184
4-10-75
LA-5894-PR

Progress Report

DL-1266
UC-38

Issued: March 1975

72374

**Ventilation Systems Analysis
During Tornado Conditions
July through December 1974**

by

**W. S. Gregory
G. A. Bennett**

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

An Affirmative Action/Equal Opportunity Employer

MASTER

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 38

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

This is the first report in this series. In the interest of prompt distribution, this report was not edited by the Technical Information staff.

**Work supported by the Division of Operational Safety,
U.S. Energy Research and Development Administration.**

**Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy \$4.00 Microfiche \$2.25**

VENTILATION SYSTEMS ANALYSIS DURING
TORNADO CONDITIONS

by

W. S. Gregory and G. A. Bennett

ABSTRACT

A review of several facility ventilation systems is essentially complete. The types of facilities reviewed include plutonium reprocessing and fabrication plants as well as reactors and research facilities. The purpose of this review was to identify the complexity and types of systems involved. In addition, typical ventilation system components were identified. The principal result of this review was the identification of several basic models which are common to all of the systems reviewed.

A literature search for pressure-flow data reveals a large amount of data for normal ventilation flow but very little for high flow rates. Identification of the experimental data required and relative priority of component testing is complete.

- Several Architect-Engineering firms have been contacted to determine if
- a computer code to analyze ventilation systems would be useful to them?
 - what type of computing hardware do they have at their disposal?

A basic formulation for the dynamic response of a simple system has been developed. A "lumped-parameter" assumption for the fluid dynamics portion of the problem coupled with an isothermal assumption for the thermodynamics is the basis for this initial formulation. A simple system consisting of valves or dampers, filters, fan and cell or building volumes has been analyzed. The response of this system to tornado depressurization transients at both the supply and exhaust is presented in graphical form. In addition, a computer movie has been developed which presents the pressure and flow data for the system.

I. INTRODUCTION

A. General

The regulatory guides and standards established by the Atomic Energy Commission have led to the requirement and need for evaluation of the safety aspects of various facilities.⁽¹⁾ Plutonium reprocessing and fuel fabrication facilities are examples of the types of facilities which must now undergo intensive safety review. Part of the safety review consists of posing hypothetical accidents which may be man-caused or result from natural phenomena such as earthquakes and tornados. In order to pass a rigorous safety analysis it is necessary for the analyst to be able to analyze the consequences of these hypothetical accidents. Use of the results from such an analysis should allow the designer to

construct and operate the facility so that radioactive release is a remote possibility.

The principal concern of this investigation is to develop the capability of predicting analytically the consequences due to a hypothetical tornado on the ventilation system of a facility. The operation of a ventilation system is highly dependent upon stable atmospheric pressure to maintain the pressure differentials between containment zones and also to prevent release of contamination to the atmosphere. Characteristically, a pressure drop as large as 3-psi is associated with tornados so that the generation of undesirable pressures and flow rates within a ventilation system is possible.⁽²⁾ Large pressure drops could cause filtration failures, duct collapse or fan failures. Failure of any of these components

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

could result in radioactive releases to the environment.

In order to design a safe ventilation system it is necessary for the designer to be able to estimate the consequences of a tornado on his particular ventilation system. The objective, then, of this work is to develop an analytical tool which will allow the analyst to simulate the dynamic effects of a tornado generated pressure transient on his ventilation system.

B. Program Schedule

The program schedule is shown in Table I. The organization of this report is subdivided into the topics which are shown to be achieved within the first six months of the program and are discussed within the remainder of this report.

II. FACILITY VENTILATION SYSTEM REVIEW

The review of several nuclear facility ventilation systems was conducted in order a) to identify the complexity and types of systems in use, b) to determine subsystems of components that are repeated in a design, c) to identify the components that would be subjected to the initial tornado depressurization transient, and d) to identify ventilation system components typical to each type of facility. The four types of facilities reviewed are irradiated fuel reprocessing plants, a light water reactor fuel fabrication plant, plutonium research facilities, and nuclear reactors. Table II lists each facility and its location. This review is essentially complete.

The main sources of information proved to be safety analysis reports, license applications, system design descriptions and technical papers written concerning each facility. (3, 4, 5, 6, 7, 8, 9, 10, 11, 12, & 13) System descriptions, design information, schematic flow diagrams, design evaluations and tornado criteria were collected for each facility. A simplified flow schematic was used to check the air balance and to determine vulnerable components in each system.

The results of the review are shown in Tables III-V. Table III lists each facility, describes the ventilation systems, lists the pressures in each zone, and lists the components on the exhaust and supply that would initially be subjected to the tornado depressurization transient. Table IV shows a schematic of component subsystems that were

identified in various designs. An entire facility ventilation system model could be built up from these subsystems. Table V lists system components, the typical manufacturers, and the types of design data available. Normal ventilation flow data is available for many of the components but high flow data is almost nonexistent.

III. EXPERIMENTAL DATA REQUIRED

Experimental data of component behavior at high flow rates is required of virtually all the components listed in Table V. The priority for testing components is directly related to those components identified as being most likely to experience the initial tornado depressurization transient. Those components will most likely experience the largest pressure drops and flow rates. The components recommended for testing in order of priority are:

- a) HEPA filters (High Efficiency Particle Air)
- b) Dampers
- c) Centrifugal fans
- d) Medium, high efficiency and roughing filters.

It is possible for the HEPA filters to fail structurally due to large pressure differentials across the filter. In addition, there is the possibility that the HEPA filter may also fail although no structural damage may occur. At high flow rates the HEPA filter may not perform its function of filtering the particulate contamination. Structural stability of the dampers should also be considered. Sudden failure of a damper could attenuate the pressure transient. Outrunning fan flow or reverse fan flow is also possible due to atmospheric depressurization. Data in this area is relatively unknown. Medium, high efficiency and roughing filters should be investigated to determine their behavior at high flow rates.

IV. ARCHITECT-ENGINEERING CONSULTING FIRMS SURVEY

A survey of several architect-engineering consulting firms currently engaged in the design of nuclear facilities was conducted to determine a) if a computer code that analyzes the response of a ventilation system during a tornado depressurization transient would be useful and b) what computer hardware is at their disposal. The results of the

survey are shown in Table VI. Several of the firms expressed an interest in exchanging ideas and information on this problem. The end result of the study

promises to provide data that was previously unavailable and should be very useful in future design efforts on nuclear facilities.

Table I

FY 1975 PROGRAM PLAN SCHEDULE

TABLE II

LIST OF FACILITIES THAT HAVE BEEN REVIEWED

- I. Irradiated Fuel Reprocessing Plants
 - A. Nuclear Fuel Services; West Valley, New York
 - B. Midwest Fuel Recovery Plant; Morris, Illinois
 - C. Barnwell Nuclear Fuel Plant; Barnwell, South Carolina
- II. LWR Fuel Fabrication Plants
 - A. Westinghouse; Columbia, South Carolina
- III. Reactors
 - A. PWR - Davis-Besse Nuclear Power Station; Oak Harbor, Ohio
 - B. BWR - Douglas Point Nuclear Generating Station; Charles County, Maryland
 - C. HTGR - Fort St. Vrain; Platteville, Colorado
 - C. LMFBR - Fast Flux Test Facility; Hanford Reservation, Washington
- IV. Research Facilities
 - A. Transuranic Development Waste Facility; Los Alamos, New Mexico
 - B. Plutonium Processing Facility, Los Alamos, New Mexico

TABLE III

COMPARATIVE RESULTS OF FACILITY REVIEW

FACILITY NAME	VENTILATION SYSTEM DESCRIPTION	CONTAINMENT ZONES	PRESSURE LEVELS	COMPONENTS CLOSEST TO OUTSIDE AIR
<u>I. Fuel Reprocessing Plants</u>				
A. Nuclear Fuel Services	System composed of: Building Ventilation, Class I Exhaust, Process Off-Gas, ILW/HLW Process Off-Gas, ILW/HLW Building Ventilation, Iodine/Acid Main Recovery Building and Cell Ventilation, and Miscellaneous. Main exhaust through building stack (59,890 CFM) and through process stack (69,330 CFM), with miscellaneous exhaust to outside air	9 Cascading	+ .3, + .2, + .1, 0.0, -.1, -.3, -1.0, -2.0, -5.0	Supply: Fan, dampers prefilters, heating and ventilating unit Exhaust: Stack, fan HEPA filters, deep bed fiberglass pre- filters
B. Barnwell Plutonium Pro- duct Facility	Once thru: Plutonium Product Facility, Process Vessel Off-Gas Recirculation: Conversion Dry Cells, Conversion Control Room Area	4	-.1", -.25", -.75", -2.25"	Supply: Louver, backflow damper pre- filters, high effi- ciency filters, heating/cooling coils, fan Exhaust: Stack, pressure relief valve, volume or shut-off damper, fan, 3 HEPA filters, roughing filter

(Continued . . .)

TABLE III (continued)

FACILITY NAME	VENTILATION SYSTEM DESCRIPTION	CONTAINMENT ZONES	PRESSURE LEVELS IN INCHES OF H ₂ O	COMPONENTS CLOSEST TO OUTSIDE AIR
C. Midwest Fuel Recovery Plant	Once thru: Building ventila- tion system process off-gas system 23,700 CFM supply + 5300 CFM Infiltration = 29,000 CFM Exhaust	14 Cascading	+ .2, + .1, + .05, 0.0 - .04, - .05 - .1, - .15 - .2, - .25 - 1.2, - 1.25 - 1.75, - 2.25	<u>Supply:</u> Prefilter, preheater, filter, air washer, elimin- ator, filter, fan, reverse pressure louvers <u>Exhaust:</u> Stack, fans HEPA filters, sand- filter, louvers, off-gas scrubbers
<u>II. Fuel Fabrication Plant</u>				
A. Westinghouse	= 45% recirculation with recirculation in normal access, limited access and restricted access	3	- .1, - .15 - .75	<u>Supply:</u> 95% NBS filter, heating/ cooling coils, variable inlet damper fans <u>Exhaust:</u> LUWA valve, expansion chamber, backdraft damper, valve, fan
<u>III. Reactors</u>				
		<u>SYSTEMS</u>		
A. PWR - Davis- Besse Nuclear Power Station	a) Capability for re- circulation in the winter, once thru in the summer exists in the Auxiliary Building and the Turbine Building b) 100% recirculation capa- bility in Control room. c) Radwaste Area is once thru. d) Recirculation in Containment Vessel	(1) Emergency Ventilation System, (2) Purge System (3) HVAC System	- .25 to - 1.5 - .25 to - 1.5 no info.	<u>Supply:</u> louvers, volume control damper, rollomatic filter, heating/ cooling coil, centri- fugal fans, back- draft dampers <u>Exhaust:</u> Stack, vol- ume control dampers, centrifugal fans, plenum, fans, HEPA, filters, prefilters, fire dampers

TABLE III (continued)

FACILITY NAME	VENTILATION SYSTEM DESCRIPTION	SYSTEMS	PRESSURE LEVELS	COMPONENTS CLOSEST TO OUTSIDE AIR
B. BWR - Douglas Point Nuclear Generating Station	<p><u>Once thru:</u> Diesel Generator Building, Turbine Building, Auxiliary Building, Radwaste Area</p> <p><u>Normally recirculation:</u> Control Room, Fuel Handling Building, Reactor Building, Personnel Decontamination Area.</p> <p>Also Annulus Vacuum System</p>	9 systems open to outside air	no info.	<p><u>Supply:</u> Louver, damper, prefilter, HEPA filter, charcoal filter, steam heating/cooling coils, damper, fans gravity damper</p> <p><u>Exhaust:</u> Gravity damper, fans, butterfly valves, charcoal filters, HEPA filters, prefilters. Electric heating, cooling coils, demister</p>
C. HTGR - Fort St. Vrain	<p><u>Reactor Plant Ventilation System</u></p> <p><u>Recirculation:</u> PCRV and the PCRV piping cavity.</p> <p><u>Once thru:</u> Instrument Room, Access Control Area, Chemistry Lab, Counting Room, Fuel Storage Well Vaults, Heat Service Facility</p>	Two Reactor Plant Air Handling Units open to outside air	+.125, -.125 -.25, -.5	<p><u>Supply:</u> Prefilters, heating/cooling coils, fan, volume control dampers</p> <p><u>Exhaust:</u> Stack, volume control damper, fan, charcoal filter, HEPA filter, moisture separator, prefilter, volume, control damper</p>

TABLE II: (continued)

FACILITY NAME	VENTILATION SYSTEM DESCRIPTION	SYSTEMS	PRESSURE LEVELS	COMPONENTS CLOSEST TO OUTSIDE AIR
D. LMFBR - Fast Flux Test Facility	<p>Building is divided into 5 containment zones with three supply systems and a central filtered exhaust system.</p> <p>Once thru: Auxiliary Equipment Building, Reactor Service Building, Containment Vessel</p> <p>Recirculation: Engineering, Operations and Control Building</p>	3 separate supply systems open to outside air	+ .25, 0.0, - .15, - .25, - .50	<p>Supply: Louvers, rollomatic prefilter, sprayed cooling coils, electric heating coils, volume control, damper, fan, butterfly valve</p> <p>Exhaust: Stack, butterfly valve, fan, volume control damper, charcoal filter, HEPA filter, NBS prefilter, butterfly valve</p>
IV. <u>Research Facilities</u>		ZONES		
A. Transuranic Development Waste Facility	Once thru, no recirculation $\approx 10,050$ CFM	4	No information	<p>Supply: Louvers, prefilters, H coils dust filter, fan</p> <p>Exhaust: Stack, fans, HEPA, demisters, spray chamber</p>
B. Plutonium Processing Facility	<p>Zone 1 - 100% outside air</p> <p>Zone 2 - 90% recirculation</p> <p>Zone 2A - 100% outside air</p> <p>Zone 3 - recirculated</p> <p>Total O.A. = 32,150 CFM</p>	4	-1." to -5"	<p>Supply: Prefilter, HEPA, coil, fan, fiberglass filter, sprinklers, spray chamber</p> <p>Exhaust: Stack, orifice, fan, HEPA, fire screen, spray chamber, butterfly valves</p>

TABLE IV
TYPICAL VENTILATION SUBSYSTEMS

SCHEMATIC	DESCRIPTION
Single Zone Model
Two Zone Series Model
Two Zone Series Model With Natural Bypass
Two Zone Series Model With Recirculation
Natural Branching Model

TABLE V

COMPONENT	TYPICAL MANUFACTURERS	DESIGN INFORMATION AVAILABLE
1. diffusers, grilles registers, louvers screens	Barber Coleman, Krueger Anemostat, American Warming & Ventilating	face velocity (fpm) vs. static pressure drop (in H ₂ O) face velocity (fpm) vs. angle of blade rotation
2. Turning vanes	Barber Coleman, Carrier	face velocity (fpm) vs. static pressure drop (in H ₂ O)
3. Duct silencers	Industrial Acoustics, Inc.	face velocity (fpm) vs. dynamic insertion loss in decibels
4. Unit heaters	Trane, Carrier	air flow (CFM) vs. pressure drop (in H ₂ O) temperature (°F)
5. Heating coils, Cooling coils, Retreat coils	Trane, McQuay, Aerofin	face velocity (fpm) vs. air friction (in H ₂ O)
6. Blowers, fans	Buffalo Forge, Chicago Blower, Trane, Carrier	out let velocity (fpm) vs. static pressure (in H ₂ O) also Horsepower & RPM data
7. Humidifiers, airwashers, spray chambers, hydraulic scrubbers	American Standard, Carrier, Trane, McQuay	air flow (CFM) vs. water flow (gpm) air flow (CFM) vs. pressure drop/cell (in H ₂ O)
8. Chillers - air cooled condensing units	American Standard, Carrier, Trane, McQuay	water flow (gpm) vs. pressure drop (in H ₂ O)
9. Furnaces - fan performance	Trane	air flow (CFM) vs. external static pressure drop (in H ₂ O)
10. Control dampers, backflow dampers, fire dampers, butterfly dampers	American Warming & Ventilating, American Standard	face velocity (fpm) vs. static pressure drop (in H ₂ O) and angle blade rotation
11. LUWA valves	no information	incident and reflected pressure (psf) vs. transmitted peak pressure and duration of transmitted pressure
12. Chemical hoods, Fume Hoods	Celcote, Blickman	no information
13. Glove boxes	Blickman	no information
14. HEPA filters, roughing filters, high and medium efficiency filters	Cambridge, Flanders American Air Filter	air flow (CFM) vs. static pressure drop (in H ₂ O)
15. Sand filters	no information	no information
16. Silver Zeolite Scrubbers	no information	no information
17. Charcoal Filters	no information	no information

TABLE VI
SURVEY OF ARCHITECT-ENGINEERING CONSULTING FIRMS

ARCHITECT-ENGINEERS	USEFULNESS TO THE FIRM	TYPE OF FACILITY DESIGNED BY EACH FIRM	COMPUTING CAPABILITY
1. Fluor Engineers & Constructors, Inc. Los Angeles, CA	Yes	Plutonium Processing Facility Los Alamos, NM	CDC 6400 - Basic G. E. Timesharing
2. The Ralph M. Parsons Company Los Angeles, CA	Yes	Recycle Fuels Plant; Anderson, S.C. Chemical-Metallurgy Research Building Los Alamos, NM	CDC Cyber 73 G. E. Timesharing
3. C. F. Braun & Company Alhambra, CA	Yes	New Plutonium Recovery Facility Rocky Flats, CO	Burroughs 6700 G. E. Timesharing
4. Bechtel Power Corporation Los Angeles, CA	Yes	Nuclear Power Plants and some Reprocessing Plant work	UNIVAC 1110
5. Bechtel Power Corporation San Francisco, CA	Yes	Fast Flux Test Facility Richland, WA	UNIVAC 1110 Honeywell 6680
6. Bechtel Power Corporation Gaithersburg, MD	Yes	PWR & BWR Power Plants	UNIVAC 1110
7. Sargeant - Lundy Corporation Chicago, IL	Yes	PWR, BWR & HTGR Power Plants Fort St. Vrain, Platteville, CO	UNIVAC 1106 access to McDonald Automation
8. Ebasco Services Corporation New York, NY	Yes	PWR & BWR Power Plants	Burroughs B6700 access to CDC 6600, CDC 6700 and IBM machines
9. Kaiser Engineers Oakland, CA	Yes	Nuclear Power Plants Richland Storage Facility Richland, WA	IBM 3650 access to CDC 7600
10. Stone and Webster Engineering Boston, MA	Yes	PWR, BWR, & HTGR Power Plants	IBM-370-168 158
11. Kruger, Lake & Associates Allison Engineering • Mechanical Consultants Albuquerque, NM	No	Transuranic Contaminated Solid Waste Treatment Development Facility Los Alamos, NM	access to machines in Albuquerque area
12. Dames and Moore Los Angeles, CA	No	Meteorological studies for Nuclear Facilities	CDC 6600 UNIVAC & IBM machines
13. Charles Luckman Associates Ayres & Hayakawa • Mechanical Consultants Los Angeles, CA	Yes	National Security & Resources Study Center, Los Alamos, NM	UNIVAC 1110

V. DYNAMIC ANALYSIS FOR SYSTEM RESPONSE

A. General

Systems of resistance, capacity and inertia can be utilized in a dynamic analysis of a ventilation system. The "lumped-parameter" method is one such method of dynamic analysis.⁽¹⁴⁾ Lumped-parameters of the linear and nonlinear characteristics can be connected in any manner to determine the transient behavior of the system pressure and flow relationships. This type of analysis contrasts with a "distributed parameter" approach which is necessary when wave effects are important so that spatial distributions of fluid mass, inertia and resistance can be considered. This type of analysis is only necessary when it appears that the pressure pulse is of short duration so that acoustical energy or shock effects may result. It is believed, at least for the initial analysis, that the rate of pressure change within the system is slow compared with the time required for waves to travel within the system at sonic velocity.

Thermodynamic considerations, in addition to fluid dynamic considerations, must also be used in the analysis. The air within the ventilation system may compress or expand isothermally or adiabatically. If the assumption of isothermal expansion and compression is made the temperature of the air remains constant and consequently the mass of air will also remain the same during the transient. The assumption of adiabatic conditions introduces the air temperature as an additional variable and another relationship is required in the analysis.

B. Basic Formulation

The initial formulation of the system equations is based upon two fundamental assumptions. First, the system parameters are treated as "lumped" quantities where spatial variations are neglected. Second, the compressibility and the expansion of the air within the system is treated isothermally. In addition, inertial forces, duct resistance, and entrance and exit losses were neglected and only straight through systems without recirculation or branching flow were considered.

System components consisting of valves or dampers, filters, fan and cell and building volumes have been modeled using the above assumptions for a basic formulation of the system. A plan view of a

system consisting of these components is shown in Figure 1 below. These components were modeled as

Fig. 1. System configuration for initial dynamic analysis.

contributors of resistance and volumetric capacity or compressibility. A view of these components as modeled is shown below.

The resistive components of the system are the valves and the filters. When a fluid flows through these components a drop in pressure takes place. The pressure-flow relationships through these types of components can be related through an empirical

Fig. 2. Model arrangement for system configuration.

relationship such as:

$$\dot{m} = K \{ \Delta P \}^n \text{sgn } \Delta P$$

where
 $\dot{m}$ = flow rate
 K = resistance coefficient
 ΔP = pressure drop
 n = exponent (linear and nonlinear)
 sgn = notation for sign of ΔP .

In many cases it may be necessary to experimentally determine the exponential value, n , as well as the coefficient, K , for particular components. In this initial analysis the valves or dampers are assumed to behave in a nonlinear manner with a value of n equal to 0.5. The flow versus pressure drop relationship for the filters was assumed to be linear. It has been shown, however, that this relationship changes to a nonlinear value for high rates of flow.^(4,5) Therefore, a capability must exist in the analysis to alter the relationships for various regimes of flow experienced during a transient condition.

Volumetric capacity or the compressibility of the system is represented by both building and cell volumes. Two equations, the continuity equation and the equation of state using the isothermal condition, were used to model the capacitance or compressibility of the system. The equation of continuity is

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

where

$$\frac{dm}{dt} = \text{time rate of change of flow}$$

$$\dot{m}_{in} = \text{flow in}$$

$$\dot{m}_{out} = \text{flow out.}$$

The equation of state is

$$\frac{dP}{dt} = \frac{RT}{V} \frac{dm}{dt}$$

where

$$\frac{dP}{dt} = \text{rate of change of pressure with respect to time}$$

R = universal gas constant
 T = temperature
 V = gas volume.

Combining the above algebraic and differential equations for both the resistive and capacitive components resulted in a set of simultaneous equations for the system shown in Figure 2. A digital computer code was then written to numerically solve the set of simultaneous equations. The algorithm used consisted of finite differencing the differential equations so that an explicit set of algebraic equations were derived. By combining this procedure with an iterative method a set of implicit equations was then numerically solved.

The set of equations describing the system was then solved to determine the steady state pressures and flows. At this point, the numerical simulation of the tornado pressure transient was initiated within the code. Numerical results for the pressure and flow at various points within the system are the output from this code.

VI. RESULTS USING BASIC FORMULATION

The principal aim of this presentation is to illustrate the type of analysis which can be attained with the lumped-parameter approach. The simple system used for this analysis is a reasonable approximation to a subsystem in an actual facility. However, the arrangement of the components and the characteristics of the components can vary a large amount. For example, the values used in this analysis present a larger restriction than what might be found in a facility. In addition, the simulated rate of pressure drop used in the analysis was 1-psi/sec in contrast to a possible 2-psi/sec rate.

Figures 3, 5, and 7 show the pressure values in the building and cell when the tornado is at the supply, exhaust and both supply-exhaust respectively. Figure 9 illustrates the effect when a depressurization occurs at both the supply and exhaust but with a time delay between the two. Flow versus time plots were also made for the following tornado conditions: a) tornado at supply b) tornado at exhaust c) tornado at both supply and exhaust at the same time d) tornado at both supply and exhaust with a time delay. Figures 4, 6, 8, 10, depict these cases.

Fig. 3. Pressure values at selected points (tornado at air supply).

Fig. 4. Flow versus time values (tornado at supply).

Fig. 5. Pressure values for selected points (tornado at exhaust).

Fig. 6. Flow versus time values (tornado at exhaust).

Fig. 7. Pressure values for selected points (tornado at air supply and exhaust simultaneously).

Fig. 8. Flow versus time (tornado at supply and exhaust simultaneously).

Fig. 9. Pressure values at selected points (tornado at air supply and exhaust with time delay).

Fig. 10. Flow versus time (tornado at supply and exhaust with time delay).

VII. OBJECTIVES FOR NEXT WORK PHASE

- Extend the basic formulation to include adiabatic conditions.
- Extend the basic formulation to include branching and recirculating flow.
- Add inertia effects to the duct momentum equation. Component resistance to flow would also be included in this equation.
- Examine the possibility of slow development of shocks by including the energy equation.

REFERENCES

1. U.S. Atomic Energy Commission, Regulatory Guide 3.12, General Design Guide for Ventilation Systems of Plutonium Processing and Fuel Fabrication Plants (August 1973).
2. E.H. Markee, Jr., Beckerley and K.E. Sanders, U.S. Atomic Energy Commission, Office of Regulation, Technical Basis for Interim Regional Tornado Criteria, WASH-1300 (May 1974).
3. Nuclear Fuel Services, Inc., "Safety Analysis Report, Nuclear Fuel Services, Inc., Reprocessing Plant, West Valley, N.Y.," Docket Number 50-201 (1973).
4. U.S. Atomic Energy Commission, Directorate of Licensing, Fuels and Materials, "Safety Evaluation of the Midwest Fuel Recovery Plant - General Electric Company," Docket Number 50-268 (December 1972).
5. General Electric Company, "Midwest Fuel Recovery Plant Technical Study Report," (July 5, 1974).
6. Allied-General Nuclear Services, "Barnwell Nuclear Fuel Plant Preliminary Safety Analysis Report, July 1974 Revision of Addendum No. 7, Plutonium Product Facility," Docket Number 50-332 (July, 1974)
7. Westinghouse Nuclear Fuel Division, "Recycle Fuels Plant, License Application" (July, 1973).
8. Toledo Edison Company, "Davis Besse Nuclear Power Station - Final Safety Analysis Report," Docket Number 50-346 (December, 1972).
9. Potomac Electric Power Company, "Douglas Point Nuclear Generating Station - Preliminary Safety Analysis Report, Amendment No. 2," Docket Numbers 50-448 and 50-449 (October 1973).
10. Public Service Company of Colorado, "Fort St. Vrain Nuclear Generating Station - Final Safety Analysis Report," Docket Number 50-267 (December 1970).
11. B.O. Shaver, "Ventilation Systems for the FFTF, Proceedings of the Eleventh AEC Air Cleaning Conference, Richland, Washington, August 31-September 3, 1970, CONF 700816, Volume I, pp. 317-346.
12. Los Alamos Scientific Laboratory, "Transuranic Contaminated Solid Waste Treatment Development Facility," Drawing Numbers LA-NY-M7, LA-NY-M8, LA-NY-M11, LA-NY-M12, (August 15, 1974).
13. Los Alamos Scientific Laboratory, "DP Site Plutonium Processing Facilities, TA-55," Drawing Numbers LA-KY-SK-3315, LA-KY-SK-3316 (March 21, 1973).
14. J.J. Perona, W.E. Dunn and H.F. Johnson, Calculated Transient Pressures due to Impulse and Ramp Perturbations to Ventilating Systems in Buildings 3019, 3026, 3508, and 4507, ORNL-3086 (August 1961).
15. W.S. Gregory, HEPA Filter Effectiveness During Tornado Conditions, Los Alamos Scientific Laboratory, LA-5352-MS, (August 1973).