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TITLE: INVESTIGATION OF ANALYTICAL AND EXPERIMENTAL BEHAVIOR OF NUCLEAR FACILITY VENTILATION SYSTEMS

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ANALTYICAL AND EXPERIMENTAL INVESTIGATION OF NUCLEAR FACILITY VENTILATION SYSTEMS FOR ACCIDENT CONDITIONS

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We are investigating the behavior of nuclear facility ventilation systems subjected to both natural and man-caused accidents. The purpose of this paper is to present a program overview and highlight recent results of our investigations. The program includes both analytical and experimental investigations. Computer codes for predicting accident-induced gas dynamics and test facilities to obtain supportive experimental data to define structural integrity and confinement effectiveness of ventilation system components are described. A unique test facility and recently obtained structural limits for high efficiency particulate air filters are reported.

1. Introduction

Many questions can be posed concerning behavior of off-gas and ventilation systems under accident situations. Only a few of these questions are listed below.

- Are methods available to predict gas dynamic conditions and loadings in ventilation systems for various accident conditions?
- Are methods available to predict transport of material within ventilation systems under accident conditions?
- Do experimental data exist to define structural limits of confinement devices such as high efficiency particulate air (HEPA) filters?
- Do ventilation component response data exist that can be used in mathematical modeling?
- Do various filtration devices maintain their effectiveness throughout transient accident conditions?

This list represents only a small sample of the serious questions regarding ventilation system behavior under the stress of accident conditions. However, we believe that the answers to the above questions are unknown or are only partially understood. For this reason, we have established a program to answer these questions.

We believe that our program as outlined in Figure 1 is a step toward answering the questions posed above. We are developing analysis tools that will allow prediction of accident-induced loads and conditions on confinement systems. At the same time we are investigating structural integrity and transient filtration effectiveness through experimental simulation of accident conditions.

2. Program Overview

The objective of our program is to provide methods and supportive experimental data that will allow analysts and designers to evaluate the impact of accidents within nuclear facilities. Our emphasis has been on accident-induced gas dynamics and airborne material movement within ventilation systems. The analyses and experimental data are particularly suited to fuel cycle and chemical processing facilities rather than reactors, but can be applied or extended into the reactor area. As shown in Figure 1, our approach has been to investigate the accidents depending on whether they originate from natural phenomena (tornadoes, high winds, earthquake) or are man-caused (fires, explosions, nuclear excursions).

Figure 1 shows activities, sponsored by several US government organizations, that are all interrelated. For example, the flow resistance and blower response data are essential for proper computer models. The experimental data will be transformed into a mathematical model that can be used in the computer codes. The experimental effect of components on shock wave characteristics is needed for prediction of shock wave propagation within a ventilation system and for use in the computer programs.

The analytical area concerns development of computer codes for predicting effects of tornado depressurization, explosions, fires, and material movement within a facility. These computer codes involve multidimensional models that are tailored to be very user-oriented, that is, of particular use to safety

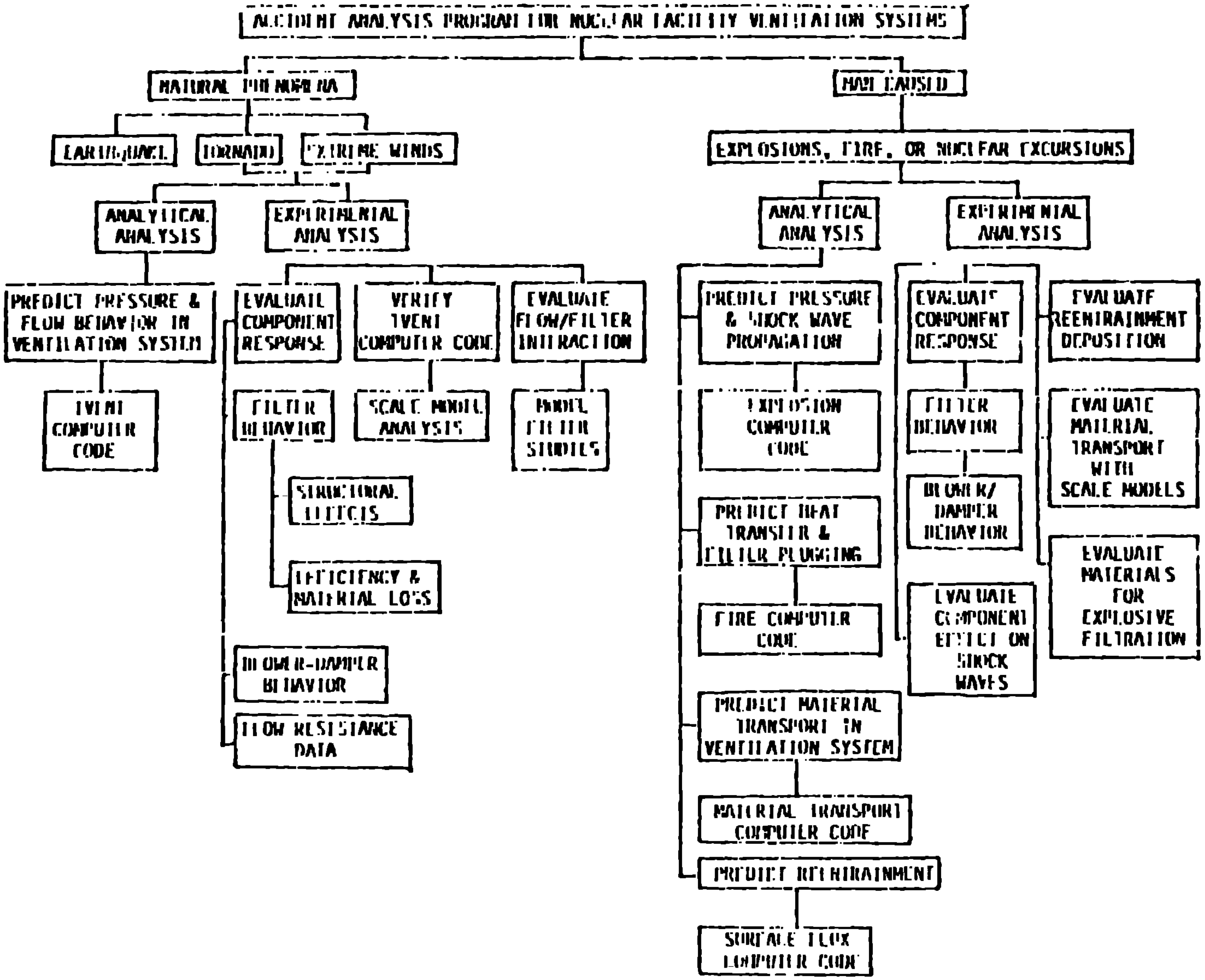


Figure 1. Organization of accident analysis program.

analysts and heating, ventilating, and air conditioning (HVAC) system designers. The computer code for predicting tornado depressurization has been developed and is being used by government and industry. We will describe this code in more detail. The first version of the computer code to predict explosive-induced effects is nearing completion and will also be described. Computer codes to predict effect of fire spread are in initial stages of development as is the code for predicting movement of airborne material within facilities.

The experimental facility is located on the campus of New Mexico State University (NMSU) at Las Cruces, New Mexico, and is operated by NMSU personnel for the Los Alamos Scientific Laboratory (LASL). The test facility can simulate both slow (tornado) and fast (explosive) overpressure transients across ventilation system components. The major components of the test facility include a large compressor, high-pressure air storage tanks, a tornado simulator, a shock tube, and instrumentation required for measuring transient aerosol releases.

B. Analytical Investigations

A. TVENT Computer Code

TVENT was developed at LASL over a period of approximately three years [1--3]. Its main purpose was to predict the flow rates and pressures that would exist within the ventilation systems of a building if a tornado passed over that building. This is a complex problem because the ventilation systems of large buildings are very intricate. These systems consist of many branching and looping ducts, large volumes such as rooms and glove boxes, and many blowers, dampers, and filters. Furthermore, the flow through the ventilation system is not steady but changes with time because the pressure pulse caused by the tornado passage over the building changes with time. An additional complication is the compressible nature of the air flowing through the system.

As we developed TVENT, we could see that because of the relatively small peak pressures expected from tornadoes (20.7 kPa, 3 psi) and the relatively slow occurrence of the pressure pulse, we could make several simplifying assumptions. These assumptions are listed below.

- One-dimensional, incompressible flow.
- Isothermal (constant temperature) flow.
- System components treated as lumped parameters.
- Fluid storage or compressibility allowed only at rooms or glove boxes.
- Inertial effects and shock formation are neglected.

The equations that govern flow through the system are the momentum equation, the continuity equation (conservation of mass), the energy equation, and the equation of state of the fluid. For all components except large volumes, the equation of motion and energy equation can be replaced by a relationship between the flow rate through the component and the pressure drop across the component. The continuity equation is satisfied by demanding that mass be conserved at each node between components.

When a component has a large volume, we assume that there is no pressure drop across it because the velocity within the volume is small. However, mass storage can occur within the volume so that its pressure does change with time. The time derivative of the equation of state for a perfect gas coupled with the conservation of mass allows this change in pressure to be calculated.

Thus the numerical solution technique conceptually appears fairly simple. At a given instant of time, the nonlinear equations for flow rate as a function of pressure through each component are solved in an iterative manner until conservation of mass is attained at each node. Time is then incremented, the tornado pressure value is changed, and once again the pressures at each node are adjusted in an iterative procedure that assures conservation of mass. This stepping in time continues until the pressure pulse has ended and the system has returned to its nominal steady-state operation.

The application of TVENT to various ventilation systems has been quite successful [4--7]. When applied to steady-state conditions, it closely predicts the actual performance of the building's ventilation systems. Transient performance will soon be verified by construction of a small-scale ventilation system where tornado pressure pulses can be modeled. In general, instability of the numerical solutions has not been a difficulty with TVENT.

3. Explosion Computer Code

a) General - Our approach in developing a computer code that will predict propagation of explosively-driven transients within a ventilation system was to extend TVENT to model the more complex phenomena [3].

As the explosion code evolved from the TVENT code, we retained the basic input/output format and the steady-state portions of the code. However, the transient analysis portion of the code was modified extensively. The transient analysis is subdivided into two major categories as shown in Figure 2. The two categories are called near- and far-field and apply to regions of the ventilation system that are near or far away from the explosive event.

The near-field analysis consists of three main segments, as shown in Figure 2. Depending upon the characteristics of the explosive event, a deflagration, detonation, or transition to detonation will take place. We have chosen to delay development of the near-field analysis in favor of the far-field analysis shown in Figure 2.

By developing the far-field analysis first, we can develop an early first-order version of the explosion code. The analysis is treated as a gas dynamics problem with the explosion modeled parametrically. Further, this analysis is particularly suitable when the flow dynamics are relatively insensitive to the explosive event or when there is little detailed information about the explosive event. Later development of the near-field analysis will allow us to couple the two analyses, and the near-field analysis will provide the driving potential for the far-field analysis. The far-field version of the code has been used on several simple problems and compared with experimental results. They compared quite well and are explained below.

b) Example of Explosion Code Results - Some experimental data can be found in Reference [9], which describes the discharge of high-pressure gas (air) from a vessel to the atmosphere. It also describes the pressurization of a vessel by a high-pressure air supply reservoir. We feel that these are the interesting cases for initial tests of our explosion computer code, especially in the areas of mass and energy conservation, orifice flow relation, and choked flow conditions. The schematic of the problems being investigated is shown in Figure 3. In both cases shown in Figure 3, the initial pressure differential is quite large, and the flow is choked during the early phase of the transient. As the vessel pressure approaches ambient or that of the supply reservoir, the unchoked orifice flow relationship applies. We should note that although the unchoked orifice relation is essentially an incompressible formulation, the choked flow calculation does include the effect of dissipation given in Reference [10].

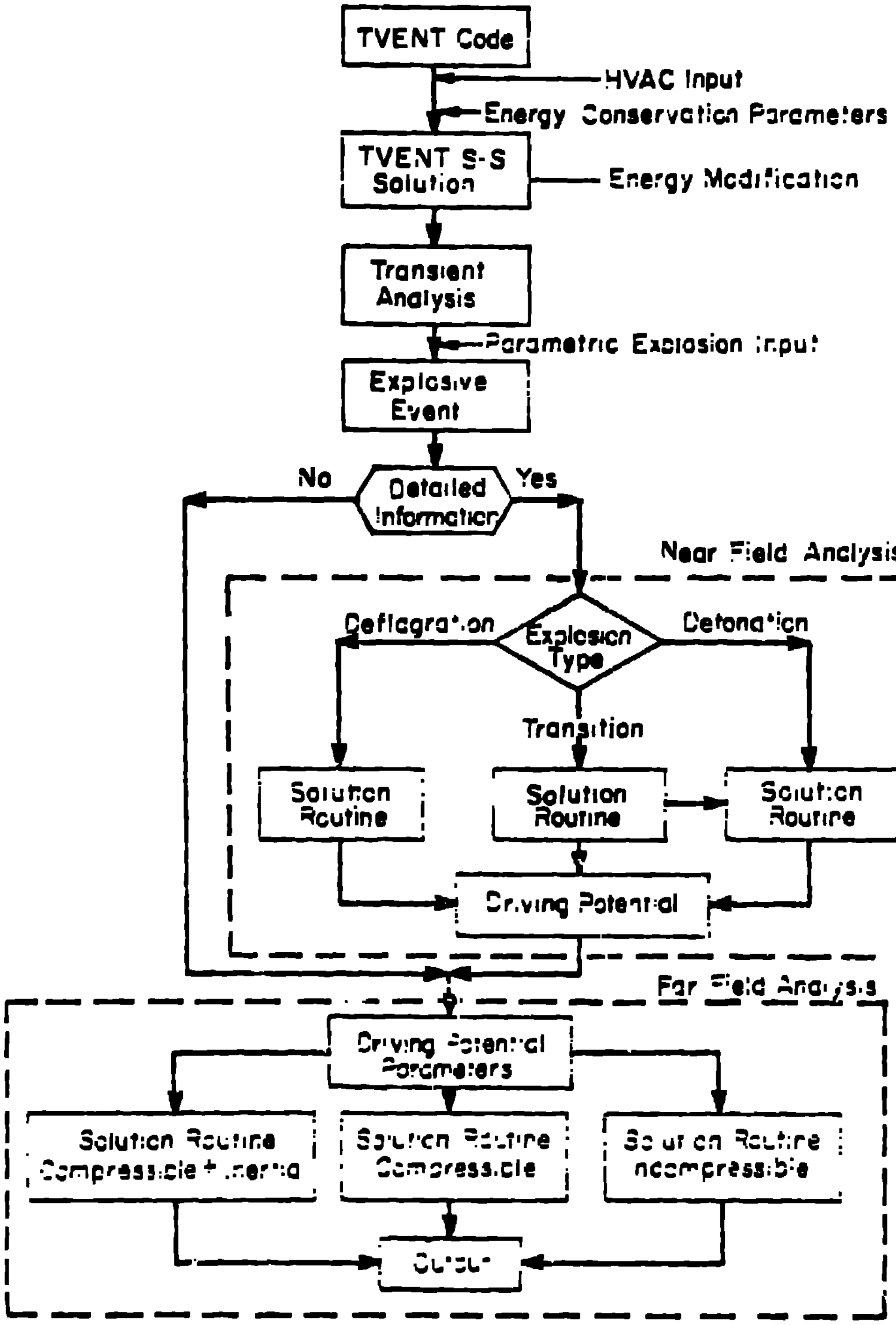
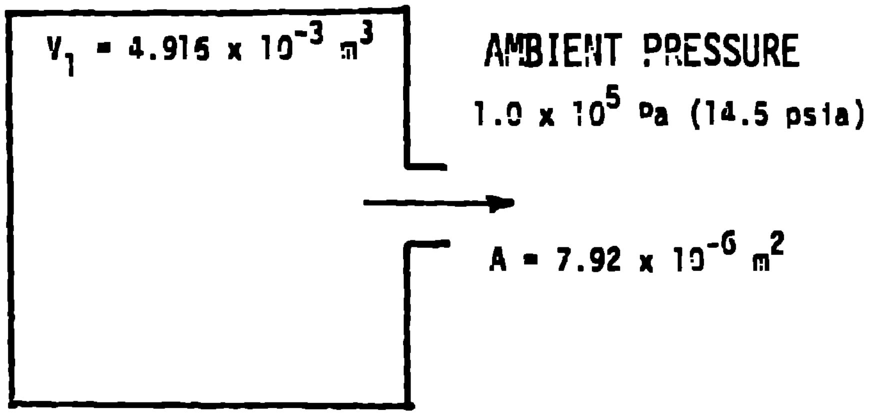


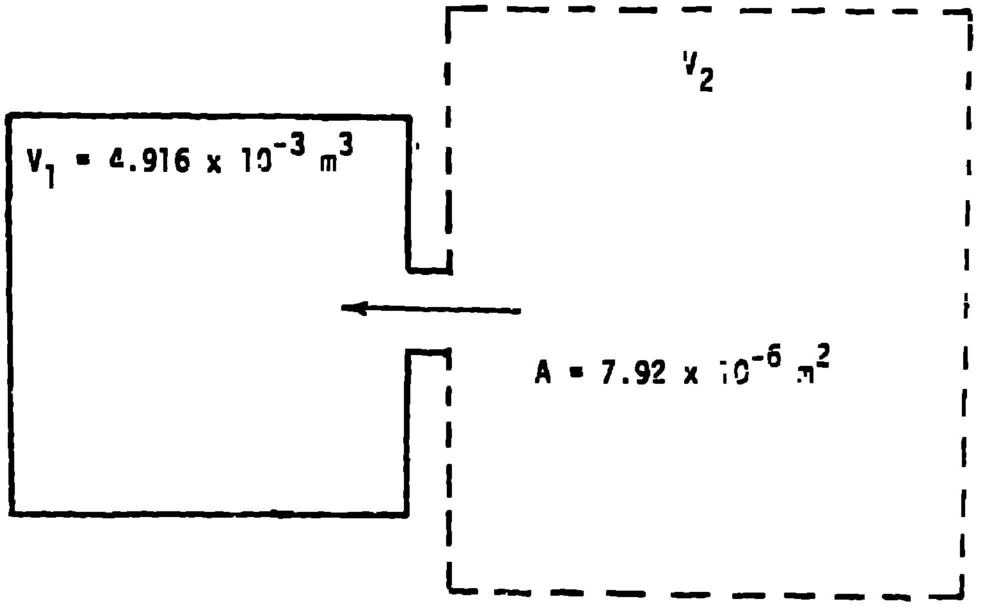
Figure 3. Explosion code organization.



INITIAL PRESSURE: 1.479×10^6 Pa (214.5 psia)

INITIAL TEMPERATURE: 294 (69 °F)

(a) VESSEL DISCHARGE



INITIAL PRESSURE: 1.0×10^5 Pa (14.5 psia)

INITIAL TEMPERATURE: 294 K (69 °F)

SUPPLY PRESSURE: 6.83×10^5 Pa (99 psia)

$V_2 >> V_1$

(b) CHARGING VESSEL

Figure 3. Schematic and conditions for charging and discharging problems.

The resulting analytical and experimental pressure transients are given in Figures 4 and 5. All pertinent parameters are shown in Figure 3. For the theoretical calculations, the dimensionless resistance coefficient is first estimated based on some typical orifice information, and then the dimensional resistance coefficient is calculated because the latter is the required input used in the explosion code. As we can see in these figures, the analytical result compares quite well with the experimental results even though there is some uncertainty about the orifice resistance. The transition from choking to unchoked flow is best illustrated in the charging vessel case. The constant mass and energy supply from an infinite reservoir throughout the choking phase yields a constant slope in the pressure transient curve. The pressure rise eventually levels off, resulting from decreasing mass and energy flow rates because of their dependence on the pressure differential between the vessel and the reservior. The vessel discharge case has a similar transition, namely from choking to nonchoking, but it is not so easy to detect by the pressure transient alone because the choked flow depends on the vessel condition as well as on the unchoked flow. We believe that the explosion code predicts the relatively simple cases quite well. We plan further tests of the code for cases where experimental data with inertia effects are also available.

II. Experimental Investigations

A. Facility Description

The LASL test facility is located on the NMSU campus with operation and testing provided by the Mechanical Engineering Department. Many of the test components are located outside the test building and are shown in Figure 6. From left to right in the foreground of Figure 6, the components are the model ventilation system, the large blowdown tanks, and the shock tube. The test building is in the background.

The apparatus at this test facility is used to accomplish the activities outlined in Figure 1. Using this apparatus, we are able to generate varying degrees of flow transients to simulate both natural and man-caused accidents. This apparatus and associated instrumentation have been described in References [11] and [12]. A large wind tunnel that will also be used to obtain experimental data on reentrainment and deposition is under construction at LASL. Some of the experimental apparatus is described in greater detail below.

a) Blowdown apparatus - The purpose of the blowdown apparatus is to impose relatively slow (0.5 s to 6 s) pressure pulses across ventilation system components. The system is capable of generating pressure levels of 27.2 kPa (4 psi) and volumetric flows of 14.7 m^3/s (25 000 cfm). The system consists of two large pressurized tanks, sonic nozzles, a prefilter chamber, and a wind tunnel. The prefilter chamber, wind tunnel, test filter, and high-speed camera is shown in Figure 7.

The air flows from the pressurized tanks through twelve 31.75-mm (1.25-in.) solenoid valves. The mass flow rate is regulated by sonically choking the flow at each valve, and the pressure pulse rise is regulated by controlling the number of valves opened at any time.

The air passes from the valves into a 3.1- by 3.1- by 3.1-m (10- by 10- by 10-ft) expansion chamber. Here the air impinges on an impaction plate and then is prefiltered by a bank of 25 HEPA filters.

From the prefiltering chamber the air passes through a 0.6- by 0.6-m (2- by 2-ft) duct and impinges on a test component at the end of the duct. The

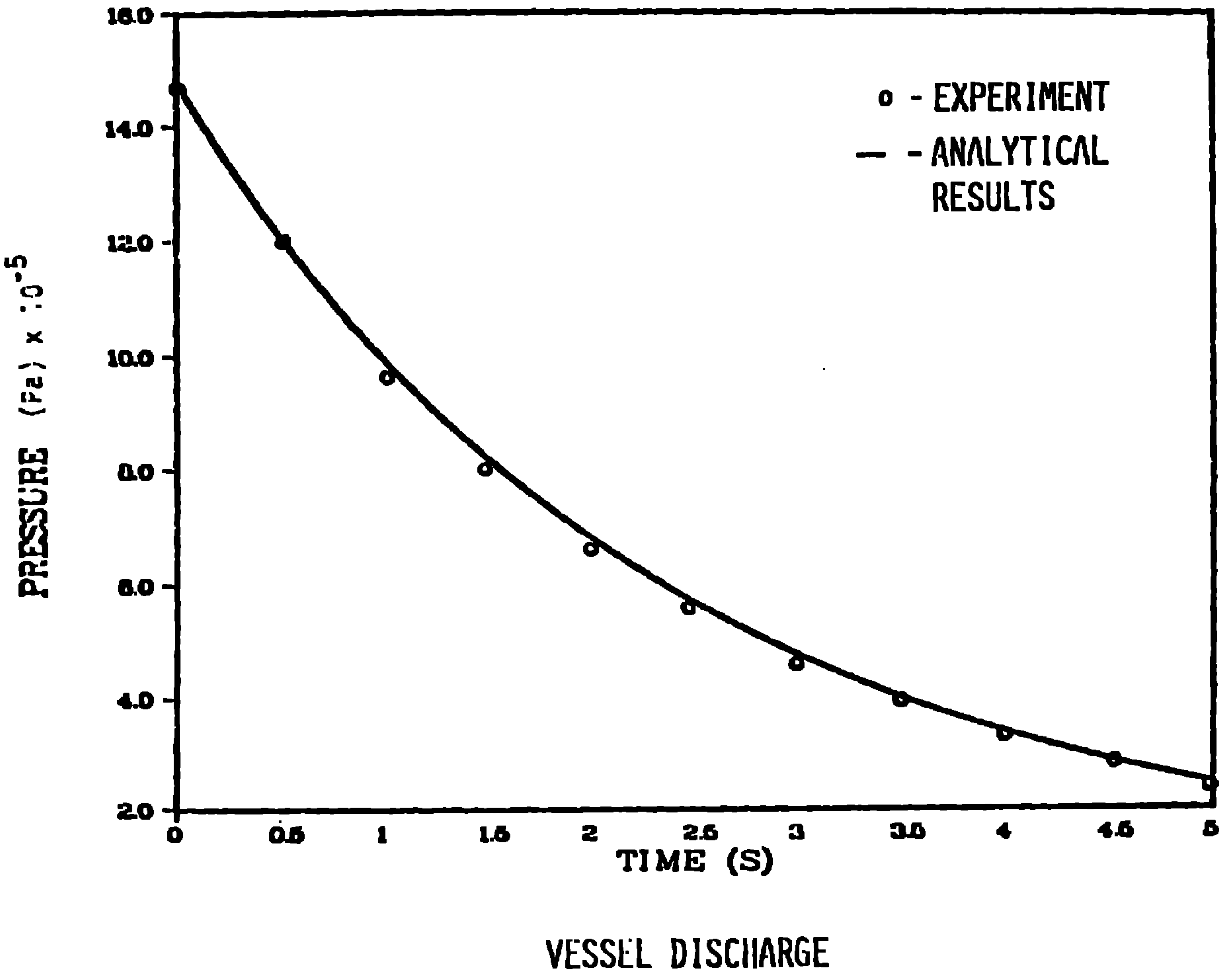
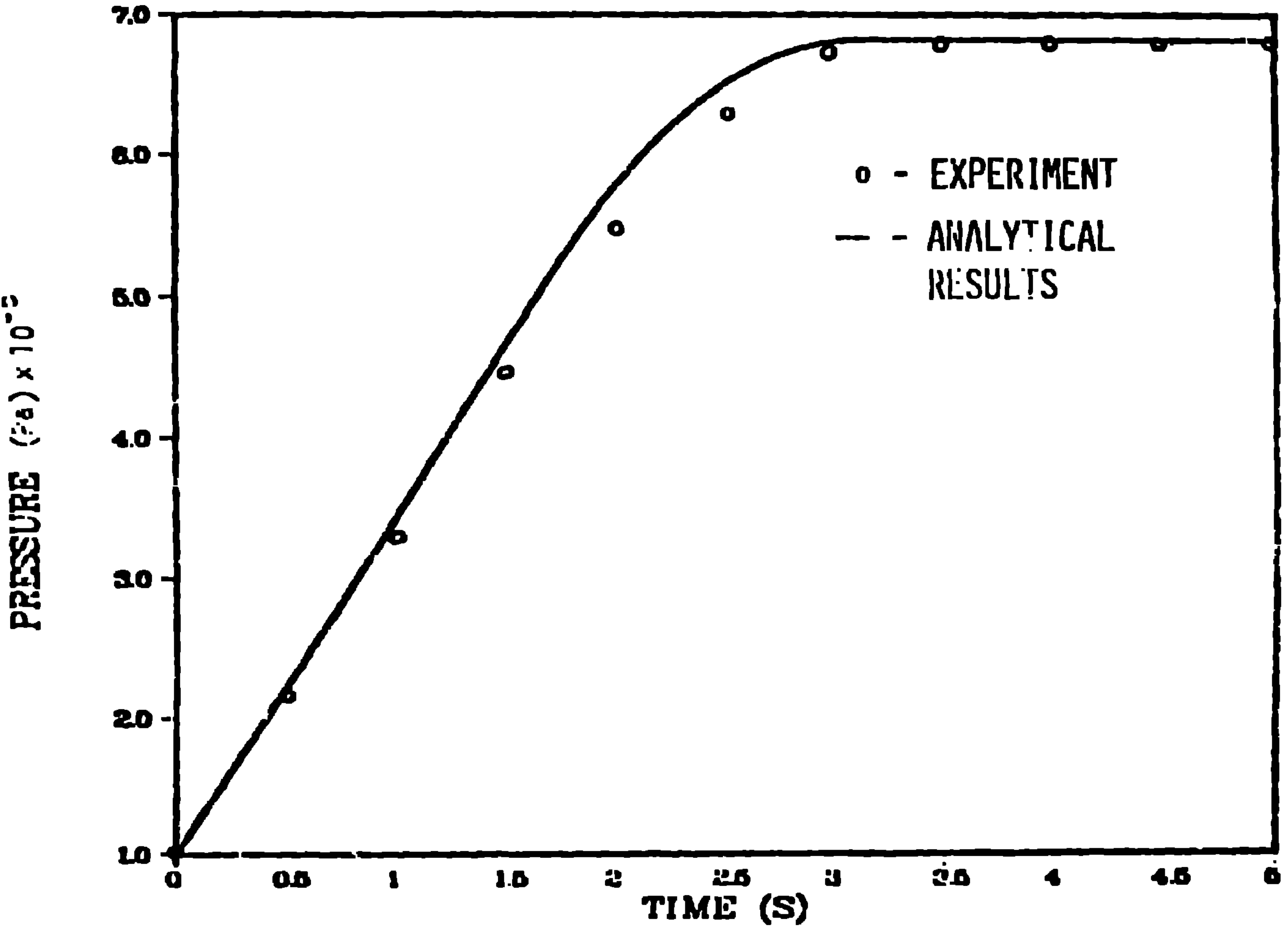


Figure 4. Analytical and experimental results for discharging problem.



CHARGING VESSEL

Figure 5. Analytical and experimental results for charging problem.

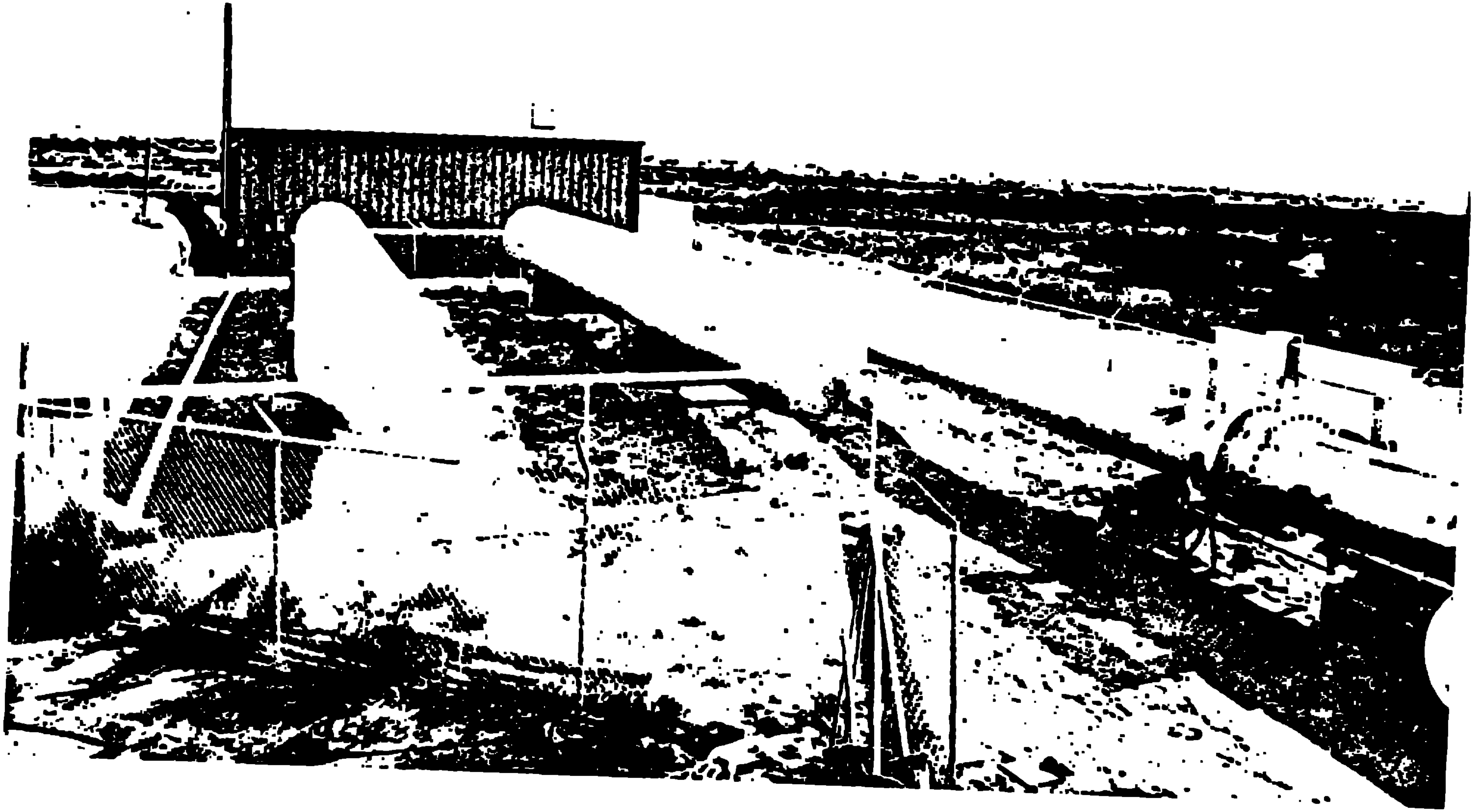


Figure 6. Experimental apparatus at test facility.

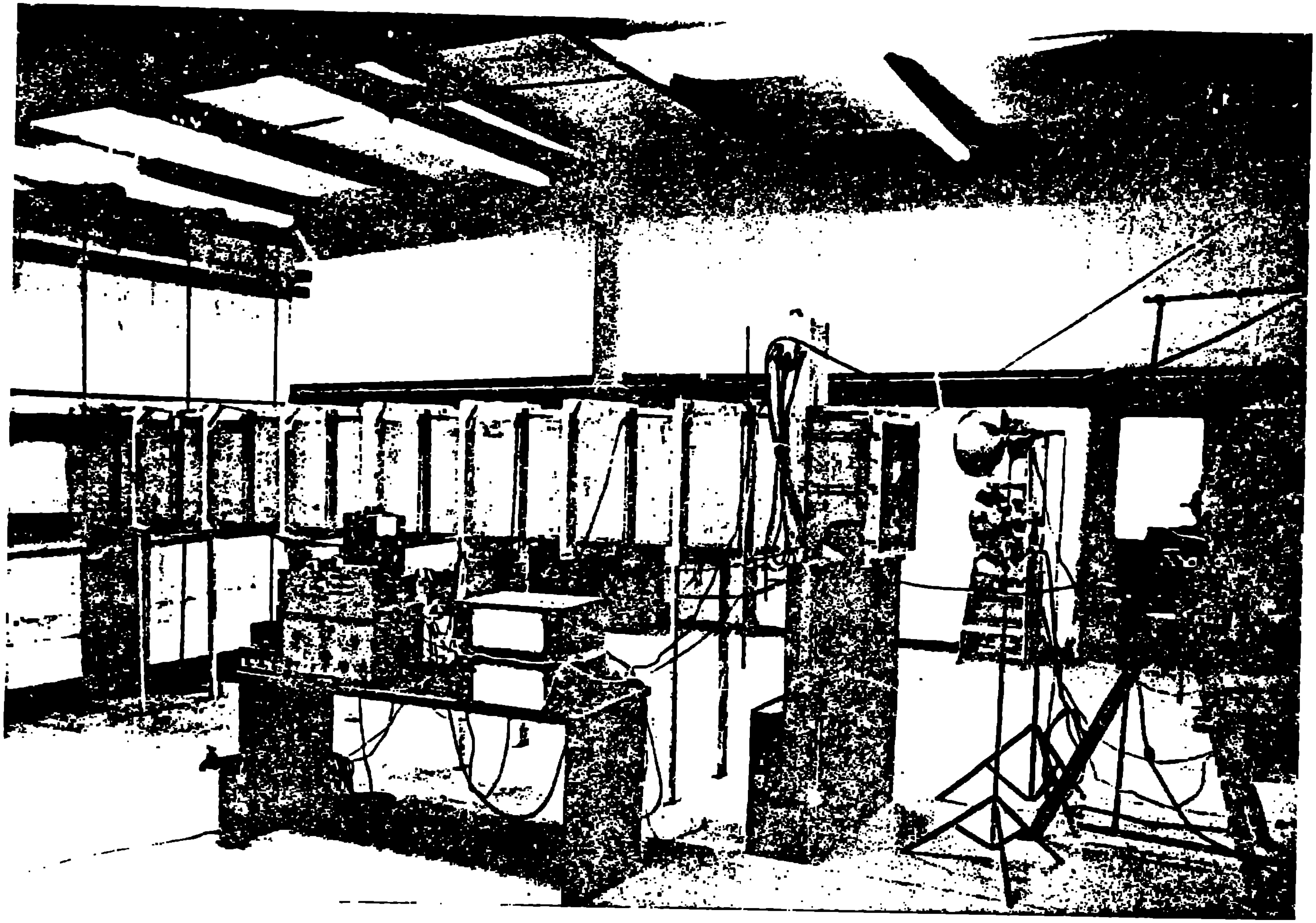


Figure 7. Blowdown chamber and HEPA filter testing apparatus.

test components that have been evaluated thus far are HEPA filters. Recent structural testing results for HEPA filters will be presented in later sections.

b) Scale Model Ventilation Systems - The purpose of the model ventilations systems is to obtain experimental data to compare with and thus verify TVENT computer code predictions. The model ventilation systems are composed of representative components such as blowers, dampers, ducts, filters, and rooms. Figure 8 shows the larger of the two model ventilation systems. The construction of the second model is in progress.

To test a model ventilation system, we had to scale down all of the prototype system variables including size, flow properties, and component characteristics. This must be done not only to build the model, but also to later scale up the measured model results to prototype proportions. A similitude study was completed and has been reported [13].

We will also evaluate the scaling laws used to build our model in addition to comparing the model results with TVENT predictions. To investigate the scaling laws used, we have chosen to design and test two models based on similitude theory. The test results from the larger model will be called prototype results for comparison with the smaller model results. We believe that this will provide confidence that the performance of either of the models can be used to predict full-scale performance and hence, provide a valid test of TVENT. Tests using the larger model or prototype ventilation system are in progress.

3. Shock Tube

The purpose of the shock tube facility is to simulate low-grade explosions and thereby create shock waves that can be imposed on ventilation system components. The shock tube is shown in Figure 9 and is 914 mm (36 in.) in diameter with a 12.1-m (36.9-ft) driver section and a 35.1-m (115.1-ft) driven section. A double-diaphragm technique is used to control driver firing pressure. This method allows us to reduce diaphragm costs by eliminating the need for machine-scored diaphragms. The conceptual design and small scale experiments are reported in References [14] and [15].

We intend to control the total impulse that is imposed on the test specimen. That is, we will control both peak pressure and duration (i.e. dwell time) of the high pressure behind the shock wave. A wide range of dwell times can result from internal explosions. Diverse systems within facilities and their geometrical configurations are responsible for part of the variability in dwell times, but other conditions may be even more influential. These conditions result from the character of the material causing the explosions. Fuel cycle operations typically involve gases, vapors, and dust or fine granular material. These materials often have explosive potential and vary widely in their deflagration or detonation characteristics. We have concluded that it is impossible to pick a single representative dwell time for a detonation wave. Thus we have devised a method to allow variable dwell times with the shock tube.

The method used is suggested by the physical phenomena occurring in the shock tube. Gas at different pressures is separated by a diaphragm. When the diaphragm is ruptured, a compression wave is sent down the low-pressure region of the shock tube while an expansion wave travels in the opposite direction into the high-pressure region of the shock tube. When the expansion wave arrives at the end of the high-pressure section, it is reflected and races back down the shock tube, tending to overtake the shock wave. By varying the

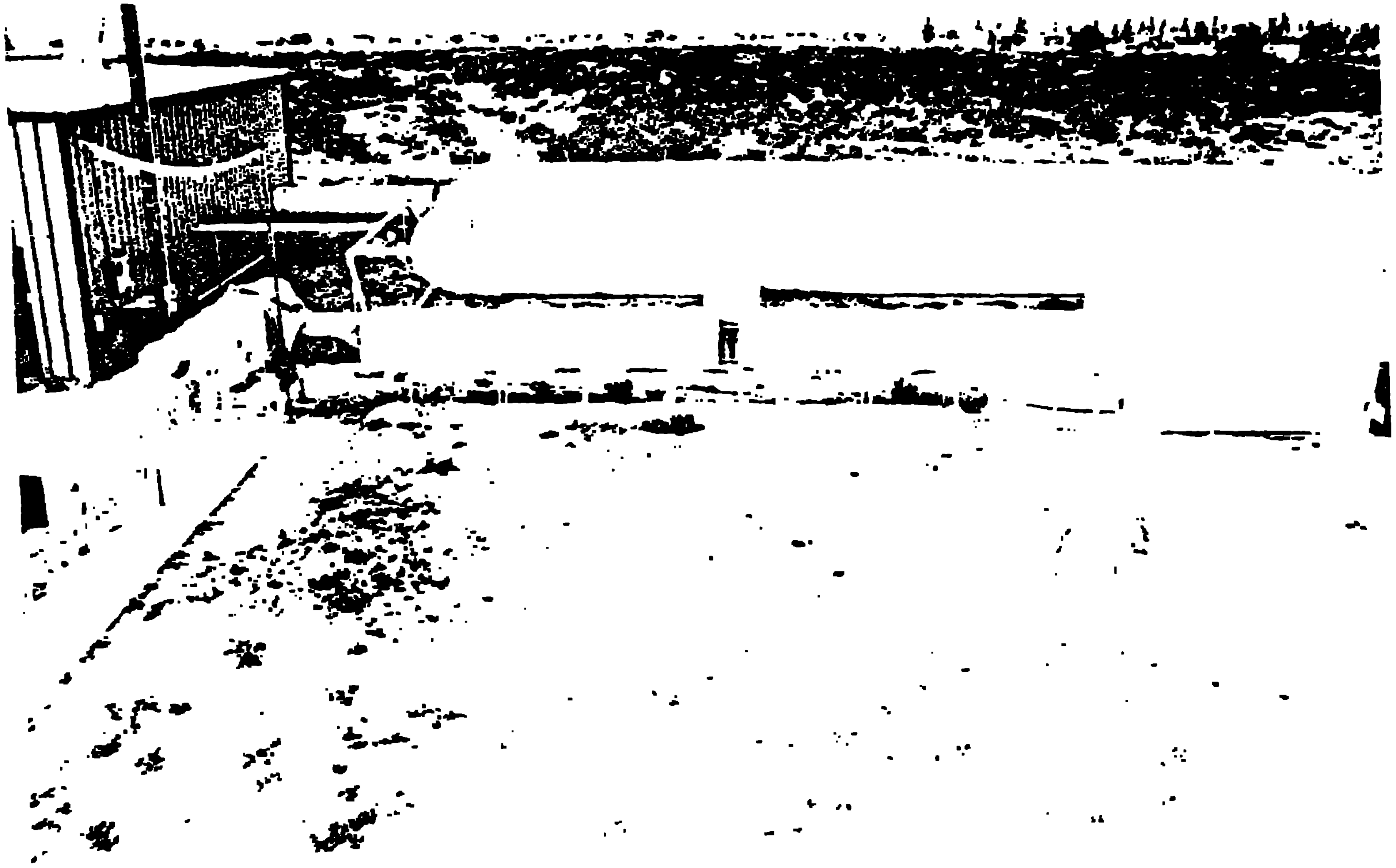


Figure 8. Model ventilation system.

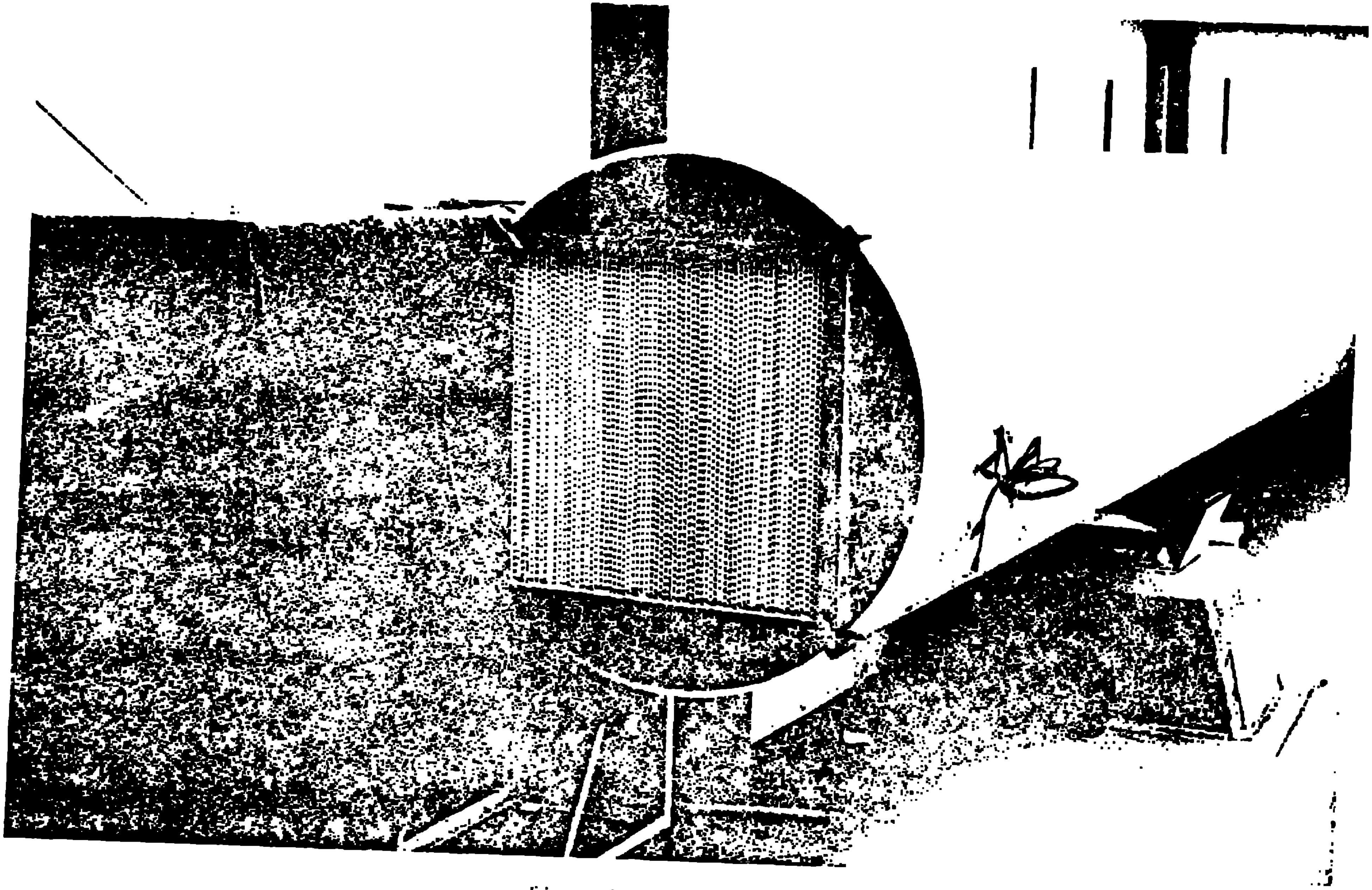


Figure 9. Shock tube.

length of the driver section of the shock tube, we can obtain any dwell time desired. The dwell time will be the difference between the arrival times of the compression and expansion waves at the test specimen.

We plan to evaluate the effect of total impulse on ventilation system components during the remainder of 1979. Initial tests are in progress using standard HEPA filters.

5. Overpressure Tests of HEPA Filters

A. General

Our initial testing emphasis has been placed on subjecting HEPA filters to simulated tornado pressure differentials. The characteristics (pressurization rate, maximum pressure) of the pressure differentials were chosen to simulate tornado conditions described in the US Nuclear Regulatory Commission's Guide 1.76. The most severe design basis tornado described in the Guide is for a pressurization rate of 13.8 kPa/s (2 psi/s) and 20.7 kPa (3 psi) pressure differential. Although our tests are centered around these design basis tornado specifications, the results obtained are valid for any design basis tornado of interest.

The investigation was a parametric study where tornado and HEPA filter characteristics were examined for their effect on structural integrity. The test procedure and the results are described below. All HEPA filters were nuclear grade and met MIL-F-5-108-79, MIL-Std-282, and MIL-F-51068 specifications. In addition, all filters were sent through a Department of Energy filter test station before shipment to NMSU. Only filters meeting the above specifications were sent on to NMSU for structural testing.

B. Test Procedure

Using the blowdown device described above, a pressure differential at a selected pressurization rate was imposed across the filters. The test was continued until the pressure differential across the filter was above the maximum of 20.7 kPA (3 psi). A high-speed movie camera and all instrumentation recorders were started simultaneously with the sequencing valves. Pressure differential across the filters and dynamic pressure were measured by electronic pressure transducers and recorded by strip chart recorders. A timing mark was simultaneously recorded on the high-speed film and pressure recorder at 10 ms intervals. The actual times of filter failure were then found by observing the high-speed movies of the downstream filter face. Also photographed by the camera (for reference) during the test were a clock and manometer mounted beside the filters. All tests were performed at air humidities from 40 to 60%.

C. Test Results

a) Structural Limits - Table I contains statistical values for the structural limits of 610- by 610-mm (24- by 24-in.) HEPA filters from four manufacturers. The average break pressure for each of the four manufacturers' filters and for all filters are presented in Table I. In addition to break pressure, the standard deviation is also listed in Table I. As shown in Table I, the strongest filter is from manufacturer B with a mean break pressure of 20.1 kPa (2.91 psi) and a standard deviation of 3.2 kPa (0.46 psi). The weakest filter was from manufacturer C with a mean break pressure of 9.1 kPa (1.32 psi) and a standard deviation of 1.5 kPa (0.22 psi). Also, the least amount of data scatter was found with manufacturer C (smallest S). We also have photographs of the 16-mm movie frames at the

TABLE I
STRUCTURAL LIMITS

Manufacturer	$\bar{P}_B$		S		$\bar{P}_B$-S		$\bar{P}_B$-2S	
	kPa	psi	kPA	psi	kPa	psi	kPa	psi
A	17.3	2.50	3.9	0.56	13.4	1.94	9.5	1.38
B	20.1	2.91	3.2	0.46	16.9	2.45	13.7	1.99
C	9.1	1.32	1.5	0.22	7.6	1.10	6.1	0.88
D	18.4	2.66	2.2	0.32	16.2	2.34	13.9	2.02
All filters	16.4	2.37	4.9	0.71	11.5	1.66	6.6	0.95

$\bar{P}_B$ = Mean HEPA filter peak pressure
S = Standard deviation

break point time and also at 20.7 kPa (3 psi). Examples are shown in Figures 10 and 11. In Figure 10 the downstream face of one of the stronger filters is shown. Notice that the initial break point occurs in a single fold and the opening at that fold increases with time. However, the failure for the weakest filters is entirely different. See Figure 11.

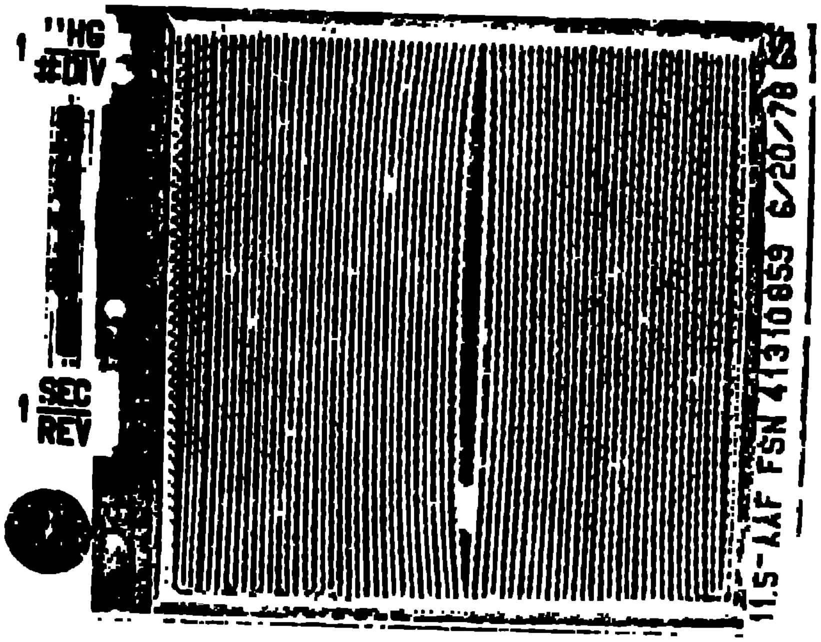
When all of the data from all manufacturers is consider as a single data set, we obtain the last row shown in Table I. Thus we can say that we are 68.26% confident that the structural limit will be equal to or greater than 11.5 kPa (1.66 psi).

b) Parametric Study - We have tried to evaluate the effect of several parameters on the structural limits or initial break pressure of the 610- by 610-mm (24- by 24-in.) HEPA filters. Table II lists parameters under

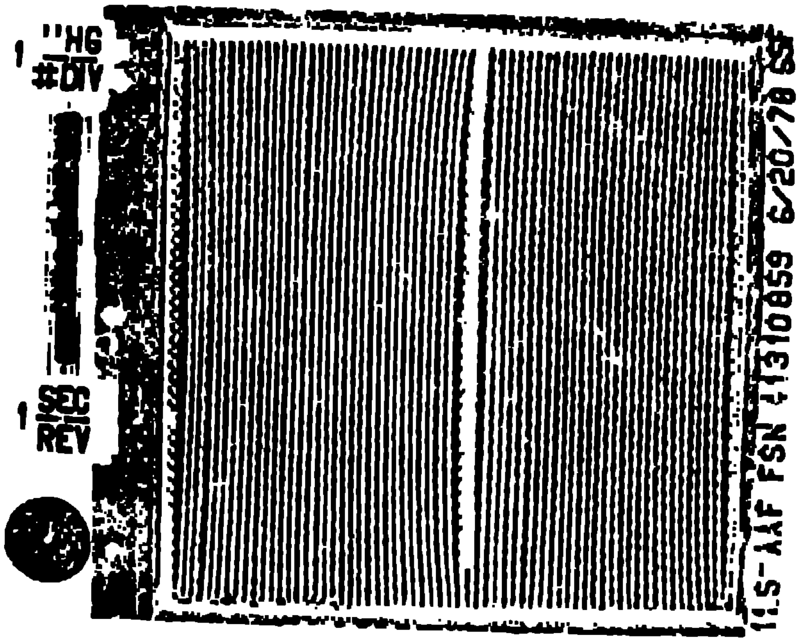
TABLE II
PARAMETERS AND EFFECT ON FILTER BREAK PRESSURE

Parameter or Effect	Statistical Effect
1. Manufacturer	YES
2. Pressurization rate	NO
3. Flow direction	NO
4. Time at maximum pressure	NO
5. Number of folds (pack tightness)	NO
6. Metal vs asbestos separators	NO
7. Location of initial break	+
8. Medium area destroyed	+
9. Medium tensile strength	*
10. Medium DOP** penetration	*

\+ Data recorded during testing
* Statistical analysis not yet performed
** Dioctylphthalate

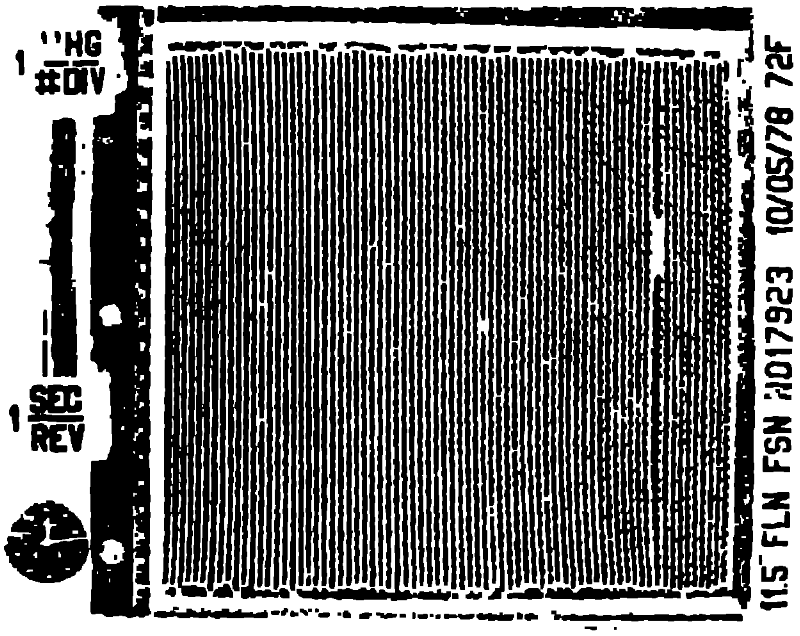


(a) Breakpoint pressure

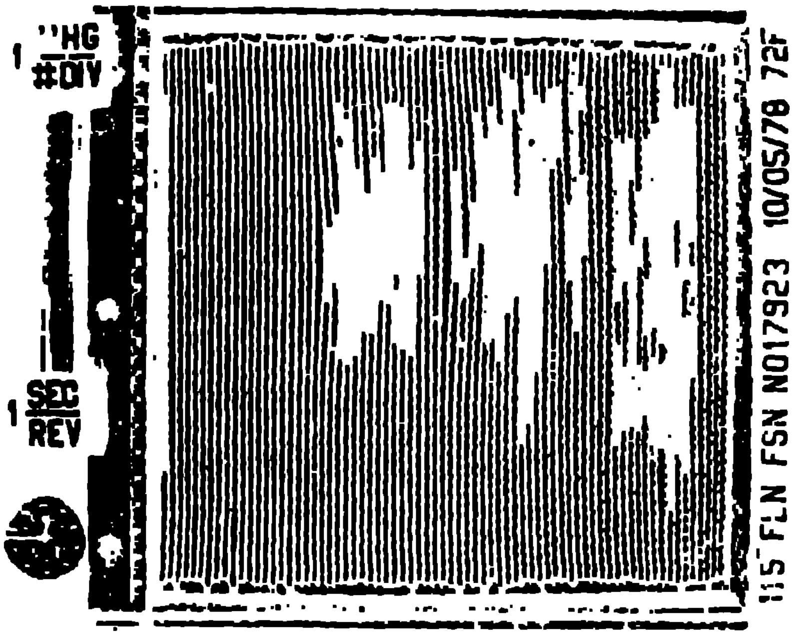


(b) 20.7 kPa (3 psi) pressure

Figure [illegible]. Typical view of downstream filter face for a stronger filter at break point pressure and at 20.7 kPa (3 psi).



(a) Breakpoint pressure



(b) 20.7 kPa (3 psi) pressure

Figure [illegible]. Typical view of downstream filter face for the weakest filter at break point pressure and at 20.7 kPa (3 psi).

evaluation in addition to parameters recorded during the testing. Table II also shows the statistical effect of each parameter. However, our statistical analysis was limited because of the small number of filters available for each test. For example, there seems to be a trend toward lower break pressures as pressurization rate increases. However, we cannot say statistically that pressurization rate has an effect. Therefore Table II indicates that only manufacturer variability has statistical effect on filter break pressure.

6. Future Investigations

Some of our future work is outlined below.

- Efficiency tests of HEPA filters under artificial loading conditions and airstream-entrained aerosol. These will be performed for simulated tornado transients. A laser particle counter is being fabricated to measure the transient aerosol release. Small-scale experiments have been performed [16--17].
- Shock tube tests to simulate explosive transients across HEPA filters and other ventilation components.
- Verification tests for the explosion computer code.
- Wind tunnel reentrainment/deposition experiments.
- Development of fire and material transport computer codes.

7. Summary

In this paper we have discussed unanswered questions dealing with the safety and behavior of off-gas and ventilation systems. We have described LASL's accident analysis program for providing answers to or some understanding of these questions. Our approach is both analytical and experimental in developing predictive computer codes and supportive experimental data. A unique test facility was described that will provide some answers regarding behavior of ventilation components to simulated accidents. Further, we believe that this facility is very flexible and can be easily modified to study many types of accident response phenomena. Finally, we presented results for structural limits of HEPA filters for transient overpressure loadings.

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