (BCD) files except unit 10, which is binary.

1. The resident or root segment calls the overlays, controls the overall program flow, provides a common area for transfer of information between overlays, and contains utility routines used by several overlays.
2. The input processor overlay reads and lists the input data, performs error checks on the data, and prints messages when errors are detected.
3. The preprocessor overlay performs checks for modeling errors, initializes parameters and arrays used by the system solver overlay, and edits and lists this processed information.
4. The system solver overlay solves the system of equations discussed in Appendix E and outputs the solution to a scratch file for processing by the output overlay. The steady state solution is checked for possible instability, and warning messages are printed identifying areas in the ventilation system where the pressure drops are extremely low. A deck of punched cards is produced if the restart option is requested.
5. The output processor overlay reads the temporary output file generated during the transient, edits and formats the data for printing, and generates line-printer plots.

Line-printer plotting was chosen to preserve program portability. Users may wish to substitute nonportable plotting to obtain higher quality plots. Source code lines in the subroutines OUTPRC and PLOTPR are isolated with comments to facilitate this substitution.

A significant degree of portability has been achieved. Deletion of seven source statements and replacement of nine source statements converts the CDC version of the program to a form compatible with other machines (IBM, Xerox, etc.).

C. Program Size

The program requires fewer than 30k decimal words to run in the nonoverlaid mode on the CDC 7600 computer. The overlaid version of TVENT requires fewer than 20k decimal words on the same computer.

TVENT requires approximately 136k decimal bytes (34k decimal words) on an IBM 360-91 computer system.

Other computer systems with shorter word lengths will require correspondingly increased storage requirements; that is, the DEC PDP 11 computer (16-bit word or two bytes) requires approximately 69k words to retain the accuracy of the IBM 360.

The nonoverlaid version of TVENT has run on the following computers:

- CDC 7600
- UNIVAC 1108
- UNIVAC 1110
- IBM 360-91
- DEC PDP 10
- CDC CYBER 174
- CDC CYBER 73

D. Problem Size Limitations

The maximum problem size that can be run on TVENT is listed in Table II-1. This has been adequate for problems encountered to date; however, these maximum numbers can easily be increased.

III. MODELING AND SYSTEM DEFINITION

A. General

References 1 through 4 are but a few of the excellent sources on the subject of modeling. A ventilation system model includes system elements (components such as filters, dampers, ducts, blowers) connected together at nodal points (sometimes called junctions) to form networks. The reader is referred to Appendix D and Appendix E for a description of explicit and implicit assumptions made in the formulation of the mathematical model of the system. Other assumptions are frequently made in reducing the size and

TABLE II-1
MAXIMUM PROBLEM SIZE

<u>Maximum Number</u>	<u>System Parameter</u>
500	Branches
400	Nodes
60	Rooms
40	Blowers
20	Boundary Nodes
5	Time Functions
20	Points per Time Function
15	Blower Functions
20	Points per Blower Function
50	Points per Plot
4	Plots per Frame
10	Frames

complexity of large systems. Computer size limitations and cost are instances where size reduction is essential. A model that is too detailed often obscures the primary (first-order) effects and makes analysis difficult. The tradeoff between minimum complexity and an adequate representation of the system is resolved by what most authors call "engineering judgment." Chapters 5-6 of Ref. 5 and Chapters 3-4 of Ref. 4 can help in making modeling decisions. The following discussion provides the user with helpful hints and suggestions specific to setting up the ventilation system model and interpreting the results.

The first and most critical step in setting up the ventilation system model is making a comprehensive schematic showing the system components with their interconnections. Drawings, specifications, material lists, design worksheets, and existing schematics are sources that can be used in deriving a system description. A physical inspection of a facility and consultations

Fig. III-1.
Ventilation system components.

Fig. III-2.
Schematic for ventilation components.

with the designer(s) before and after the schematic is drawn may be necessary to verify that the schematic is an accurate description. At this stage, a lack of data is frequently apparent to the user. While there is no substitute for accurate data, certain assumptions and techniques can make the problem tractable. These techniques, such as worst case analysis, averaging, sensitivity studies, and conservative estimates are discussed later. Figures III-1 and III-2 are presented to show how ventilation system components may be connected in a schematic. Figure III-1 represents a simple ventilation system consisting of several dampers, filters, and one blower inside a building containing a cell or isolated room. The schematic for this simple system is shown in Fig. III-2. Dots indicate nodal points on the schematic. The comprehensive schematic may be subsequently refined and reduced; however, at this stage nothing should be overlooked that might make a contribution to the overall system performance.

B. System Description

1. Definitions

- System - network of components (branches) joined together at points called nodes.
- Branch - defined as a connecting member between upstream and downstream nodal points. A branch contains one component.

Ducts, dampers, filters, and blowers are components that can exist in a branch. Flow is defined for a branch.

- Node - connection point or junction for one or more branches. Volume elements such as rooms, gloveboxes, and plenums are defined as capacitance nodes. Compressibility of the system fluid is accounted for at these capacitance nodes. Boundary points (inlet and exhaust) are defined at nodes. System pressure is also defined at nodes.

2. Simple Systems. Figure III-3 illustrates a simple ventilation system. Nodes are shown as small filled circles and are numbered 1 through 9 without parentheses. Nodes 1 and 9 are boundary nodes. Capacitance node 4 represents the sampling room. Branches are shown in Fig. III-3 at the tips of arrows. The branch numbers are enclosed in parentheses adjacent to their corresponding branches. Note that branch 3 is connected on the upstream side by node 3 and on the downstream side by capacitance node 4. Duct resistance is shown separately in branch 2, whereas it is lumped or considered insignificant compared to the component resistance for branches 4 through 8.

A sample ventilation system is shown in Figs. III-4 and III-5. This example is simple but contains most of the elements common to real ventilation systems. The system features

Fig. III-3.
Simple ventilation system with one-to-one modeling.

Fig. III-4.
Sample ventilation system.

Fig. III-5.
Sample ventilation system schematic.

- Natural bypass around rooms,
- Recirculation,
- Combinations of series and parallel component arrangements,
- Rooms (confinement volumes) with multiple inlets and outlets,
- Duct friction, and
- A network consisting of 30 components and 25 nodal points.

Some components were omitted from Fig. III-4 for clarity, but are included in the schematic of Fig. III-5.

C. System Elements and Modeling Tips

1. System Elements. A branch is defined as a connecting member between nodes and contains only one component. Boundary conditions (pressures

as a function of time) and capacitance are prescribed at the nodal points. Following the lumped-parameter approach, all of the pressure losses for a branch are ascribed to the components contributing the largest pressure loss; thus duct losses may be lumped with the damper loss. Similarly, the effects of components such as elbows or turning vanes are lumped with the duct losses. This is correct so long as the characteristic relationship between pressure drop and flow is the same (has the same exponent value). However, branches should be added when the relationship is not the same, for example, where a duct contains a filter and the duct loss is significant. A common method of representing the pressure-flow relationship is

$$\Delta H = R_c Q^m, \quad (1)$$

where

ΔH = pressure drop across the component (measured or calculated),

R_c = resistance coefficient,

Q = branch volumetric flow (design or measured), and

m = flow exponent (varies between 1.0 for filters to approximately 2.0 for dampers and ducts).

TVENT calculates the resistance coefficients of dampers, filters, ducts, and leakage based on Eq. (1) and the input values of pressure and flow. A user-supplied resistance overrides the calculated value from Eq. (1) and is particularly useful in parameter and sensitivity studies. However, note that any supplied R_c will be used with Eq. (1) in obtaining steady-state and transient results. Consequently, the supplied value must be compatible with Eq. (1).

a. Ducts. Ducts are modeled using the Darcy-Weisbach⁴ equation

$$\Delta H = fL/4R_h(u^2/2g), \quad (2)$$

where

f = nondimensional friction coefficient obtained from the Moody⁴ diagram,

R_h = hydraulic radius defined as the cross-sectional area divided by the wetted perimeter,

L = duct length,
u = average velocity in duct, and
g = acceleration of gravity (ft/s^2 or m/s^2).

Replacing u in Eq. (2) with its equivalent Q/A_c (volume flow divided by the cross-sectional area) one obtains an expression similar to Eq. (1). The friction coefficient varies little for transition or turbulent flow and is considered constant for transient calculations. Note that the quantity $fL/4R_h$ in Eq. (2) can be considered as a number of velocity heads for comparing the relative effects of elbows, duct fittings, and valves (Table 3.1 of Ref. 4 and Tables 3 and 4 of Ref. 6). The duct length L in Eq. (2) should be replaced with L plus the summation of equivalent duct lengths for duct losses given in lengths of equivalent duct.

b. Dampers and Valves. The treatment of dampers is similar to that of ducts. Ducts and dampers are nonlinear system elements. The resistance coefficient is given in terms of a loss coefficient (velocity heads as in Section a). The duct losses may thus be freely lumped with those of dampers. Control valves are not included in this analysis (no change in setting is permitted) as conventional valves would not have time to respond to a rapid tornado transient. Later versions of TVENT may include control valves.

c. Filters. The filters are considered to be linear elements (m in Eq. (1) equals 1). One cannot strictly lump duct effects with the filter losses. In this case, one should linearize the duct losses before lumping with the filters. The user should obtain an $P' = R_c$ (R_c at average flow) and add this to the resistance obtained for the filter. A separate branch should be considered for the duct if losses are a significant fraction of the filter loss. The filter resistance coefficients can be obtained from Ref. 7 for small, clean filters. The resistance of dirty filters is usually estimated as 2 to 5 times that of clean filters.

Clean HEPA filters may be specified on branch description cards. Experimental curves reside in TVENT for clean, 24-in. (0.61-m) and 8-in. (0.203-m) HEPA filters. The curves are used when filter types H24 and H8 are specified on the branch definition cards. User-supplied resistance will be

ignored for this selection. Experimental curves for dirty HEPA filters will be added when information becomes available.

d. Blowers and Fans. The blower head/flow characteristic curve is approximated by a series of straight line segments as in Fig. III-6. The curve is valid for a given blower speed and will be shifted vertically for other blower speeds. The appropriate curve can be obtained from the manufacturer's literature. The blower is placed in a branch as are filters, dampers, and ducts. A blower is considered an active element in the system because it supplies energy to the system.

Tornado depressurization can produce backflow (negative flow) when applied to the supply side of a blower and outrunning flow (positive flow with negative head) when applied to the discharge side. Little is known about blowers operating in these regions.

Surface effect ships experience backflow in their lift fans when traversing heavy seas. The fans are similar to those used in ventilation systems. Static and dynamic tests have been performed on these fans.⁸

Figure III-7 illustrates a typical test for these fans. Note the steep slope in the backflow region. The

Fig. III-6.
Blower characteristics
representation.

Fig. III-7.
Backflow characteristics.

nondimensional flow and head coefficients are defined as

$$\text{Flow coefficient } \phi = Q / \pi D_o^2 \omega (\pi D_o N / 60) \quad (3)$$

$$\text{Head coefficient } \psi = P_t / \rho (\pi D_o N / 60)^2 \quad (4)$$

where,

Q = volumetric flow rate through one fan inlet (one-half the flow of a double entry), m^3/s ,

D_o = impeller tip diameter, m ,

ω = impeller tip width ratio,

N = fan speed, rpm ,

P_t = fan discharge total pressure (static + dynamic) that exists within the fan discharge duct and near the exit, Pa , and

ρ = ambient density of the air, kg/m^3 .

Since D_o , ρ , ω , and N are assumed constant for our application, this curve is indicative of what might occur for a ventilation fan. Data were not available for the outrunning case; however, one designer felt that the normal curve could be extrapolated into the fourth quadrant to the extent of one cut-off head (head at zero flow).

The above information is only qualitative, and more data are needed before the blowers can be accurately modeled in these abnormal flow regions. However, this information combined with worst case assumptions may give a designer guidelines for determining the effects of these abnormal operating conditions on system integrity.

As an approximation, we use the same slope in the backflow quadrant as that to the right of the typical operating point in our blower models. This practice is felt to be conservative.

Blower oscillation has been observed for some problems. The solution algorithm tends to cycle during the transient between the maximum/minimum point and the zero flow axis on the blower characteristic curve (see Fig. III-7). Convergence is not achieved in these cases, and an alternate representation of the blower characteristic curve must be used. The slope of the alternate curve should be negative as in Fig. III-6. The curve may be nearly flat (the

slope may approach but not equal zero). The dynamic tests³ indicate a band of values around the steady-state characteristic curve shown in Fig. III-7. Further, the transient induced by a tornado does not dwell for a significant period of time in the oscillatory region of the blower curve. Therefore, the required alternate representation may not be a poor assumption.

e. Rooms and cells. Rooms, cells, and containment volumes are specified at nodal points. The capacitance coefficient is a function of room volume estimated from construction drawings. A room acts as an accumulator and provides damping for the flow and pressure transients. Manifolds and returns may also have sufficient volume to require a capacitance node. This is indicated by a message produced by TVENT when it finds that the duct volume is greater than half the volume of the smallest room. The capacitance coefficient can be varied for parameter studies by adjusting the room volume.

The capacitance of ducts is not included automatically when duct dimensions are specified; capacitance is included only for rooms defined at nodal points. A fictitious room must therefore be added to prescribe the capacitance of a duct.

Dimensions of rooms must always be specified although capacitance only enters into transient calculations.

f. Boundary Nodes. A supply or exhaust opening in the ventilation system exposed to ambient pressure or the tornado is considered a boundary node. This node can be held at a constant initial pressure or pressure can vary by specifying a time function as described in the input section. In either case, the pressure is known and the node acts as a source or a sink to the rest of the system.

g. Leakage. Effective leakage can be approximated in the model through the use of a boundary node and a fictitious duct. The leak rate is usually specified as a flow rate. However, a variable leak can be attained by calculating a resistance coefficient from Eq. (1) based on the steady leak (flow rate) and a pressure drop across the fictitious duct. This pressure drop can be calculated from the boundary node pressure minus the steady-state pressure at the point where the fictitious branch is connected to the system. One could specify a filter in the fictitious branch and use an exponent of 1.0

in Eq. (1). However, it is usually more convenient to use the default (blank) specification on the branch description and use an exponent of 2.0 in Eq. (1).

2. Reduction of System Complexity. A complex ventilation network can be simplified by using any or all of the following techniques:

(1) ignoring minor effects, (2) reducing of the system to smaller subsystems by partitioning, and (3) using the concept of equivalency. The overriding assumption in implementing these techniques is that the dominant system characteristics remain unaltered for the assumed perturbations to the system.

The comprehensive schematic frequently contains subsystems that might be considered peripheral to the system of interest. We wish to determine whether or not contaminated materials are released from the ventilation system because of component failure or loss of pressure differentials between containment volumes. One should use this information in partitioning the system into subsystems. Clearly, subsystems with separate supplies that provide only small flows to a common return might be ignored for this analysis. Similarly, loops that are normally isolated from the system by a valve, such as gas sampling or cleanup systems in parallel with the main system, might be ignored or replaced by two or three elements representing resistance and capacitance. Sample problems 4-7 in Sec. VI show how this might be accomplished. The simple ventilation system in Fig. III-3 was reduced from 9 nodal points and 8 branches to 6 nodal points and 5 branches (Fig. III-8) by lumping two dampers and the duct resistance (branches 1, 2, and 3 of Fig. III-3). Other subsystems may be partitioned and the nodes that connect them to the main system can be perturbed to observe the transient response of the subsystems. This enables the user to determine what parameters or time functions can be used to approximate the subsystem for the larger, more comprehensive model.

The method of equivalent networks in Thevenin and Norton,⁵ must be applied carefully since the method is applicable only to linear networks. The rooms provide damping of the tornado-induced transient, and it is therefore conservative to underestimate room volumes. In general, the main system of interest should be modeled as accurately as possible and later peripheral subsystems can be added to determine their effect. An added bonus (the minimum

Fig. III-8.

Lumped modeling of simple ventilation system.

using this method of successively increasing the complexity of the model.

A sensitivity study can be performed in which coefficients of individual components are varied by a factor of two about the design value, holding other values constant during the transient. This study can show the effects of an individual component on overall system response and indicate areas where better values should be obtained for accurate modeling.

3. Evaluation of Results. The results obtained from a model should be correct at steady-state and during a transient. The user should verify that the inlet flow equals the outlet flow plus the leakage for the overall system at steady-state. A smaller convergence criterion may be required if the summation of flows differs from zero by more than a small percentage.

Bearing in mind that intuition can lead one astray in analyzing complex systems, the user should examine the output critically and ask, "Does this physically make sense?" Warning messages produced by TVENT, such as "Pressure Drop Extremely Low in Branch n," can be useful in detecting a poor design or model. The printer plots can be used advantageously in checking the transient response (up to 40 variables can be shown on ten frames of printer plots). Sensitivity analysis is useful in observing the ranges of variables, for averaging the coefficients when required, and for refining the model.

The current mathematical model in TVENT does not contain the logic necessary for determining failure of a component. Consequently, the user must determine this, recognizing that the transient occurring after the failure will not be modeled accurately. Experimental data (not currently available) are required to determine the point of failure and the component response after failure.

IV. INPUT PREPARATION

A. Data Deck Organization

A typical data deck contains: a) data separator cards that must be present but may be blank or contain descriptive information, b) run control cards that contain problem run parameters (time step size, convergence criterion, etc.), c) input control cards that contain information that governs the reading of input data, and d) data cards describing other aspects of the problem. Table IV-1 shows the card order in which the data must occur. If the number of data items specified on the input control card does not agree with number of data cards provided, the program will try to read data from an adjacent category and will abort with a diagnostic message.

B. Input Card Description

Input cards are described in Tables IV-2 through IV-17 in the approximate order they occur in the card deck.

Abbreviations used under the heading "Data Type" are: a) A/N, for alphanumeric data (any combination of letters and numbers), b) FP, for floating point data, and c) I, for integer data. Alphanumeric data should be left-justified with respect to the first column of the field definition (data should start in the first column of the field). For example, the first character (H) of filter types H24 and H8 should appear in column 47 of the branch description card. The filter type field is defined as columns 47 through 50 of the branch description card. Integer data should be right-justified in the data field (the last data character should appear in the right-most column of the field). For example, the integer 5 placed in column 4 of the branch description card would be interpreted as branch 50, since the field definition encompasses columns 1 through 5. Floating point data are also right-justified. Only large or small floating point numbers require the form $\pm N N N E \pm M M$ where N and M are integers. Intermediate floating point numbers may be specified as $\pm N N \dots N N \dots$ with the decimal point given, or as integers with the decimal point assumed to the extreme right of the number.

Values of data occurring under the heading "Default Value" are used by TVENT if the input data field is left blank.

Appendix B summarizes the extensive input card descriptions. The summary should be useful after the user gains experience in setting up problems for TVENT.

TABLE IV-1
TVENT DATA DECK ORGANIZATION

<u>Card Order</u>	<u>Card Name</u>	<u>Note</u>
1	*Data separator	1
2	TITLE	6
3	*Data separator	1
4	*Data separator	1
5	RUN CONTROL CARD I	2
6	*Data separator	1
7	PRINT/PLOT CONTROL CARD	3
8	*Data separator	5
9	PLOT FRAME DESCRIPTION (cards)	4
10	*Data separator	1
11	RUN CONTROL CARD II	2
12	*Data separator	1
13	BOUNDARY CONTROL CARD	3
14	*Data separator	1
15	GEOMETRY AND COMPONENT CONTROL CARD	3
16	*Data separator	1
17	BRANCH DESCRIPTION DATA (cards)	6
18	*Data separator	1
19	BOUNDARY NODE DATA (cards)	6
20	*Data separator	1
21	TIME FUNCTION CONTROL CARD	} Set
22	TIME FUNCTION DEFINITION (cards)	
23	*Data separator	5
24	ROOM DATA (cards)	4
25	*Data separator	5
26	BLOWER CURVE CONTROL CARD	} Set
27	BLOWER CURVE DESCRIPTION (cards)	
-----+		
28	*Data separator	5
29	SYSTEM PRESSURE (cards)	4

- Notes:
1. Information not used on this card, but card required.
 2. Contains run parameters, required data.
 3. Controls reading of input, required data.
 4. Optional, required only when specified on input control (3).
 5. Optional, as in (4), data ignored as in (1).
 6. Required data.
 - + Restart data replaces cards (28) and (29).

TABLE IV-2 - DATA SEPARATOR CARD DESCRIPTION

Col.(s)	Data Description
1-80	These cards may be left blank or may contain alphanumeric data. The card is used to separate different types of data cards. Contents of this card are ignored by TVENT.

TABLE IV-3 - TITLE CARD DESCRIPTION

Col.(s)	Data Description
1-80	Eighty columns of alphanumeric data are available to the user. These data are used for headings on output lists.

TABLE IV-4 - RUN CONTROL CARD I DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-3	Not used			
4-5	Run option SS - steady-state solution only ST - steady-state plus transient RS - restart problem TP - punch restart deck after transient SP - punch restart deck after steady-state	A/N	ST	
6-10	Problem start time(s)	FP	0.0	
11-15	Transient time step size(s)	FP	1.0	
16-20	Total problem run time(s)	FP	1.0	
21-23	Not used			
24-25	Number of output times	I	10	50
26-29	Not used			
30	Number of special outputs	I	0	5
31-35	First special output time(s)	FP	0.0	
36-40	Second special output time(s)	FP	0.0	
41-45	Third special output time(s)	FP	0.0	
46-50	Fourth special output time(s)	FP	0.0	
51-55	Fifth special output time(s)	FP	0.0	

Transient values of pressure and flow are saved for listing and plotting. These values are equidistant in time between problem start time and total problem time. The number of output times saved is that specified plus one. Additionally, special output times (up to 5) may be requested. These special output times are not included in printer plots.

TABLE IV-5 - PRINT/PLOT CONTROL CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-2	Units for output lists and plots. SI specified here yields pressures (kPa) and flow (m^3/s).	A/N	English Units	
3-5	Entering the letters "ALL" produces lists at every output time (including special outputs).	A/N	(BLANK) Lists produced only at start time, total run time and special output times.	
6-10	Number of pressure plot frames	I	0	10
11-15	Number of flow plot frames	I	0	10

The maximum number of plot frames that can be requested is 10; therefore, the sum of pressure frames and flow frames is 10. These entries may be left blank if printer plots are not desired.

TABLE IV-6 - PLOT FRAME DESCRIPTION CARD

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Total number of curves this frame	I	0	4
6-10	Node/branch number for first curve	I	0	
11-15	Node/branch number for second curve	I	0	
16-20	Node/branch number for third curve	I	0	
21-25	Node/branch number for fourth curve	I	0	
26-35	Scale limit for frame	FP	Blank	

Pressures are calculated at nodal points (nodes), and flows are calculated for branches. This card identifies how many and which nodes or branches are to appear as curves on the print/plot frame. Pressure and flow curves cannot be mixed on the same frame. Pressure frame description cards should appear before the flow frame description cards. These cards may be omitted if plot frames are not requested on the print/plot control card for steady-state runs. A scale limit may be specified for the frame; otherwise, the plot routine finds the maximum value of all the pressures or flows and uses this value as 100% of full scale.

TABLE IV-7 - RUN CONTROL CARD II DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Maximum iterations permitted per time step. The program will abort if convergence has not been achieved for this number of iterations. Ten times this number is permitted for the steady-state calculations.	I	300	
6-15	Convergence criterion.	FP	0.0001	
21-25	Relaxation parameter. A value greater than 1.0 and less than 2.0 can be specified to reduce the number of iterations per time step. This is determined through successive runs and is different for each problem.	FP	1.0	
26-29	Not used			
30	Pressure input option. Insert the letter "P" in this column if pressures at nodal points are to be supplied.	A/N	(Blank) no input pressures supplied	

TABLE IV-8 - BOUNDARY CONTROL CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Total number of time functions for all boundary nodes	I	0	5
6-10	Total number of boundary nodes for this problem	I	2	20
11-20	Value for atmospheric pressure (absolute, psia)	FP	14.7 psia	
21-30	Value for atmospheric temperature (absolute, R)	FP	530 R (60°F)	

TABLE IV-9 - GEOMETRY AND COMPONENT CONTROL CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Number of branch description data cards	I	0	500
6-10	Number of nodes defined for problem (includes boundary nodes)	I	0	400
11-15	Not used			
16-20	Number of rooms defined for problem	I	0	60
21-25	Total number of blower characteristic functions defined for problem	I	0	15

Values of these parameters control the reading of input data and therefore should not exceed maximum values.

TABLE IV-10 - BRANCH DESCRIPTION DATA CARDS

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Branch number	I	0	500
6-10	Upstream node number	I	0	400
11-15	Downstream node number	I	0	400
16-25	Initial estimate of flow (cfm). This value is used to calculate damper, filter, and duct resistance coefficient and to indicate the proper segment on the blower characteristic curve.	FP	0.0	
26-35	Hydraulic radius of duct (in.). Defined as the cross-sectional area divided by the wetted perimeter.	FP	0.0	
36-45	Duct length (ft). This value and the hydraulic radius are used to calculate duct volume. This volume is compared to room volumes for model consistency checks.	FP	0.0	
46	Component type V Damper F Filter B Blower D Duct	A/N	D	
47-50	Component subtype H24 and H8 used in conjunction with component type F specify 24-in. (0.61-m) and 8-in. (0.203-m) clean HEPA filters, respectively.	A/N	Blank	
51-60	Branch pressure differential (in. water gage).	FP	0.0	

TABLE IV-10, CONTD.

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
61-70	Resistance coefficient for branch. This value (if greater than zero) overrides that calculated by TVENT from pressure differential and initial flow.	FP	TVENT calculated value	
71-72	Blower curve identification. Identifies which blower curve to use for component type B.	I		

The branch pressure differential is used with the initial estimate of branch flow to calculate a resistance coefficient employing Eq. (1). The differential pressures are also used to calculate initial guess system pressures if these pressures are not input separately.

The BRANCH DESCRIPTION cards need not be ordered in the input deck (branch 10 might precede branch 5). However, the number of cards should agree with that specified in cols. 1 through 5 of the GEOMETRY AND COMPONENT CONTROL CARD.

TABLE IV-11 - BOUNDARY NODE DATA CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Boundary node number	I	0	400
6	Not used			
7-16	Initial value of pressure at node (in. water gage)	FP	0.0	
17-20	Identification number of time function at this boundary node (see time function data card).	I	0 (Steady value of pressure)	5

TABLE IV-12 - TIME FUNCTION DATA CONTROL CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Time function identifier	I	0	5
6-10	Number of data points in time function definition. A data point is defined as an ordered pair of values of time and pressure.	I	0	20

This card controls the reading of subsequent TIME FUNCTION DEFINITION cards and should precede each time function definition. The TIME FUNCTION DATA CONTROL card is followed by one or more TIME FUNCTION DEFINITION data cards. This set of cards may be present, but is not required for steady-state runs.

TABLE IV-13 - TIME FUNCTION DEFINITION DATA CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-10	Value of time(s), for first time function data point.	FP	0.0	
11-20	Value of pressure (in. water gage), for first time function data point.	FP	0.0	
21-30	Value of time for second time function data point.	FP	0.0	
31-40	Value of pressure for second time function data point.	FP	0.0	
41-50	Value of time for third time function data point.	FP	0.0	
51-60	Value of pressure for third time function data point.	FP	0.0	

Insert as many TIME FUNCTION DEFINITION cards as needed to define all the data points.

TABLE IV-14 - ROOM DATA CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Node number for room.	I	0	400
6-15	Room width (ft)	FP	0.0	
16-25	Room height (ft)	FP	0.0	
26-35	Room length (ft)	FP	0.0	

One card is required per room. The dimensions are used in the calculation of capacitance coefficients and zero volume is not permitted. Room volumes are required input for steady-state runs although they are not used. Duct volume (if significant) must be input as a pseudo room requiring an additional node. Rooms cannot be located at boundary nodes. The ROOM DATA cards need not be in numerical order.

TABLE IV-15 - BLOWER CURVE CONTROL CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-5	Blower curve number identifier	I	0	15
6-10	Number of points defining this blower curve. A point is defined as an ordered pair of values of flow (cfm) and head (in. water gage).	I	0	20

The blower curve data are ordered in the same way as time function data--a curve input control card is followed by one or more curve description cards. One curve control card is required for each blower type. The order of the blower curve is unimportant (curve 3 might precede curve 1); however, this card is used in reading the following blower curve data points and must appear just before the appropriate curve description card(s).

TABLE IV-16 - BLOWER CURVE DATA CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-10	Flow (cfm) for the first point	FP	0.0	
11-20	Blower head (in. water gage) for the first point	FP	0.0	
21-30	Flow for the second point	FP	0.0	
31-40	Blower head for the second point	FP	0.0	
41-50	Flow for the third point	FP		
51-60	Blower head for the third point	FP	0.0	

Figure III-6 illustrates a sample blower characteristic curve that contains backflow (negative flow), normal flow, and outrunning flow (negative head for positive flow). The points that define the linear segments of the blower curve should be ordered algebraically in flow (- to +). A card can accommodate three pairs for values of flow and blower head. Values for curves containing more than three points would appear on successive cards.

TABLE IV-17 - PRESSURE INPUT CARD DESCRIPTION

Col.(s)	Data Description	Data Type	Default Value	Maximum Value
1-15	Pressure (in. water gage) at the first node	FP	0.0	
16-30	Pressure at the second node	FP	0.0	
31-45	Pressure at the third node	FP	0.0	
46-60	Pressure at the fourth node	FP	0.0	
61-75	Pressure at the fifth node	FP	0.0	

One data separator card precedes the PRESSURE INPUT data cards. These cards are required only if column 30 of the RUN CONTROL CARD II is set to P. The values of pressure for boundary nodes may be left blank since these values are supplied on the BOUNDARY NODE DATA cards. Use as many cards as required to define all the system pressures.

C. Restart Procedure

The restart option permits continuation of a solution starting from the last calculated time of the previous solution. This restart capability is useful in debugging large problems before committing to runs that require large amounts of computer time.

RUN CONTROL CARD I is used to specify the restart option. The run option (cols. 4-5) is set to the value RS if restart of a previous problem is desired. Restart is valid only if the run option for the previous problem was selected as TP or SP (transient calculation plus punch, or steady-state calculation plus punch, respectively). Parameters on RUN CONTROL CARD I should be altered for restart. Columns 4-5 should be set to RS, cols. 6-10 (problem start time) should be set to the total problem time of the previous problem and cols. 16-20 should be set to the new total problem time.

A restart deck is listed before output lists. The punched restart deck does not contain spaces between fields (see Table IV-18). This deck should be placed at the end of the normal input deck, and it replaces the data separator card and PRESSURE INPUT cards if they are present.

TABLE IV-18 - RESTART DECK DESCRIPTION

Card Type	Card Description
1	Header card containing the information *^^^RESTART^DATA, in Columns 1-16
2	System pressure card(s). Five values of pressure (in. water gage) are included per card (cols. 1-15, 16-30,60-75). All system pressures (1 to the number of nodal points) are defined on these cards.
3	System flows. Five values of flow (cfm) appear on each card formatted the same as system pressures. All branch flows (1 to the number of branches) are defined on these cards.
4	System resistance coefficients. Each branch resistance is defined, five per card as in system pressures, in order of increasing branch number (1 to number of branches).

D. Sample Input

A simple problem is posed in Fig. IV-1 consisting of 5 nodal points and 4 branches. Boundary conditions are imposed at nodes 1 and 2. Branch numbers are enclosed in parentheses, and nodal point numbers are shown without parentheses (Fig. IV-1(a)). A prefilter is placed in branch 1 ahead of the room at node 3. A bank of HEPA filters appears in branch 2. A damper is placed in Branch 3 before the blower in branch 4. The blower characteristic curve is shown in Fig. IV-1(b), and the tornado transient is shown in Fig. IV-1(c).

The following discussion is keyed to Table IV-19. The input data required for the simple problem shown in Figs. IV-1(a), (b), and (c) are discussed. The required data separator cards are shown as cards 1, 3, 4, 6, 8, 12, 14, 16, 18, 23, 26, 30, and 32. The title card is shown as card 2. The title data will appear as shown on output lists and need not be left-justified.

Nodal Pressures	
Node	IN.W.G. (kPa)
1	0.0 (0.0)
2	-2.0 (-0.5)
4	-3.0 (-0.75)
5	-3.5 (-0.875)

(a)

(b)

(c)

Fig. IV-1. Simple example problem.

TABLE IV-19
INPUT FOR SIMPLE EXAMPLE PROBLEM

CARD NO.	1	56	1011	1516	2021	2526	3031	3536	4041	4546	5051	5556	6061	6566	7071	73	80
1	*																
2			SIMPLE		INPUT	EXAMPLE											
3	*																
4	*	RUN	CONTRL	1													
5		ST	0.0	0.1	10.0	50											
6	*	PRINT/PLT	CONTRL														
7	SI		2	1													
8	*	FRAME	DESCRIPTIONS														
9		2	1	2													
10		4	1	3	4	5											
11		4	1	2	3	4											
12	*	RUN	CONTRL	2													
13		300	0.0001		1.00												
14	*	BOUNDARY	CONTRL														
15		1	2	14.7	530.0												
16	*	GEOMETRY	AND COMPONENT	CONTRL													
17		4	5	1	1	1											
18	*	BRANCH	DATA														
19		1	1	3	10000												
20		3	4	5	10000												
21		2	3	4	10000												
22		4	5	2	10000												
23	*	BOUNDARY	NODE	DATA													
24		1	0	0	1												
25		2	0	0													

TABLE IV-19 CON'T

[illegible]

A run option of steady-state solution followed by transient calculation is specified by characters ST on card 5. The initial value of time is shown as 0.0, followed by a value of 0.1 for the transient time step. The length of the transient is shown as 10.0 s followed by a request for 50 outputs for plotting (every second time step).

Print/plot control information is shown on card 7. A request for Standard International (SI) units on output lists and plots are specified by the characters SI in cols. 1 and 2. Two pressure plot frames are requested on card 7, followed by a request for one flow plot frame. The absence of characters ALL following the request for SI units means that only the first (steady-state) and last (time = 10.0 s) output lists will be printed. The pressure plot frames are described on cards 9 and 10. Two boundary node pressure curves are requested for frame one. Four pressure curves (associated with nodal points 1, 3, 4 and 5) are requested for frame two. A flow plot frame is described on card 11 following the pressure plot frame descriptions. Four branch flows are requested for branches 1, 2, 3, and 4. Since scale limits have not been specified in cols. 26-35, TVENT will search the calculated data for each frame and determine the scale.

The run control information on card 13 need not be punched since the values shown are the default values. The information on card 15 indicates that one time function is defined for the tornado transient, two boundary nodes exist, and standard pressure and temperature are to be used in capacitance coefficient calculations.

The geometry and component control information appear on card 17. Four branches, five nodal points, one blower, one room, and one blower characteristic function are defined for this problem.

Branch descriptions are shown as cards 19 through 22. The information specified on these cards follows the format given in Table IV-5. Note that the cards are not in numeric order (the branch 3 description precedes the branch 2 description). The damper in branch 3 is contained in a duct of cross section 2 by 4 ft (0.61 by 1.22 m), which yields a hydraulic radius of 10.8 in. (0.27 m). The duct is 30 ft (9.14 m) long. The duct dimensions are shown only for completeness since its volume is only 0.5% of the room volume and is not considered significant for capacitance effects. The input resistance coefficient (+5.0 E-9) for branch 3 need not be given since the initial flow and pressure differential were specified; it merely illustrates the

requirements for right-justified data in this field. The specification of a 24-in. (0.61-m) HEPA filter is shown in cols. 46-49 of card 21. The blower characteristic curve identification for the blower in branch 4 is given in col. 72 (again right-justified) on card 22.

Boundary nodes 1 and 2 are defined on cards 24 and 25 in Table IV-19. Zero initial pressures are shown for both boundary nodes. Boundary node 1 is driven by time function number 1; boundary node 2 remains at initial zero pressure as indicated by a time function identifier of zero.

The time function data consist of one set of data, the time function control information on card 27, and the curve definition on cards 28 and 29. This time function consisting of five points is illustrated in Fig. IV-1(c).

Only one room data card is required for this problem (card 31). The room is located at node 3 and has dimensions 40 by 15 by 80 ft (12.19 by 4.57 by 24.38 m).

The blower data, like the time function data, consist of one set of cards for this problem (cards 33-35). Column 5 of card 33 contains a 1 indicating that this is blower characteristic function number one. The integer 4 appearing in column 10 indicates that the curve is defined by four data points (see Fig. IV-1(b)). The curve is described on cards 34 and 35 in algebraic order of flow (- to +).

Pressure input cards are not required for this run since the pressure differentials are defined on the BRANCH DESCRIPTION CARDS. Had the character P been specified in column 30 of card 13 (RUN CONTROL CARD II), pressure cards would have been required and these pressures would override those implied by the pressure differentials on the BRANCH DESCRIPTION cards.

V. PROGRAM OUTPUT

A. Input Return

The input return consists of two parts. The first category of input return is an echo of the input data card images with the card column heading across the top of the list and the card number to the left of the card image (see Fig. V-1). The second part of input return consists of edited lists of input after the input has been converted to a form usable by the system solver algorithm. This output (illustrated in Fig. V-2) expands the abbreviated input and gives default values that are not specified on the input cards. The

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L I S T O F I N P U T D A T A

	10	20	30	40	50	60	70	80
123456789012345678901234567890123456789012345678901234567890								
1##								
2#	SIMPLE VENTILATION SYSTEM							
3##								
4##	RUN CONTROL CARD 1							
5#	ST	0.0	0.1	10.0	50			
6##	PRINT/PLOT CONTROL CARD							
7##	2	1						
8##	FRAME DESCRIPTION CARDS							
9#	2	1	2					
10#	4	1	3	4	5			
11#	4	1	2	3	4			
12##	RUN CONTROL CARD 2							
13#	300	0.0001		1.0				
14##	BOUNDARY CONTROL CARD							
15#	1	2	14.7		530.0			
16##	GEOMETRY AND COMPONENT CONTROL CARD							
17#	4	5	1	1	1			
18##	BRANCH DESCRIPTION DATA							
19#	1	1	3	10000.		F	2.0	
20#	3	4	5	10000.	10.0	30.0	V	0.5
21#	2	3	4	10000.			FH24	1.0
22#	4	5	2	10000.			B	73.5
23##	BOUNDARY CODE DATA							
24#	1	0.0		1				
25#	2	0.0						
26##	TIME FUNCTION DATA (TRANSIENT)							
27#	1	5						
28#	0.0	0.0	2.0	-20.0	6.0		-20.0	
29#	0.0	0.0	10.0	0.0				
30##	ROOM DATA							
31#	3	40.0	15.0	80.0				
32##	BLOWER CURVE DATA							
33#	1	4						
34#	-8000.0	8.2	0.0	4.2	9000.0		4.0	
35#	17000.0	0.0						

Fig. V-1. Input data echo.

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SIMPLE VENTILATION SYSTEM

C O N T R O L I N F O R M A T I O N

PROBLEM TYPE	SS/TRANS	MAXIMUM ITERATIONS PER TIME STEP	300
INITIAL DELTA T	.100000	CONVERGE CRITERIA	.000100
START TIME	0.	RELAXATION PARAMETER	1.00000
TOTAL TIME	10.000		

O U T P U T T I M E S

0.	.2000	.4000	.6000	.8000	1.0000	1.2000	1.4000
1.6000	1.8000	2.0000	2.2000	2.4000	2.6000	2.8000	3.0000
3.2000	3.4000	3.6000	3.8000	4.0000	4.2000	4.4000	4.6000
4.8000	5.0000	5.2000	5.4000	5.6000	5.8000	6.0000	6.2000
6.4000	6.6000	6.8000	7.0000	7.2000	7.4000	7.6000	7.8000
8.0000	8.2000	8.4000	8.6000	8.8000	9.0000	9.2000	9.4000
9.6000	9.8000	10.0000					

T I M E F U N C T I O N D A T A

T	FI	T	FI	T	FI	T	FI	T	FI	T	FI
1	0.	2.0000	-20.0000	6.0000	-20.0000	8.0000	0.	10.0000	0.		

B O U N D A R Y D A T A

P-AMBIENT= 14.7000 T-AMBIENT= 530.000 NUMBER OF BOUNDARY NODES= 2

NODE TYPE NO. NODE PRESSURE	INITIAL NO.	T FN NO.	NODE TYPE NO. NODE PRESSURE	INITIAL NO.	T FN NO.	NODE TYPE NO. NODE PRESSURE	INITIAL NO.	T FN NO.	NODE TYPE NO. NODE PRESSURE	INITIAL NO.	T FN NO.
1 -0 0.	1		2 -0 0.	-0							

G E O M E T R Y A N D C O M P O N E N T D A T A

NUMBER OF BRANCHES=	4	NUMBER OF NODES (BOUNDARY+ ORDINARY)=	5
NUMBER OF BLOWERS =	1	NUMBER OF BLOWER CURVES=	1
NUMBER OF ROOMS =	1		

Fig. V-2. Edited input return.

		IN OUT		INITIAL	HYDRL	BRANCH DATA		EXP	RESIST	INTERCEPT	INITIAL
NO.	NODE	NODE	NODE	FLOW	RADIUS	COMP	CURVE	0			DELTA-P
1	1	3	10000.000	-0.		FILT	0	1.00	2.000E-04	0.	2.000000
2	3	4	10000.000	-0.		FILT	10	1.00	1.000E+03	0.	1.000000
3	4	5	10000.000	10.000		VALV	0	2.00	5.000E-09	0.	.500000
4	5	2	10000.000	-0.		BLWR	1	1.00	-2.000E+03	1.7000E+04	3.500000

ROOM DATA

ROOM	NODE	VOL.	ROOM	NODE	VOL.	ROOM	NODE	VOL.	ROOM	NODE	VOL.
1	3	48000.0									

BLOWER CURVE DATA

COEFFICIENTS

CURVE NO.	SEGMENT	LEFT BOUND(FLOW)	RIGHT BOUND(FLOW)	A	B	C
1	1	-8.000E+03	0.	8.4000E+03	-2.0000E+03	0.
	2	0.	0.000E+03	1.8900E+05	-4.5000E+04	0.
	3	9.000E+03	1.700E+04	1.7000E+04	-2.0000E+03	0.

NODE NO.	NODE(-, FOR BOUNDARY TYPE(+, ROOM NO+1000)
1	-1
2	-1
3	1001
4	0
5	0

PRESSURE
0.
0.
-2.000000
-3.000000
-3.500000

NODE INFORMATION

ASSOCIATED BRANCHES
1 2
2 3
3 4

Fig. V-2. Continued.

card image list always appears regardless of the occurrence of errors in the input data. A table of possible error messages appears in Appendix C.

B. Output Lists and Summaries

Flow, pressure, and extreme values are written to a scratch file during the transient calculation for editing or plotting by the output processor. Lists for each output time requested consist of tables of archival data showing 1) pressures and flows, 2) differential pressures and flows by component type (filters and dampers), 3) a table of differential pressures between rooms, and 4) a summary of extreme values for a specified output time. Figure V-3 shows this output for the simple ventilation system at time = 10 s. A summary of extreme values spanning the entire period of the problem is produced at the end of the problem. Pressures and flows are inspected each time step during the calculation in compiling data for this list so that extreme values are not missed by poor selection of output frequency. Frequently, one might wish output lists for a specific point in time not covered in the selection of output frequency. A maximum of five special output times may be selected according to the format given in Table IV-4. These special output times do not appear in the printer plots since these points must be equidistant in time.

C. Printer Plots

Line-printer plots may be requested on the PRINT/PLOT CONTROL card and the PLOT FRAME DESCRIPTION cards. Figures V-4 and V-5 show sample plot frames for the simple ventilation system. A maximum of 10 frames can be requested. The pressure at any node or the flow in any branch can be selected for time-history plots up to a maximum of 4 curves on a single frame. Each curve is identified by an alphabetic character A through D. Overlapping curves are shown by the character X at the point of overlap. The first and last archival lists and summaries are automatically produced when plots are requested. Intermediate lists are suppressed since the volume of output data can be quite large. The intermediate lists can be requested with nonblank specification in cols. 3-5 of the PRINT/PLOT CONTROL card.

The program attempts to fill the plot frame page when the number of output times is sparse by spacing with blank lines between points. The

SIMPLE VENTILATION SYSTEM

NODAL PRESSURES								
	0	1	2	3	4	5	6	7
	0.	0.	0.	-.66565	-.89194	-.99484		
BRANCH FLOWS								
	0	1	2	3	4	5	6	7
	0	6.3	4.3	4.3	4.3			

TIME = 10.00000

TIME = 10.00000

DIFFERENTIAL PRESSURE ACROSS FILTERS								
BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	TIME = 10.00000
1	.665647	2	.226295					
FLOW THROUGH FILTERS								
BRANCH	FLOW	BRANCH	FLOW	BRANCH	FLOW	BRANCH	FLOW	TIME = 10.00000
1	6.3	2	4.3					
DIFFERENTIAL PRESSURE ACROSS DAMPERS								
BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	BRANCH	D. P.	TIME = 10.00000
3	.102895							

DIFFERENTIAL PRESSURE BETWEEN ROOMS								
NODE	ROOM							TIME = 10.00000
3	1	0.						

Fig. V-3. Output listing at 10 s.

SIMPLE VENTILATION SYSTEM

SUMMARY

FOR TIME= 10.00000

```

*   *   *   *   *   *   *   *   *   *   *   *   *
*   HIGHEST PRESSURE OF  0.      OCCURS AT NODE    2
*   LOWEST PRESSURE OF  -.97484 OCCURS AT NODE    5
*   LARGEST POSITIVE FLOW OF    6.31 OCCURS IN BRANCH    1
*   FILTER WITH LARGEST PRESSURE DIFFERENTIAL OF  .665647 IS IN BRANCH    1
*   FILTER WITH LARGEST FLOW OF    6.31 IS IN BRANCH    1
*   DAMPER WITH LARGEST PRESSURE DIFFERENTIAL OF  .102095 IS IN BRANCH    3
*   ROOM NO.    1 HAS THE LOWEST NEGATIVE PRESSURE OF  -.66565

```

PROBLEM SUMMARY OF EXTREME VALUES

```

*   *   *   *   *   *   *   *   *   *   *   *   *
*   HIGHEST PRESSURE OF  0.      OCCURS AT NODE    2 AT TIME  10.00000
*   LOWEST PRESSURE OF  -4.97688 OCCURS AT NODE    1 AT TIME   6.00000
*   LARGEST POSITIVE FLOW OF   18.56 OCCURS IN BRANCH    1 AT TIME   8.00000
*   LARGEST NEGATIVE FLOW OF  -24.26 OCCURS IN BRANCH    1 AT TIME   2.00000
*   FILTER IN BRANCH    1 HAS THE LARGEST DIFFERENTIAL PRESSURE OF   2.55888 AT TIME   2.00000
*   FILTER IN BRANCH    1 HAS THE LARGEST FLOW OF   -24.26 AT TIME   2.00000
*   DAMPER IN BRANCH    3 HAS THE LARGEST PRESSURE DIFFERENTIAL OF   .38062 AT TIME   6.00000
*   ROOM NO.    1 HAS THE LOWEST NEGATIVE PRESSURE OF  -4.03713 AT TIME   6.00000

```

Fig. V-3. Continued.

Fig. 4. Pressure plot.

Fig. V-5. Flow plot.

extreme value summaries can serve as valuable guides in selecting the node or branch candidates for plotting. Further, the final extreme value summary can be checked for missing extremums on the plots.

Printer-plots by their nature are not precise; however, they can give the analyst a good picture of how the system behaves.

D. Diagnostic Messages

Diagnostic (warning or error) messages are provided to help the user isolate possible input data or modeling errors. In Appendix C, the messages are listed with discussion of their origin and possible remedies. In most cases, the error is easily discerned from the message; however, out-of-order or missing cards tend to produce messages that may confound the reader. In these cases, a careful check of the input return list and a review of input preparation (Section IV) can usually isolate the problem.

Diagnostic messages are produced during input processing or the system solver calculations, hence, there is no set pattern to their location in the output. ***DIAGNOSTIC MESSAGES always precede these messages, and if the error is fatal, either ERROR WITH INPUT CAN'T CONTINUE or ****FATAL ERROR**** SEE PREVIOUS MESSAGES is printed following the message. See Fig. V-6 for an

****DIAGNOSTIC MESSAGES**

```
BRANCH 6 FLOW NEGATIVE, UP AND DOWN-STREAM NODES 6 5 REVERSED BY PROGRAM-----
-----PRESSURES READ IN (NOT CALC, FROM DP)
      INPUT RESISTANCE    1.00000E-04  USED FOR BRANCH    4
      INPUT RESISTANCE    6.94400E-07  USED FOR BRANCH    5
CANT CALC. RESISTANCE (SET TO MIN. VALUE) FOR BRANCH    6
      INPUT RESISTANCE    6.94400E-07  USED FOR BRANCH   13
      INPUT RESISTANCE    1.42800E-03  USED FOR BRANCH   14
      INPUT RESISTANCE    6.94400E-07  USED FOR BRANCH   23
      INPUT RESISTANCE    3.08600E-07  USED FOR BRANCH   24
BRANCH COUNT IMPOSSIBLE FOR NODE    1  COUNT =    1
BRANCH COUNT IMPOSSIBLE FOR NODE   25  COUNT =    1
*****FATAL ERROR****SEE PREVIOUS MESSAGES
```

Fig. V-6.
Multiple diagnostic list.

illustration of the mixture of informative (nonfatal) messages and fatal error messages that can occur.

VI. SAMPLE PROBLEMS

A. General

Sample problems 1-3 illustrate different input options and the restart feature for the sample problem shown in Fig. VI-1. Sample problems 4-7 illustrate the techniques of reducing complex networks. The output for the sample problems is abbreviated. However, the input for each sample problem is given and the full output can be obtained for code verification checks with the output shown below.

B. Illustrative Sample Problems

1. Sample Problem One. Sample problem one is a continuous run (zero to sixteen seconds) featuring a) printer plots of flow and pressure, b) use of the pressure input option for system pressures, and c) special output requests. Figure VI-2 shows an echo of the input data. Results from this problem, Figs. VI-3 through VI-5(c), are used as a basis for comparison with sample problems two and three.

2. Sample Problem Two. This problem illustrates the first run of a restart problem. The input data echo is shown in Fig. VI-6. Note the letters TP in columns 4 and 5 of RUN CONTROL CARD I. This tells the computer program to punch out a restart deck after the total transient time for this problem has expired (in this case, 4 s).

The output messages for an initial restart problem are shown in Fig. VI-7, as are the pressure, flow, and problem summary of extreme values. The pressures and flows are the same as those given in Fig. VI-3 for time ≈ 4 s. The extreme values are the same in sample problems one and two except for the room that does not reach its peak value until 6.4 s have elapsed.

Fig. VI-1
Schematic for sample problem one.

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L I S T O F I N P U T D A T A

	1#	2#	3#	4#	5#	6#	7#	8#
1234567890123456789012345678901234567890123456789012345678901234567890								
1##								
2#	SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)							
3##								
4##	RUN CONTROL I							
5#	STW.2	0.1	16.0	50	32.0	4.0	8.0	
6##	PRINT/PLOT CONTROL							
7#	2	1						
8##	FRAME DESCRIPTIONS							
9#	4	1	2	3	4			
10#	3	4	5	6				
11#	2	1	2					
12##	RUN CONTROL II							
13#				P				
14##	BOUNDARY CONTROL							
15#	2	2						
16##	GEOMETRY AND COMPONENT CONTROL							
17#	5	6	1	1	1			
18##	BRANCHES							
19#	1	1	25000.			V		
20#	2	2	35000.			V		
21#	3	3	45000.			F		
22#	4	4	55000.			R		1
23#	5	5	65000.			V		
24##	BOUNDARY DATA							
25#	1							
26#	6		1					
27##	TORNADO TRANSIENT							
28#	1	5						
29#0.			2.	-20.	6.	-20.		
30#8.		0.	10.	0.				
31#	2	6						
32#0.		0.	6.	0.	8.	-20.		
33#12.		-20.	14.	0.	20.	0.		
34##	ROOMS							
35#	210.	20.	250.					
36##	BLOWER DATA							
37#	1	6						
38#-1500.		7.35	0.	5.1	2500.	5.		
39#5000.		4.5	6500.	2.25	8000.			
40##	PRESSURES							
41#	0.0	-0.8		-3.0	-4.0		0.5	
42#	0.0							

Fig. VI-2. Input for sample problem one.

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

NODAL PRESSURES										TIME = 0.
0	1	2	3	4	5	6	7	8	9	
0	-0.	-1.00000	-3.00000	-4.00000	5.00000	-0.				

BRANCH FLOWS										TIME = 0.
0	1	2	3	4	5	6	7	8	9	
0	5000.0	5000.0	5000.0	5000.0	5000.0					

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

NODAL PRESSURES										TIME = 4.00000
0	1	2	3	4	5	6	7	8	9	
0	-0.	-2.24150	-11.94400	-14.04400	-17.79500	-20.00000				

BRANCH FLOWS										TIME = 4.00000
0	1	2	3	4	5	6	7	8	9	
0	8369.5	10500.0	10501.0	10501.0	10501.0					

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

S U M M A R Y										F O R T I M E = 4.00000
*	*	*	*	*	*	*	*	*	*	*
*	HIGHEST PRESSURE OF	-0.	OCCURS AT NODE	1						
*	LOWEST PRESSURE OF	-20.00000	OCCURS AT NODE	6						
*	LARGEST POSITIVE FLOW OF	10501.00	OCCURS IN BRANCH	5						
*	FILTER WITH LARGEST PRESSURE DIFFERENTIAL OF	2.100000	IS IN BRANCH	3						
*	FILTER WITH LARGEST FLOW OF	10501.00	IS IN BRANCH	3						
*	DAMPER WITH LARGEST PRESSURE DIFFERENTIAL OF	9.702500	IS IN BRANCH	2						
*	ROOM NO.	1	HAS THE LOWEST NEGATIVE PRESSURE OF	-2.24150						

Fig. VI-3. Sample problem one steady-state output.

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

NODAL PRESSURES										TIME = 16.00000
	1	2	3	4	5	6	7	8	9	
0	-0.	-0.83416	-3.01400	-4.00930	.49533	0.				

BRANCH FLOWS										TIME = 16.00000
	1	2	3	4	5	6	7	8	9	
0	5105.6	4977.0	4976.8	4976.6	4976.6					

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

S U M M A R Y F O R T I M E = 1 6 . 0 0 0 0 0

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

* H I G H E S T P R E S S U R E O F . 4 9 5 3 3 O C C U R S A T N O D E 5

* L O W E S T P R E S S U R E O F - 4 . 0 0 9 3 0 O C C U R S A T N O D E 4

* L A R G E S T P O S I T I V E F L O W O F 5 1 0 5 . 6 0 O C C U R S I N B R A N C H 1

* F I L T E R W I T H L A R G E S T P R E S S U R E D I F F E R E N T I A L O F . 9 9 5 3 0 0 I S I N B R A N C H 3

* F I L T E R W I T H L A R G E S T F L O W O F 4 9 7 6 . 8 0 I S I N B R A N C H 3

* D A M P E R W I T H L A R G E S T P R E S S U R E D I F F E R E N T I A L O F 2 . 1 7 9 8 4 0 I S I N B R A N C H 2

* R O O M N O . 1 H A S T H E L O W E S T N E G A T I V E P R E S S U R E O F - 0 . 8 3 4 1 6

PROBLEM SUMMARY OF EXTREME VALUES

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

* H I G H E S T P R E S S U R E O F . 5 0 0 0 0 O C C U R S A T N O D E 5 A T T I M E 0 .

* L O W E S T P R E S S U R E O F - 2 0 . 0 0 0 0 0 O C C U R S A T N O D E 6 A T T I M E 6 . 0 0 0 0 0

* L A R G E S T P O S I T I V E F L O W O F 1 0 6 9 5 . 7 2 O C C U R S I N B R A N C H 4 A T T I M E 2 . 0 0 0 0 0

* F I L T E R I N B R A N C H 3 H A S T H E L A R G E S T D I F F E R E N T I A L P R E S S U R E O F 2 . 1 3 9 1 4 A T T I M E 2 . 0 0 0 0 0

* F I L T E R I N B R A N C H 3 H A S T H E L A R G E S T F L O W O F 1 0 6 9 5 . 7 0 A T T I M E 2 . 0 0 0 0 0

* D A M P E R I N B R A N C H 2 H A S T H E L A R G E S T P R E S S U R E D I F F E R E N T I A L O F 1 0 . 0 6 6 1 0 A T T I M E 2 . 0 0 0 0 0

* R O O M N O . 1 H A S T H E L O W E S T N E G A T I V E P R E S S U R E O F - 2 . 7 0 9 6 0 A T T I M E 6 . 4 0 0 0 0

Fig. VI-4. Sample problem one final results.

Fig. VI-5(a). Sample problem one pressure transient (nodes 1-4).

SAMPLE PROBLEM NO. 1 (TYP. ARCHITECT-ENGINEERING FORMAT)

***FRAME 2 PRESSURE NODES * 4 5 6
 ** CORRESPONDING CURVES= A B C
 ** X CORRESPONDS TO MULTIPLE CURVES AT POINT

100 PER CENT CORRESPONDS TO 2.00000E+01

Fig. VI-5(b). Sample problem one pressure transient (nodes 4-6).

Fig. VI-5(c). Sample problem one flow transient.

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L I S T O F I N P U T D A T A

	10	20	30	40	50	60	70	80
1234567890123456789012345678901234567890123456789012345678901234567890								
1**								
2**	SAMPLE PROBLEM NO. 2 (TO BE RESTARTED)							
3**								
4**	RUN CONTROL I							
5#	TP0.0	0.1	4.0	40	32.0	4.0		
6**	PRINT/PLOT CONTROL							
7#	2	1						
8**	FRAME DESCRIPTIONS							
9#	4	1	2	3	4			
10#	3	4	5	6				
11#	2	1	2					
12**	RUN CONTROL II							
13#					P			
14**	BOUNDARY CONTROL							
15#	2	2						
16**	GEOMETRY AND COMPONENT CONTROL							
17#	5	6	1	1	1			
18**	BRANCHES							
19#	1	1	25000.			V		
20#	2	2	35000.			V		
21#	3	3	45000.			F		
22#	4	4	55000.			R		
23#	5	5	65000.			V		
24**	BOUNDARY DATA							
25#	1							
26#	6		1					
27**	TORNADO TRANSIENT							
28#	1	5						
29#0.			2.	-20.	6.	-20.		
30#8.		0.	10.	0.				
31#	2	6						
32#0.		0.	6.	0.	8.	-20.		
33#12.		-20.	14.	0.	20.	0.		
34**	ROOMS							
35#	210.	20.	250.					
36**	BLOWER DATA							
37#	1	6						
38#-1500.	7.35	0.	5.1	2500.	5.			
39#5000.	4.5	6500.	2.25	8000.				
40**	PRESSURES							
41#	0.0	-0.8	-3.0	-4.0	0.5			
42#	0.0							

Fig. VI-6. Sample problem two input.

```

FINAL PRESSURES FOR RESTART
0.          -2.24154E+00      -1.19430E+01      -1.40439E+01      -1.77948E+01
-2.02000E+01

FINAL FLOWS FOR RESTART
0.36940E+03      1.05002E+04      1.05005E+04      1.05005E+04      1.05005E+04

RESISTANCES FOR RESTART
5.59017E+03      3.37100E+03      5.00000E+03      -6.66667E+02      7.07107E+03
TOTAL ITERS FOR PROBLEM= 1061

```

SAMPLE PROBLEM NO. 2 (TO BE RESTARTED)

```

                                MODAL PRESSURES                                TIME = 0.00000
0      0      1      2      3      4      5      6      7      8      9
      -0.      -2.24150 -11.94400 -14.04400 -17.74500 -20.00000
                                BRANCH FLOWS                                TIME = 4.00000
0      0      1      2      3      4      5      6      7      8      9
      0369.5  10500.0  10501.0  10501.0  10501.0

```

PROBLEM SUMMARY OF EXTREME VALUES

```

*      *      *      *      *      *      *      *      *      *      *
*  HIGHEST PRESSURE OF .50000 OCCURS AT NODE 5 AT TIME 0.
*  LOWEST PRESSURE OF -20.00000 OCCURS AT NODE 6 AT TIME 4.00000
*  LARGEST POSITIVE FLOW OF 10695.72 OCCURS IN BRANCH 4 AT TIME 2.00000
*  FILTER IN BRANCH 3 HAS THE LARGEST DIFFERENTIAL PRESSURE OF 2.13914 AT TIME 2.00000
*  FILTER IN BRANCH 3 HAS THE LARGEST FLOW OF 10695.70 AT TIME 2.00000
*  DAMPER IN BRANCH 2 HAS THE LARGEST PRESSURE DIFFERENTIAL OF 10.06619 AT TIME 2.00000
*  ROOM NO. 1 HAS THE LOWEST NEGATIVE PRESSURE OF -2.24154 AT TIME 4.00000

```

Fig. VI-7. Sample problem two final results.

3. Sample Problem Three. Sample problem three is a continuation of sample problem two through the use of a restart deck obtained from the run of sample problem two. The input data echo for this problem is shown in Fig. VI-8. The letters RS in columns 4 and 5 of RUN CONTROL CARD 1 signal TVENT that the restart deck is present in the data. Note that the restart deck replaces the pressure input cards of sample problem 2.

The final values of pressure and flow for sample problems one and three are the same as Figs. VI-4 and VI-9. The problem summaries of extreme value are not the same since the peak values (except for the room) were passed before 4 s had elapsed.

4. Sample Problems Four and Five. Sample problem four is a complex, series-parallel arrangement of components similar to what one might find attached to a main ventilation network (Fig. VI-10(a)). Sample Problem Five (Fig. VI-10(b)), is a reduced version of sample problem four. The room at node 3 is attached to the main ventilation network. Nodes 2 and 4 are the connection points to the peripheral network. The question that must be answered is, "Can the pressures and flows in the main network be adequately modeled with a simplified representation of the peripheral network?"

The number of rooms in Fig. VI-10(a) was collapsed from four to one. A similar treatment was accorded the filters and dampers. This technique is similar to but not the same as that used in Ref. 9. The flows and pressures in the main loop were plotted using the scale limit cols. 26-35 on the frame description cards. This can be seen on Figs. VI-11 and VI-12 (the input data echo) where the scales used are the same for easy comparison between sample problems four and five.

The room pressure at node 3 and flow in branch 2 are the only system variables that show slightly different values during the transient. Figures VI-13 and VI-14 show comparison of pressures. Figures VI-15 and VI-16 show comparison of flow for the sample problems. The simplified model (sample problem five) is less conservative (yields lower pressure and flow), but the qualitative agreement is good.

5. Sample Problems Six and Seven. These problems illustrate a parallel arrangement of loops. The original system is shown in Fig. VI-17(a) and the reduced version in Fig. VI-17(b). The main loop is again characterized in

each problem by components on either side of the room at node 3. The input for these examples is given in Figs. VI-18 and VI-19. This component configuration is a severe test of modeling since the flows in parallel with the main loop flow are a significant fraction ($2/3$) of the total flow. The only variable that shows any degree of departure from the original transient response is the flow upstream of the room in the main loop (Figs. VI-20 and VI-21). Better agreement has been achieved in tests where the parallel flow is a smaller fraction of the total flow.

```

IVLNF      JAN 77  LASL
LIST OF INPUT DATA
123456789012345678901234567890123456789012345678901234567890
1# 10 20 30 40 50 60 70 80
2# SAMPLE PROBLEM NO. 3 (RESTART)
3#
4# RUN CONTROL I
5# RS 4.0 .1 16. 50 10.
6# PRINT/PLOT CONTROL
7# 2 1
8# FRAME DESCRIPTIONS
9# 4 1 2 3 4
10# 3 4 5 6
11# 2 1 2
12# RUN CONTROL II
13# P
14# BOUNDARY CONTROL
15# 2
16# GEOMETRY AND COMPONENT CONTROL
17# 5 6 1 1
18# BRANCHES
19# 1 1 25000. V
20# 2 2 35000. V
21# 3 3 45000. V
22# 4 4 55000. F
23# 5 5 65000. B
24# BOUNDARY DATA
25# 1
26# 6
27# TORNADO TRANSIENT
28# 1 5
29# 20.0. 2. -20. 6. -20.
30# 8. 10. 0.
31# 2 6. 0. A. -20.
32# 0. -20. 0.
33# 12. 14. 20. 0.
34# ROOMS
35# 21.0. 250.
36# FLOWER DATA
37# 1 6
38# -1500. 7.35 0. 5.1 2500. 5.
39# 5000. 4.5 6500. 2.25 0000.
40# RESTART DATA
41# -.224154300E+01-.119430300E+02-.140039456E+02-.177947694E+02
42# -.260000000E+02
43# .836948155E+04 .105001596E+05 .105005381E+05 .105005491E+05
44# .559016994E+04 .337099931E+04 .500000000E+04-.666666667E+03 .707106781E+04

```

Fig. VI-8. Sample problem three input.

SAMPLE PROBLEM NO. 3 (RESTART)

NODAL PRESSURES										TIME = 4,00000
0	1	2	3	4	5	6	7	8	9	
0.		-2,24150	-11,94400	-14,04400	-17,79500	0.				
BRANCH FLOWS										TIME = 4,00000
0	1	2	3	4	5	6	7	8	9	
0	0369,5	10500,0	10501,0	10501,0	10501,0	10501,0				

NODAL PRESSURES										TIME = 16,00000
0	1	2	3	4	5	6	7	8	9	
0.		-,03416	-3,01400	-4,00930	.49533	0.				
BRANCH FLOWS										TIME = 16,00000
0	1	2	3	4	5	6	7	8	9	
0	5105,6	4977,0	4976,8	4976,6	4976,6					

PROBLEM SUMMARY OF EXTREME VALUES

- * * * * *
- * HIGHEST PRESSURE OF .49533 OCCURS AT NODE 5 AT TIME 16,00000
- * LOWEST PRESSURE OF -20,00000 OCCURS AT NODE 6 AT TIME 4,00000
- * LARGEST POSITIVE FLOW OF 10493,50 OCCURS IN BRANCH 4 AT TIME 4,10000
- * FILTER IN BRANCH 3 HAS THE LARGEST DIFFERENTIAL PRESSURE OF 2,00070 AT TIME 4,10000
- * FILTER IN BRANCH 3 HAS THE LARGEST FLOW OF 10493,40 AT TIME 4,10000
- * DAMPER IN BRANCH 2 HAS THE LARGEST PRESSURE DIFFERENTIAL OF 9,60914 AT TIME 4,10000
- * ROOM NO. 1 HAS THE LOWEST NEGATIVE PRESSURE OF -2,70968 AT TIME 6,40000

Fig. VI-9. Sample problem three final results.

Fig. VI-10 (a).
Sample problem four schematic.

Fig. VI-10(b).
Sample problem five schematic.

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LIST OF INPUT DATA

```

100 20 30 40 50 60 70 80
123456789012345678901234567890123456789012345678901234567890
1**
2** SAMPLE PROBLEM NO. 4 (SFRIES-PARALLEL NETWORK)
3**
4** RUN CONTROL I
5** .1 10. 50
6** PRINT/PLOT CONTROL
7** 2 2
8** FRAME DESCRIPTION
9** 2 3 4 40.
10** 2 5 6 30.
11** 2 2 3 6000.
12** 2 1 4 8000.
13** RUN CONTROL II
14** P
15** BOUNDARY CONTROL
16** 1 2
17** GEOM AND COMPONENT CONTROL
18** 22 22 1 5 1
19** BRANCH DATA
20** 1 1 2 V 8.000E-07
21** 2 2 3 V 8.000E-07
22** 3 3 4 F 4.000E-03
23** 4 4 5 F 4.000E-03
24** 5 5 6 V 8.000E-07
25** 6 6 7 D
26** 7 2 8 V 8.000E-07
27** 8 8 9 F 4.000E-03
28** 9 9 10 F 4.000E-03
29** 10 10 20 V 8.000E-07
30** 11 11 21 V 8.000E-07
31** 12 12 11 F 4.000E-03
32** 13 13 12 F 4.000E-03
33** 14 20 13 V 8.000E-07
34** 15 21 14 V 8.000E-07
35** 16 14 15 F 4.000E-03
36** 17 15 16 F 4.000E-03
37** 18 16 22 V 8.000E-07
38** 19 17 4 V 8.000E-07
39** 20 18 17 F 4.000E-03
40** 21 19 18 F 4.000E-03
41** 22 22 19 V 8.000E-07
42** BOUNDARY CARDS
43** 1 1
44** 7
45** TIME FUNCTION CARDS
46** 1 5
47** 1.5 -83.067 4.5 -83.067
48** 6.0 30.
49** ROOMS
50** 3 10. 10. 40.
51** 9 10. 10. 10.
52** 12 10. 10. 10.
53** 15 10. 10. 10.
54** 18 10. 10. 10.

```

Fig. VI-11. Sample problem four input.

		I V E N T		O C T 77		L A S L	
		L I S T O F I N P U T D A T A					
		10	20	30	40	50	60
1234567890123456789012345678901234567890123456789012345678901234567890							
55#* RLOWER DATA							
56# 1	4						
57#-5000.	42.832	0.0	22.0	1800.	20,832		
58#2300.	0.0						
59#* PRESSURES							
60# 0.0	-2.60		-4.55		-10.0		-10.0
61# -20.6	0.0		-3.58		-4.56		-5.53
62# -7.58	-6.60		-5.63		-7.68		-8.65
63# -9.63	-11.7		-10.7		-9.73		-5.58
64# -7.63	-9.60						

Fig. VI-11. Continued.

```

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          L I N E   U P   I N P U T   D A T A

10      10      20      30      40      50      60      70      80
123456789012345678901234567890123456789012345678901234567890
1##
2# SAMPLE PROBLEM NO. 5 (SIMPLIFIED SERIES-PARALLEL NETWORK)
3##
4## RUN CONTROL 1
5# .1 10. 50
6## PRINT/PLOT CONTROL
7# 2 2
8## FRAME DESCRIPTION
9# 2 3 4 40.
10# 2 5 6 30.
11# 2 2 3 6000.
12# 2 1 4 8000.
13## RUN CONTROL IT
14# P
15## BOUNDARY CONTROL
16# 1 2
17## GEOM AND COMPONENT CONTROL
18# 10 10 1 2 1
19## BRANCH DATA
20# 1 1 2 V 8.000E-07
21# 2 2 3 V 8.000E-07
22# 3 3 4 F 4.000E-03
23# 4 4 5 F 4.000E-03
24# 5 5 6 V 8.000E-07
25# 6 6 7 B
26# 7 2 8 V 3.200E-06
27# 8 8 9 F 1.600E-02
28# 9 9 10 F 1.600E-02
29# 10 10 4 V 3.200E-06
30## BOUNDARY CARDS
31# 1 1
32# 7
33## TIME FUNCTION CARDS
34# 1 5
35# 1.5 -83.067 4.5 -83.067
36# 6.0 30.
37## ROOHS
38# 3 10. 10. 40.
39# 9 10. 10. 40.
40## BLOWER DATA
41# 1 0
42# 5000. 42.832 0.0 22.0 1800. 20.832
43# 2300. 0.0
44## PRESSURES
45# 0.0 -2.60 -4.55 -10.80 -15.01
46# -20.62 0.0 -2.00 -6.70 -10.60

```

Fig. VI-12. Sample problem five input.

Fig. VI-13. Sample problem four pressure transient.

Fig. VI-14. Sample problem five pressure transient.

SAMPLE PROBLEM NO. 4 (SERIES-PARALLEL NETWORK)

Fig. VI-15. Sample problem four flow transient.

Fig. VI-16. Sample problem five flow transient.

Fig. VI-17(a).
Sample problem six schematic.

Fig. VI-17(b).
Sample problem seven schematic.

L I N E I N P U T D A T A

[illegible]

Fig. VI-18. Sample problem six input.

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LIST OF INPUT DATA

	1st				2nd				3rd				4th				5th				6th				7th				8th			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
55##	BLOWER DATA																															
56#	1	4																														
57#	-5000.	31.2	0.0		16.0			1800.		15.2																						
58#	2300.	0.0																														
59##	PRESSURES																															
60#	-15.0		0.0		-2.9			-4.00		-5.20																						
61#	0.0		-2.6		-2.90			-5.40		-12.6																						
62#	0.0		-2.6		-2.8			-4.0		-5.2																						
63#	-2.8		-4.0		-5.2			-2.8		-4.0																						
64#	-5.2		-2.8		-4.0			-5.2																								

Fig. VI-18. Continued.

Fig. VI-20. Sample problem six flow transient.

Fig. VI-21. Sample problem seven flow transient.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to P. R. Smith of New Mexico State University for his general program overview and his contribution in the fluid dynamic analyses. We wish to also recognize R. S. Chen of Fluor Corporation and L. O. Ford of Ralph Parsons Company for their valuable suggestions for improving the user's manual.

APPENDIX A

TVENT OVERLAY STRUCTURE

Figure A-1 shows the overlay structure of TVENT. The program modules that make up each overlay are named in parentheses. The lengths of overlays are not to scale.

Fig. A-1.
TVENT overlay structure.

APPENDIX B

TVENT INPUT SUMMARY

The input card deck is organized into control cards for establishing important run parameters and control cards indicating the exact amount of data to be read. If the number on the control card does not agree with the number of data cards defining that particular category, the program aborts because the program is trying to read incorrect data from the adjacent data category. Separator cards are used to separate the title card, the control cards, and the various data categories. Any information on these cards is ignored by the program, but the separator card must be included whenever appropriate. A separator card is not needed if data are not called for on the control card. In the following discussion of data formats, the separator cards are identified with an asterisk usually followed by a few words of explanation. Data entries are fixed or floating point unless otherwise indicated. Integer and floating point numbers must be right-justified.

*

TITLE CARD

*

* RUN CONTROL 1

Cols.	1-3	Not used
	4-5	Run option symbol
		ST or blank steady-state plus transient
		RS restart problem
		TP punch restart deck after transient
		SP punch restart deck after steady-state
		SS steady-state solution only
6-10	Starting time (default = 0.0)	
11-15	Size of time step (default = 1.0 s)	
16-20	Total run time (default = 1.0 s)	
24-25	Output frequency (maximum is 50, default = 10.)	
30	Number of special output times (a maximum of 5)	
31-35	First special output time	
36-40	Second special output time	

41-45 Third special output time
 46-50 Fourth special output time
 51-55 Fifth special output time

PRINT/PLOT CONTROL

Cols. 1-2 Entering the letters "SI" requests SI units in the output. Pressures in kilo pascals (kPa) and flows in cubic meters per/s (m^3/s).
 3-5 Entering the letters "ALL" requests printed output at every output saved, that is, the number of output frequencies plus any special output times. All but the steady-state, special, and final run outputs are suppressed when plots are requested.
 Cols. 6-10 (Integer) Number of pressure print/plot frames (max is 10).
 11-15 (Integer) Number of flow print/plot frames (max is 10).

Because the total number of print/plot frames is 10, the sum of the pressure plus flow frames cannot exceed 10.

* PLOT FRAME DESCRIPTIONS

Cols. 1-5 (Integer) Total number of plots per frame (max is 4)
 6-10 (Integer) First node/branch
 11-15 (Integer) Second node/branch
 16-20 (Integer) Third node/branch
 21-25 (Integer) Fourth node/branch
 26-35 Scale limit (defaults to the maximum value)

* RUN CONTROL 2

Cols. 1-5 (Integer) Maximum number of iterations allowed per time step (default = 300). If the problem fails to converge, this number should be increased.
 6-15 Convergence criterion (default = 0.0001). The default value has proved to be adequate in all problems investigated.

- 21-25 Relaxation parameter (default = 1.0). Sometimes a slightly higher value can result in fewer iterations per calculation step and, thereby, save on computer time.
- 30 Pressure input option. Entering the letter P indicates the existence of pressure input data.

* BOUNDARY CONTROL

- Cols. 1-5 (Integer) Number of time functions (default = 0)
- 6-10 (Integer) Number of boundary nodes
- 11-20 Value of absolute pressure (default is STP)
- 21-30 Value of absolute temperature (default is STP)

* GEOMETRY AND COMPONENT CONTROL

- Cols. 1-5 (Integer) Number of branches (500 max)
- 6-10 (Integer) Number of nodes (400 max)
- 11-15 (Integer) Number of blowers (40 max)
- 16-20 (Integer) Number of rooms (60 max)
- 21-25 (Integer) Number of blower functions (15 max)

* BRANCH DATA

- Cols. 1-5 (Integer) Branch number
- 6-10 (Integer) Upstream node number
- 11-15 (Integer) Downstream node number. Positive flow is from the upstream to the downstream nodes.
- 16-25 Estimated branch flow (CFM). This value is used to calculate damper, filter, and duct resistances and to indicate the proper segment on the blower curve.
- 26-35 Hydraulic radius of duct (in.). Defined as the cross-sectional area divided by the wetted perimeter. ($D/4$ for a circular duct).
- 36-45 Duct length (ft). Neither the hydraulic radius nor the duct length is used and these values are usually omitted. If they are given, however, a volume is calculated and compared to the smallest room volume to see whether the duct volume should be included. A diagnostic to this effect is written if this is the case.

- 46 Component type symbol
- V Damper
- F Filter
- B Blower
- D or blank duct ... Duct
- 47-50 Filter type (built-in resistance from empirical data)
- H24 Clean 24 by 24 by 12 in. HEPA
- H8 Clean 8 by 8 by 6 in. HEPA
- 51-60 Branch pressure differential (in. water gage). This value is used to calculate a branch resistance for dampers, filters, and ducts according to the relationship $\Delta P = RQ^n$ where n is assumed to be 1.0 for filters and 2.0 for dampers and ducts. This entry is superseded by the differential pressures calculated from the input pressures. These differential pressures are also used to calculate the set of nodal pressures that becomes the "guessed" answer set for the first iteration of the steady-state solution.
- 61-70 Branch resistance, $R = \Delta P/Q^n$. An entry of this value takes precedent, that is, overrides other resistances.
- 71-72 (Integer) Blower curve identifier.

* BOUNDARY NODE DATA

- Cols. 1-5 (Integer) Boundary node number
- 6 Not used
- 7-16 Initial value of pressure at node (in. water gage)
- 17-20 (Integer) The number of the associated time function.
 (Default means that the pressure stays constant.)

* TIME FUNCTION DATA (TORNADO TRANSIENT)

- Cols. 1-5 (Integer) Time function identifier
- 6-10 (Integer) Number of points defining the curve

Cols. 1-10 Time(s) for first point

 11-20 Pressure (in. water gage) for first point

21-30	Time for second point
31-40	Pressure for second point
41-50	Time for third point
51-60	Pressure for third point

Use as many cards of the second type shown above as needed to define all the points.

* ROOM DATA

Cols.	1-5	(Integer) Node number for room
	6-15	One dimension (ft)
	16-25	Second dimension
	26-35	Third dimension

The room dimensions define the volume that determines the capacitance during the transient. The program expects dimensions even for the steady-state solution.

* BLOWER CURVE DATA

Cols.	1-5	(Integer) Blower curve identifier
	6-10	(Integer) Number of points defining the blower curve

Cols.	1-10	Flow (cfm) for the first point
	11-20	Blower head (in. water gage) for the first point
	21-30	Flow for the second point
	31-40	Blower head for the second point
	41-50	Flow for the third point
	51-60	Blower head for the third point

Use as many cards of the second type shown above as needed to define all the points.

* PRESSURE DATA

Cols.	1-15	Pressure (in. water gage) at the first node
	16-30	Pressure at the second node
	31-45	Pressure at the third node
	46-60	Pressure at the fourth node
	61-75	Pressure at the fifth node

Use as many cards as needed to define the pressure at all the nodal points.

Restart Procedure

The restart option permits the continuation of a solution starting from the last calculated time of the previous solution. A TP or SP, whichever is appropriate, in cols. 4-5 of RUN CONTROL 1 requests a deck of punched cards defining the solution at the end of the previous calculation. A restart is made by

1. replacing the PRESSURE DATA at the end of the input deck with these cards,
2. changing the starting and total times on the RUN CONTROL 1 card, and
3. placing the letters RS in cols. 4-5 of this same card.

TABLE C-1

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TABLE C-1, CONTD.

	<u>ERROR TYPE</u>	<u>REMEDY</u>	<u>FATAL?</u>
-----JOB CONTROL ERROR----- OUT-TIMES EXCEEDED** N = (Sum of output frequency MAX = 51 + special outputs)	1	a,b	Yes
-----PLOT CONTROL ERROR----- TOO MANY PLOT FRAMES REQUESTED = (Sum of pressure + flow frames) MAX = 10	1	a,b	Yes
-----PLOT-FRAME CONTROL ERROR FOR FRAME = (n) NO. OF CURVES - (m) CURVE IDS = (k ₁ , k ₂ , k _m)	1,3,5	a,b	Yes
-----BOUNDARY/TIME FN CONTROL ERROR----- NO. OF TAU FNS = (Input value) MAX NO. = 5 BOUNDARY NODES = (Input value) MAX NO. = 20 MIN. = 2	1,2,5	a,b	Yes
-----GEOMETRY CONTROL ERROR----- INPUT MAX BRANCHES (Input value) 500 NODES " " 400 BLOWERS " " 40 ROOMS " " 60 FLOWER CURVES " " 15 BRANCHES, NODES MUST BE GT 0	1,2,5	a	Yes
-----PLOT-FRAME CONTROL ERROR FOR FRAME = (n) NO. OF CURVES = (m) CURVE IDS = (k ₁ , k ₂ , k _m) VALUE - (k _i) NOT VALID FOR CURVE (i) OF FRAME (n)	3	a	Yes
BRANCH (n) FLOW NEGATIVE, UP AND DOWNSTREAM NODES (j) (k) REVERSED BY PROGRAM-----			No
xxxxx BRANCH (n) IS DUPLICATED	5	a	Yes
-----BRANCH DATA ERROR----- -----POSSIBLE ERRORS A) BRANCH NO. GT. MAX or NO = 0 B) UPSTREAM DOWNSTREAM NODE GT. MAX OR = 0	1,3,5	a,b	Yes

ABLE C-1, CONTD.

	<u>ERROR TYPE</u>	<u>REMEDY</u>	<u>FATAL?</u>
C) BLOWER FN NO. GT. SPECIFIED OR = 0 1. INPUT RESISTANCE ERROR 2. GEOMETRY CONTROL ERROR (NO FNS SPECIFIED) BRCH FROM TO FLOW RAD. D LENGTH, COMP. DELTA-P RESIST. IBC (Input values)			
-----BOUNDARY NODE DATA ERROR----- BOUNDARY NODE (n) TIME FN NO. = (m) GT. MAX = 20 OR NODE NO. = 0			
NODE (n) DOES NOT APPEAR FOR ANY BRANCH	4	a	Yes
BRANCH (n) UP-NODE = (m) DOWN-NODE = (k) NOT CONNECTED TO SYSTEM	4	a	Yes
BRANCH COUNT IMPOSSIBLE FOR NODE (n) COUNT = (k)	4	a	Yes
DIMENSION EXCEEDED FOR NODE-BRANCH ARRAY MAX = (N)	4	a	Yes
*****FATAL ERROR*****SEE PREVIOUS MESSAGES (Appears with other messages)			Yes
***** WARNING ***** DIFFERENTIAL PRESSURE IN BRANCH (n) FOR TIME = (VALUE) IS EXTREMELY SMALL (Calculated value)	4	c	No
PROBLEM NOT CONVERGED FOR (Max iters) TIME = (Current value) NODE = (n) VALUE = (Local convergence) (Convergence for every node listed) *****UNCONVERGED VALUES OF PRESSURE = (Calculated pressures)		d	Yes

NOTES:

1. Input value exceeds maximum array size.
 2. Minimum value of parameter is greater than given on data card.
 3. Input value is not acceptable for this parameter (does not match known value).
 4. Possible system layout or modeling error.
 5. Missing cards or cards out of order.
- a. See Section IV and check input format.
 - b. Check INPUT RETURN LIST for missing or out-of-order cards.
 - c. Informational message only, no action required.
 - d. If values listed are "reasonably close" to convergence, set maximum iterations to a larger number and rerun the problem.

APPENDIX D

THEORETICAL ANALYSIS

A general approach to formulating the fluid dynamic equations is to use the momentum equation plus the energy and continuity equations. These equations are not easily solved numerically, but they do provide a basis for development of a simplified set of working equations. The general equations are developed to show the importance of terms on an order-of-magnitude basis. Inertia and shock are two effects that must be evaluated. Further simplification and coupling of these equations with empirical fluid-flow relationships allows development of equations that can be used to calculate the fluid dynamics in a network of connecting ducts and components.

A. General Equations

The general equations used in TVENT were formulated by considering a simple system consisting of a room with a duct that vents to the atmosphere (Fig. D-1.)

The notation used in Fig. D-1 is defined as follows:

V_r = volume of the room,
 T_r, T_o = absolute temperature of the room and outlet air,
 P_r, P_o = pressure of the room and outlet air,

Fig. D-1.
Room with duct.

ρ_r, ρ_o = density of the room and outlet air,

D = duct diameter,

L = duct length,

x = horizontal distance, and

$u(x,t)$ = air velocity in duct as a function of distance and time.

The momentum, continuity, and energy equations, and the equation of state for the air flowing through the duct are, respectively,

$$\frac{\partial u(x,t)}{\partial t} + \frac{u(x,t)}{\partial x} \frac{\partial u(x,t)}{\partial x} = - \frac{1}{\rho(x,t)} \frac{\partial P(x,t)}{\partial x} + \frac{f u^2(x,t)}{2D} , \quad (D-1)$$

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial}{\partial x} \left(\rho(x,t) u(x,t) \right) = 0 , \quad (D-2)$$

$$\rho(x,t) C_P \left\{ \frac{\partial T(x,t)}{\partial t} + \frac{u(x,t)}{\partial x} \frac{\partial T(x,t)}{\partial x} \right\} = \frac{\partial P(x,t)}{\partial t} \quad (D-3)$$

$$+ \frac{u(x,t)}{\partial x} \frac{\partial P(x,t)}{\partial x} + \mu \frac{4}{3} \frac{\partial u(x,t)}{\partial x}^2 ,$$

and

$$P(x,t) = \rho(x,t) R T(x,t) , \quad (D-4)$$

where

f = friction factor,

C_P = heat capacity,

μ = kinematic viscosity, and

R = universal gas constant.

For the room, the energy equations, the continuity equation, and the equation of state are

$$C_P \frac{d}{dt} \left(\rho_r(t) T_r(t) \right) V_r = \rho_r(t) \left(C_{P_r} T_r(t) + \frac{u^2(L,t)}{2} \right) u(L,t) A_c , \quad (D-5)$$

$$\frac{V_r d\rho_r(t)}{dt} = \rho_r(r) A_c u(L,t) , \quad (D-6)$$

and

$$P_r(t) = \rho_r(t) RT_r(t) , \quad (D-7)$$

where

A_c = duct cross-sectional area.

The flow is assumed to be one-dimensional and the fluid is initially at rest. At time, $t = 0$, the pressure at the outlet of the duct begins to decrease linearly with time in the following way:

$$P_o = P_{amb} - at , \quad (D-8)$$

where

P_o = pressure at the outlet,
 P_{amb} = ambient pressure at normal conditions,
 t = time, and
 a = depressurization rate because of a tornado.

The air expansion at the outlet is assumed isentropic, so

$$T_o = T_{amb} \left(\frac{P_o}{P_{amb}} \right)^{\frac{k-1}{k}} , \quad (D-9)$$

where

T_{amb} = absolute temperature of ambient air and
 k = specific heat ratio.

The complexity of the general equations (Eqs. (D-1) through (D-7)) makes them difficult to solve. In the sections that follow, various assumptions about the relative importance of certain terms in the equations will be investigated with the objective of simplifying the equations. Solutions to the simplified equations will then be sought to give some insight into the problem.

B. Inertia Effects

The general equations are simplified by assuming that the energy and continuity equations are not time dependent, but the momentum equation remains time dependent. The energy equation becomes

$$T \left(1 + \frac{k-1}{2} M^2 \right) = T_C , \quad (D-10)$$

where

M = Mach number, and

T_C = constant.

The continuity equation becomes

$$\rho u A_c = \text{constant}. \quad (D-11)$$

Eq. (D-1) can be reduced to the following, neglecting the Mach Number squared (M^2) compared to unity.

$$\frac{\partial M^2}{\partial t} - \left(\sqrt{\frac{RT_o}{k}} \right) \frac{1}{M} \frac{\partial M^2}{\partial x} + \left(\frac{f}{D} \sqrt{kRT_o} \right) M M^2 = 0 . \quad (D-12)$$

Consideration of inertia effects requires the solution of Eq. (D-12). The first term of Eq. (D-12) represents inertia, while the second and third terms represent convection and friction, respectively. The coefficient on the first term (inertia) is 1, while the coefficients of the second and third terms are about 1000 and 10, respectively. Since the second term is divided by the Mach

number (very small if flow starts from zero), the rate of change of M^2 with respect to time must be approximately $1000/M$ if the inertia term is to be of the same magnitude as the convective term. For example, if $M = 0.1$, the time interval in which the transient must take place is $1/10,000(s)$ if the inertia term is to be significant. The third term is multiplied by Mach number to the third power and, therefore, can never be of the order of magnitude of the convective term for $M < 1$. Hence, the convective term dominates both the inertia and friction terms.

Although inertia effects will be neglected in the remainder of this study one must remember that Eq. (D-12) was derived assuming a steady-state energy equation and a steady-state continuity equation. Therefore, further investigations of inertia effects by solution of the full set of Eqs. (D-1) through (D-7) will be necessary to completely justify this assumption.

C. Quasi-Steady Formulation

For the quasi-steady formulation we assumed that the steady-state forms of the momentum, energy, and continuity equations are valid at any instant in time. Changes with respect to time occur because the pressure is changing with time at the outlet, as given by Eq. (D-8). If the inertia term of Eq. (D-12) is neglected, the following result is obtained by integration.

$$\frac{1}{M_o^2} - \frac{1}{M_i^2} = \frac{f}{D} kL , \quad (D-13)$$

where

$$M_i = \text{Mach number at inlet, and}$$

$$M_o = \text{Mach number at outlet.}$$

Using a compressible flow relationship between pressure and Mach number with the assumption that $M^2 \ll 1$ yields

$$P = \frac{P_o M_o}{M} . \quad (D-14)$$

The temperature is approximately constant with the small Mach number approximation, and the density is given by

$$\rho = \rho_o \frac{M_o}{M} \quad . \quad (D-15)$$

As the pressure (P_o) at the outlet is reduced according to Eq. (D-8), pressure disturbances are propagated from the outlet toward the room at the speed of sound in the upstream air. Referring to Fig. D-2, a momentum balance gives

$$u_2 = u_1 + \frac{P_1 - P_2}{\rho_1(w + u_1)} \quad , \quad (D-16)$$

where

P_1 = air pressure in front of disturbance,

P_2 = air pressure behind disturbance, and

w = speed of the pressure disturbance.

Fig. D-2.
Pressure disturbances.

TABLE D-1
QUASI-STEADY FORMULATION RESULTS

Time (sec)	Outlet		Inlet Mach Number, M_i	Room	
	Pressure, P_o , (lb/in. ²)	Outlet Mach Number, M_o		Pressure, P_r , (lb/in. ²)	Velocity, u_o (ft/s)
0.0	14.7	0.0	0.0	14.7	0.0
1.4	13.29	0.0693	0.0687	14.43	82.8
2.6	12.09	0.1317	0.1278	13.84	150.6

Then, for quasi-steady flow at $x = 0$

$$u_o(t + \Delta t) = u_o(t) + \frac{P_o(t) - P_o(t + \Delta t)}{\rho_o(t) (w + u_o(t))} \Delta t, \quad (D-17)$$

where

Δt = time increment.

Using Eqs. (D-8), (D-13), (D-14), (D-15), (D-16), and (D-17), the pressures, temperatures, Mach numbers, and velocities throughout the system can be calculated as a function of time. The results are shown in Table D-1 for a depressurization rate of 1 psi/s (6895 Pa/s), duct length of 100 ft (30.48 m) and room volume of 5000 ft³ (141.44 m³).

Notice that the Mach number at the outlet is essentially equal to the Mach number at the entrance even after 2.6 s. This suggests that a lumped-parameter formulation, where the velocity and other properties are assumed constant over a specified length of conduit, is justified. The next section treats this formulation of the problem.

D. Lumped-Parameter Formulation

Since for the lumped-parameter formulation an average velocity can be used between the inlet and outlet, Eq. (D-13) becomes

$$(P_o - P_i) = \left(\frac{f L_c}{D} \right) \cdot \left(\frac{u^2}{2g_c} \right) , \quad (D-18)$$

where u is the average velocity in the duct. This semi-empirical relationship between pressure and flow can be applied to connecting elements between points (nodes) within a ventilation system. The pressure parameter is lumped at nodal points within the system and connected to other points through the nonlinear Eq. (D-18). Distributed parameters are neglected (spatial variations of fluid mass and resistance are not considered). Mechanical components of the system such as dampers, blowers, and filters can be represented by Eq. (D-18). The distributed parameter analysis is necessary when the pressure pulse is of such short duration that shock effects should be considered. A preliminary analysis of possible shock development indicated that shock effects are unlikely. This analysis is included in Appendix F. Further, Owczarek¹⁰ has determined shock formation times in a suddenly opened conduit. These times prove to be long compared to the duration of a tornado-induced pressure pulse.

In addition to the component relationship given by Eq. (D-18), the continuity equation is applied to each node. The continuity equation for nodal points that have no fluid mass storage capacity is

$$\sum_{j=1}^J Q_i = 0 , \quad (D-19)$$

where

Q_i = flow into or out of a node i ,

J = number of element connections at node i , and

j = dummy index.

The compressibility of the system is accounted for at nodal points by permitting storage of fluid at these points. Points within a structure with relatively large volumes such as rooms, cells, gloveboxes, or duct plenums are represented as nodal points where accumulation of fluid mass is allowed. The equation of state is used to calculate the pressure at a fluid storage point or node as follows.

$$\frac{dP}{dt} = \frac{\rho RT}{V} (Q_{in} - Q_{out}) , \quad (D-20)$$

where

Q_{in} = flow into node, and
 Q_{out} = flow out of node.

Programming Eqs. (D-18), (D-19), and (D-20) for solution on a digital computer allows calculation of flows and pressures at selected points within the structure's mechanical system. The form of the pressure transient at the supply and exhaust vents is arbitrary, as is the geometrical connection of mechanical components.

APPENDIX E

NUMERICAL ANALYSIS

Formulation of Equations

The equations are formulated using a lumped-parameter approximation that neglects spatial distribution of variables. The following equation types will result upon application of the lumped parameter approach:

- A simultaneous set of coupled nonlinear algebraic equations, and
- A simultaneous set of ordinary differential equations.

The lumped-parameter approach includes a number of system elements or branches joined together at points called nodes. The nodes are the connection points at the upstream and downstream ends of the branches. The pressure variable of the system is lumped into the nodes. Air cleaning system components such as dampers, filters, and blowers that have a resistive nature are located within the branches of the system. A branch without a component (the duct work) also has a resistive nature. The frictional resistance to flow in the ductwork and system components is lumped within the branches of the network. An empirical pressure-flow relationship suitable for the elements is used for all branches in the system. This relationship can be written as

$$Q(K) = \alpha(K) + \beta(K)(P(J) - P(I))^{\gamma(K)}, \quad (E-1)$$

where

- K = branch K,
- Q(K) = flow rate through a branch,
- $\gamma(K)$ = constants for a particular branch (K),
- P(I) = pressure at node I, and
- P(J) = pressure at an upstream node J so that $P(J) > P(I)$.

Application of Eq. (E-1) for the system components will yield a number of forms. These forms are summarized in Table E-1.

TABLE E-1
PRESSURE-FLOW RELATIONSHIPS FOR VARIOUS BRANCH COMPONENTS

Branch Component	$\alpha(K)$	$\beta(K)$	$\gamma(K)$	Flow Equation	Equation Number
Duct Friction	0	Variable	0.5	$\beta(K)(P(J)-P(I))^\gamma(K)$	(E-2)
Filter (Low flows)	0	Variable	1	$\beta(K)(P(J)-(P(I)))$	(E-3)
Damper	0	Variable	0.5	$\beta(K)(P(J)-P(I))^\gamma(K)$	(E-4)
Blower (linear approximation)	Variable	Variable	1	$\alpha(K)+\beta(K)(P(J)-(P(I)))$	(E-5)

At any particular time, the branch flow and the pressures at the upstream and downstream nodes are unknown. Coupling all branch equations at a particular node through use of a continuity equation allows the flow variable to be eliminated. Only the system pressures remain to be determined. An iterative process ideally suited for the digital computer is used with a linearized form of Eq. (E-1) to determine a pressure correction (ΔP) at each node. The process is repeated many times until the pressures at the nodes are within an acceptable tolerance.

Calculation of the pressure correction parallels Streeter's procedure for determining the pressures and flows in the steady-state portion of a water-hammer computer code.¹¹ Streeter located pumps at nodes, whereas this analysis requires all components to be located within the branch connections. In addition, this formulation is a transient analysis with allowance for storage of fluid at particular nodes. This condition requires derivation of a different algorithm for calculation of ΔP at fluid storage nodes.

The pressure correction for a node is calculated assuming that the true pressure at node I is equal to $P(I) + \Delta P$. Using this approximation, Eq. (E-1) becomes

$$Q(K) \approx \beta(K) [P(J) - (P(I) + \Delta P)]^{\gamma(K)} + \alpha(K) \quad (E-6)$$

Using a binomial expansion of Eq. (E-6), neglecting higher order terms, and considering $P(I)$ to be the value of pressure at node I for the previous iteration, Eq. (E-6) becomes

$$Q(K) \approx \beta(K) [P(J) - P(I)]^{\gamma(K)} \left[1 - \frac{\gamma(K) \Delta P}{P(J) - P(I)} \right] \pm \alpha(K) \quad , \quad (E-7)$$

or

$$Q(K) \approx A - C \Delta P \quad , \quad (E-8)$$

where A and C are known constants from the previous iteration and where

$$A = \beta(K) [P(J) - P(I)]^{\gamma(K)} \pm \alpha(K) \quad (E-9)$$

and

$$C = \beta(K) \gamma(K) [P(I) - P(J)]^{\gamma(K)-1} \quad . \quad (E-10)$$

If $P(I) > P(J)$,* the values of A and C become

$$A = -\beta(K) [P(I) - P(J)]^{\gamma(K)} \pm \alpha(K) \quad (E-11)$$

and

$$C = \beta(K) \gamma(K) [P(I) - P(J)]^{\gamma(K)-1} \quad . \quad (E-12)$$

Components that have relatively large volumes such as rooms, gloveboxes, and plenums are located at nodes. These nodes exhibit a capacity for fluid storage and are called capacitance nodes. The compressibility of the system is accounted for by allowing fluid storage at the capacitance nodes. However, in all cases the conservation of mass must hold at the nodes. For an ordinary node with no storage or blower connection, conservation of mass yields

* J refers to downstream node in this case.

$$\Sigma Q(K) = 0 \quad (E-13)$$

or

$$\Sigma A - \Sigma C \Delta P = 0 \quad . \quad (E-14)$$

Solving for the pressure correction ΔP gives

$$\Delta P = \frac{\Sigma A}{\Sigma C} \quad . \quad (E-15)$$

Equation (E-15) is used to determine successive pressure corrections for an ordinary node without storage. When a node is connected to a duct containing a blower, the constant $\alpha(K)$ must be added or subtracted from ΣA before the correction is calculated. In all other cases $\alpha(K)$ is equal to zero.

If only steady-state values of pressure and flow are of interest, Eq. (E-15) is sufficient for arriving at the correct pressures. However, during a transient, mass-in does not equal mass-out at nodes containing rooms, gloveboxes, or plenums. The equation of state is used at these storage nodes in addition to the continuity equation. The equation of state can be written as

$$P(I) = \rho RT \quad , \quad (E-16)$$

where

ρ = density of air at the node,

R = gas constant for air, and

T = absolute temperature of the air.

Differentiation of this equation with respect to time yields

$$\frac{dP(I)}{dt} = CF(Q_{in} - Q_{out}) \quad (E-17)$$

or

$$\frac{dP(I)}{dt} = CF \sum Q(K) , \quad (E-18)$$

where

$$CF = \rho RT/V, \quad (E-19)$$

$$Q_{in} = \text{flow rate into node}, \quad (E-20)$$

$$Q_{out} = \text{flow rate out of node},$$

and V is the volume of the node under consideration.

Using finite differencing, Eq. (E-18) can be written as

$$\sum Q(K) = \frac{1}{CF} \frac{P(I)^n - P(I)^{n-1}}{\Delta t} , \quad (E-21)$$

where

$P(I)^n$ = present iterative value of pressure,

$P(I)^{n-1}$ = past time step value of pressure, and

Δt = discrete time step.

Substituting $P(I)^n + \Delta P$ for $P(I)^n$ in Eq. (E-21) yields the following equation for determination of the pressure correction at a storage node

$$\Delta P = \frac{CF \Delta t}{1 + CF \Delta t \sum C} \frac{\sum A + P(I)^{n-1} - P(I)^n}{\Delta t} . \quad (E-22)$$

Eqs. (E-15) and (E-22) are incorporated within the computer code TVENT so that successive pressures are calculated until the true pressures that balance the system are obtained. After convergence has been achieved, the flows that result from the calculated pressure distribution are computed from the branch component equations.

A pressure correction is calculated from Eq. (E-15) or Eq. (E-22) for each nodal point excepting the boundary nodes. This correction is inserted into the following expression:

$$DELTP = \Delta P_{\lambda} \cdot RELAX , \quad (E-23)$$

where

ΔP_{λ} = Pressure correction for this iteration from Eq. (E-15) or Eq. (E-22),
RELAX = Over-relaxation factor,* and
DELTP = Total pressure correction term.

This provides a new value of nodal pressure when DELTP is added to the pressure from the previous iteration. A pressure net is considered converged when every nodal DELTP is less than CONVRG* as shown in Eq. (E-24).

$$\left| DELTP \right| \leq CONVRG . \quad (E-24)$$

*These values may be specified as input data.

APPENDIX F

SHOCK DEVELOPMENT

The following simple analysis was used to approximate the time required for a shock wave to form because of tornado-induced depressurization (Fig. F-1).

Fig. F-1.
Tornado depressurization.

Consider a sound wave moving to the left into the region of falling pressure with a velocity, c_1 , as shown in Fig. F-2.

Fig. F-2.
Sound wave.

The pressure and temperature in front of the wave are falling, so the waves generated at some later time are traveling at a higher speed than those first sent out. Hence, the later waves tend to overtake the early waves and create a shock wave. Using Eqs. (D-8) and (D-9), the following result can be obtained.

$$T_1 = T_2 \left(\frac{P_1}{P_2} \right)^{\frac{k-1}{k}} = T_2 \left(1 - \frac{at}{P_{amb}} \right)^{\frac{k-1}{k}}, \quad (F-1)$$

where

P_1, T_1 = pressure and temperature downstream of shock wave, and
 P_2, T_2 = pressure and temperature upstream of shock wave.

Using Eq. (F-1), C_1 can be calculated as follows:

$$C_1(t) = 49.1 \sqrt{T_2} \left(1 - \frac{at}{P_{amb}} \right)^{\frac{k-1}{2k}} \quad (F-2)$$

$$\hat{C}_1 = \frac{1}{t_f} 49.1 \sqrt{T_2} \int_0^{t_f} \left(1 - \frac{at}{P_{amb}} \right)^{\frac{k-1}{2k}} dt \quad (F-3)$$

Equation (F-3) can be approximated, using a binomial expansion as

$$\hat{C}_1 = \frac{49.1 \sqrt{T_2}}{t_f} \int_0^{t_f} \left\{ 1 - \frac{at}{P_{amb}} \left(\frac{k-1}{2k} \right) + \right. \\ \left. \left(\frac{k-1}{2k} \right) \left(\frac{k-1}{2k} - 1 \right) \frac{a^2 t^2}{2 P_{amb}^2} + \dots \right\} dt \quad (F-4)$$

$$C_1 \approx 49.1 \sqrt{T_2} \left\{ 1 - \frac{a}{P_{amb}} \left(\frac{k-1}{2k} \right) \frac{t_f}{2} + \right. \\ \left. \left(\frac{k-1}{2k} \right) \left(\frac{k-1}{2k} - 1 \right) \frac{a^2 t_f^2}{6 P_{amb}^2} \right\} \quad (F-5)$$

If $P = at_f = 3$ psi, then

$$\hat{C}_1 = 49.1 \sqrt{T_2} \left\{ 1 - \frac{3}{14.7} \left(\frac{k-1}{4k} \right) + \right.$$

$$\left\{ \left(\frac{k-1}{2k} \right) \left(\frac{k-1}{2k} - 1 \right) \frac{3}{2(14.7)^2} \right\}$$

$$= 49.1 \sqrt{T_2} \quad (0.98457) \quad . \quad (F-6)$$

The distance traveled by a wave generated at $t = t_f$ in a time Δt is

$$x = C_2 \Delta t. \quad (F-7)$$

If the wave, C_2 , overtakes the initial wave generated at that point, a shock wave develops. Thus,

$$x = \hat{C}_1 t_f + C_1 (t > t_f) \Delta t. \quad (F-8)$$

Eliminating x gives

$$C_2 \Delta t = \hat{C}_1 t_f + C_1 (t > t_f) \Delta t, \quad (F-9)$$

or

$$49.1 \sqrt{T_2} \Delta t = 49.1 \sqrt{T_2} (0.98457) t_f$$

$$+ 49.1 \sqrt{T_2} \left(\frac{11.7}{14.7} \right)^{\frac{k-1}{2k}} \Delta t, \quad (F-10)$$

or

$$\Delta t = 0.98457 t_f + \left(\frac{11.7}{14.7} \right)^{\frac{k-1}{2k}} \Delta t. \quad (F-11)$$

Thus, for a given value of t_f , Δt can be calculated. The time needed for the shock wave to form is $t_f + \Delta t$. Values of $\Delta t + t_f$ are located in Table F-1 for various values of t_f .

TABLE F-1
SHOCK WAVE DEVELOPMENT TIME FOR
SEVERAL DEPRESSURIZATION RATES

t_f seconds	$\Delta t + t_f$ seconds
1	31.69
0.5	15.85
0.1	3.17
0.05	1.58

From Table F-1 one can see that if the total duration of the pressure drop is 3.17 s, then the initial drop in pressure must occur within 0.1 s if a shock wave is to form. Assuming an average wave speed of 1000 ft/s (304.8m/s), this would require a duct length of approximately 3000 ft (914.4m).

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