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*Efficiency Testing of Standard  
High-Capacity High-Efficiency Particulate  
Filters Subjected to Simulated Tornado  
Pressurization and Explosive Shock Waves*

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# Summary of Efficiency Testing of Standard and High-Capacity High-Efficiency Particulate Air Filters Subjected to Simulated Tornado Depressurization and Explosive Shock Waves



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SUMMARY OF EFFICIENCY TESTING OF STANDARD AND HIGH-CAPACITY  
HIGH-EFFICIENCY PARTICULATE AIR FILTERS SUBJECTED TO SIMULATED  
TORNADO DEPRESSURIZATION AND EXPLOSIVE SHOCK WAVES

by

P. R. Smith and W. S. Gregory

ABSTRACT

Pressure transients in nuclear facility air cleaning systems can originate from natural phenomena such as tornadoes or from accident-induced explosive blast waves. This study was concerned with the effective efficiency of high-efficiency particulate air (HEPA) filters during pressure surges resulting from simulated tornado and explosion transients. The primary objective of the study was to examine filter efficiencies at pressure levels below the point of structural failure. Both standard and high-capacity 0.61-m by 0.61-m HEPA filters were evaluated, as were several 0.2-m by 0.2-m HEPA filters. For a particular manufacturer, the material release when subjected to tornado transients is the same (per unit area) for both the 0.2-m by 0.2-m and the 0.61-m by 0.61-m filters. For tornado transients, the material release was on the order of micrograms per square meter. When subjecting clean HEPA filters to simulated tornado transients with aerosol entrained in the pressure pulse, all filters tested showed a degradation of filter efficiency. For explosive transients, the material release from preloaded high-capacity filters was as much as 340 g. When preloaded high-capacity filters were subjected to shock waves approximately 50% of the structural limit level, 1 to 2 mg of particulate was released.

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I. INTRODUCTION

Pressure transient conditions within nuclear facilities can result from natural phenomena or accidents. Natural phenomena, such as tornadoes with their characteristic depressurizations, can induce pressure surges within these structures. Accidents might include gas (for example, hydrogen), dust, or chemical explosions. Therefore, a knowledge of how pressure transients from such events will affect the ventilation system of a nuclear facility is necessary to evaluate the probability of a release of radioactive particulate to the atmosphere. High-efficiency particulate air (HEPA) filters, common to nuclear facility ventilation systems, reduce the release of radioactive particulate to

the atmosphere at the facility boundaries under normal operating conditions to acceptably low levels. These filters are required by regulation to have efficiencies in excess of 99.97% under normal operating conditions. However, little is known about their efficiency or how they might release trapped particulate when subjected to tornado-induced depressurization or when struck by an explosively driven shock wave. Therefore, as part of an ongoing study by the Los Alamos National Laboratory and New Mexico State University (NMSU) of the reponse of nuclear facility ventilation systems and system components to catastrophic occurrences, the efficiency and release characteristics of HEPA filters during pressure transients were investigated. This report summarizes the results of that investigation.

The filters chosen for the study included the 0.61-m by 0.61-m and the 0.2-m by 0.2-m sizes. Six types of HEPA filters from five manufacturers were tested. Four were standard HEPA filters (that is, having a rated airflow capacity of  $0.47 \text{ m}^3/\text{s}$  for the 0.61-m by 0.61-m size and of  $0.024 \text{ m}^3/\text{s}$  for the 0.2-m by 0.2-m size); two were high-capacity HEPA filters (that is, having a rated airflow capacity of  $0.85 \text{ m}^3/\text{s}$  for the 0.61-m by 0.61-m size). The experimental investigation used equipment previously used to study the structural strength of HEPA filters.

## II. DESCRIPTION OF TEST APPARATUS

### A. Tornado Transient Simulation

A schematic of the Los Alamos National Laboratory/NMSU blowdown wind tunnel used to simulate flow through a HEPA filter resulting from a tornado-induced pressure differential is shown in Fig. 1. High-pressure air from large storage tanks was introduced into the blowdown tunnel through 12 sonically limited solenoid valves. The pressure pulse across the HEPA filters was shaped by opening the solenoid valves sequentially under the control of a solid-state sequencer. Two versions of the blowdown tunnel exist: a small-scale version for testing 0.2-m by 0.2-m filters and a large-scale version for testing 0.61-m by 0.61-m filters. The HEPA filters are mounted at the exhaust end of the tunnel. Pressure differences across the test filters as high as 100 kPa and flow rates as high as  $5 \text{ m}^3/\text{s}$  can be produced. W. S. Gregory et al. describe this equipment and its operation in detail.<sup>1,2</sup>

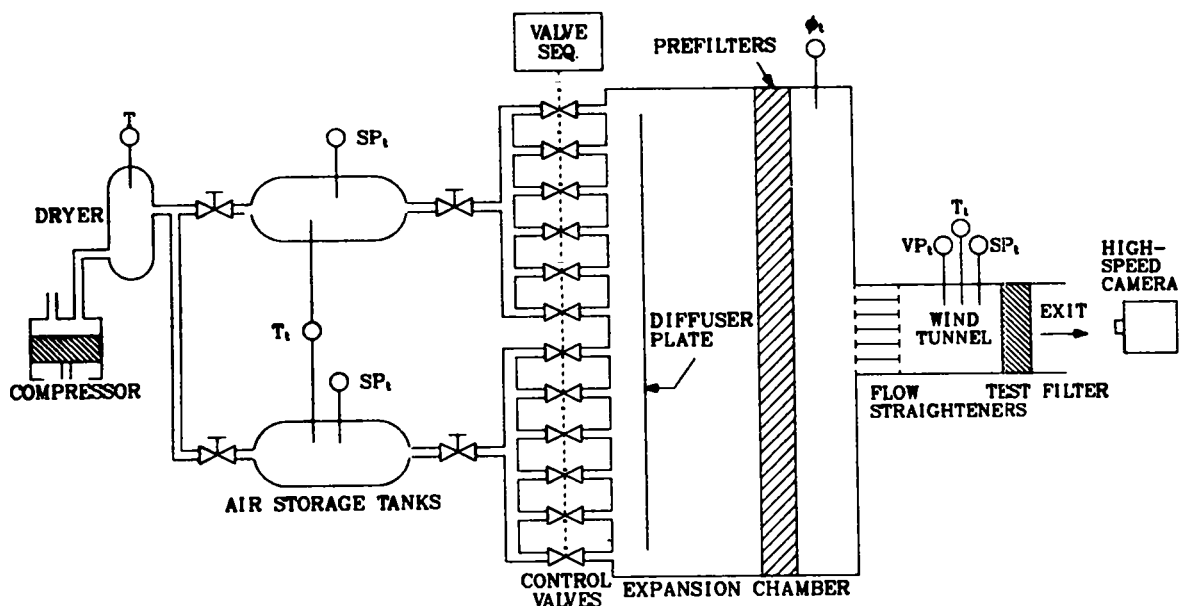


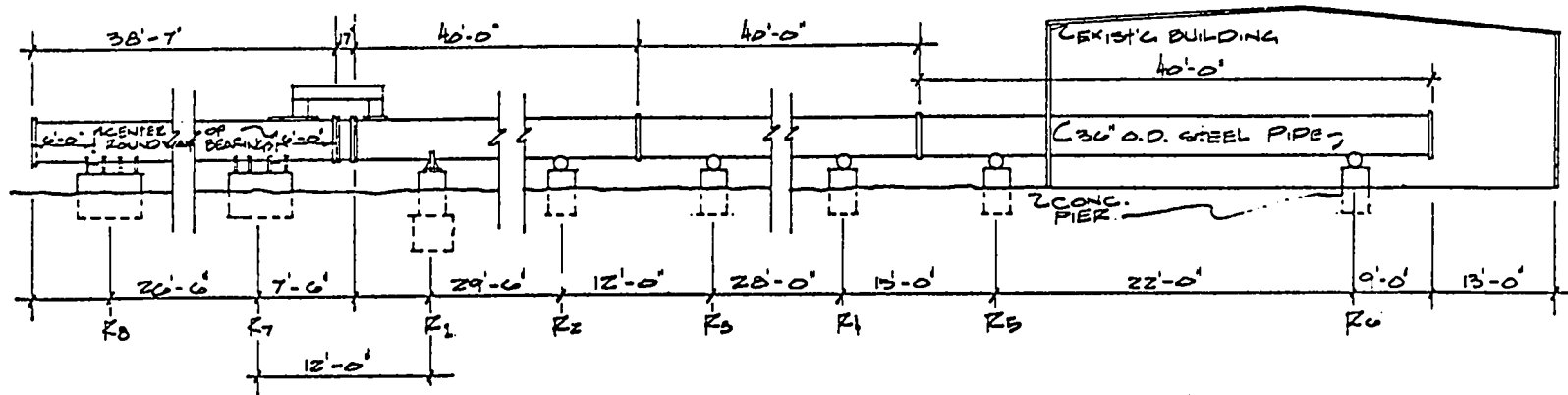
Fig. 1.  
Schematic of blowdown wind tunnel.

### B. Explosive Simulation

Shock waves simulating explosively driven shock waves were produced using the Los Alamos/NMSU shock tube. This shock tube is 0.91 m in diameter and has a variable driver length that is used to control both shock overpressure and shock impulse. Thus, explosive shock waves can be simulated in terms of magnitude and distance from the source of the explosion.

Figure 2 is a schematic of the overall shock tube, which is located on the NMSU campus. The shock tube consists of three sections, all made from 0.91-m-diam steel pipe: (1) a driver or high-pressure section (11.76 m long), (2) an interstage or double-diaphragm section (0.43 m long), and (3) a driven or low-pressure section (36.58 m long). These sections appear from left to right in Fig. 2. The test HEPA filter was placed in the outlet of the driven (low-pressure) section. The driver (high-pressure) section can be pressurized to a maximum of about 241 kPa by a large diesel-driven air compressor. Therefore, the peak pressure differences across the generated shock waves will be a maximum of approximately 345 kPa. The dwell time of the pressure rise behind

<u>FOUNDATION</u>	<u>DESCRIPTION</u>
R <sub>1</sub>	PIPE RIGIDLY FIXED TO CONCRETE PIER
R <sub>2</sub> , R <sub>4</sub>	PIPE SITTING ON GRINNELL PIPE ROLL STAND
R <sub>3</sub> , R <sub>5</sub> , R <sub>6</sub>	PIPE SITTING ON GRINNELL PIPE ROLL STAND W/TIE DOWN STRAP
R <sub>7</sub> , R <sub>8</sub>	PIPE SITTING ON ROUNDWAY BEARING ASSEMBLY



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Fig. 2.  
Reduced copy of construction blueprint of the overall shock tube.

the shock wave can be varied from a few milliseconds to about 50 ms by varying the length of the driver section with a pneumatically sealed movable rear wall. Smith and Gregory describe this shock tube and its operation in detail.<sup>3</sup>

### III. METHOD OF TESTING

#### A. Tornado Transients

1. Material Loss from Loaded 0.61-m by 0.61-m HEPA Filters. The 0.61-m by 0.61-m size HEPA filters were preloaded with polystyrene latex particulate having a size from range of 0.3  $\mu\text{m}$  to 1.0  $\mu\text{m}$  with a mean of 0.46  $\mu\text{m}$ . Particulate was generated by a Laskin-type generator; the particulate was entrained by an airflow of 0.47  $\text{m}^3/\text{s}$  for the standard filters and 0.85  $\text{m}^3/\text{s}$  for the high-capacity filters and then impinged on the filters. The filters were loaded until a pressure drop of 38.1 cm of water across them was obtained. At this pressure drop, approximately 1.0 kg of material had been deposited on each filter. Most filters are replaced when they receive loadings that generate loadings of approximately 21 cm of water pressure drop. For these tests we loaded the filters to an excessive amount to assure conservative results.

To determine the amount of mass that might be released from loaded standard HEPA filters, the filters were placed at the exhaust of the blowdown tunnel. Five nucleopore filters, each 5 cm in diameter and arranged in the pattern shown in Fig. 3, were placed downstream of the HEPA filters. A vacuum applied to the rear of the nucleopore filters during the tornado transient assured that the particulate released from the HEPA filters would collect on the nucleopore filters. Also, each nucleopore filter was fitted with a cone-shaped diffuser, as shown in Fig. 4, with a 0.64-cm inlet diameter that allowed isokinetic collection of particulate at the maximum test flow rate for each HEPA filter through the adjustment of the vacuum applied to the nucleopore filters.

Each loaded HEPA filter was subjected to only one simulated tornado pressure transient. Pressure transients were selected to be just below the magnitude known to cause structural failure of the filter medium, as determined in our previously reported studies.<sup>2</sup> Four manufacturers' filters were tested in



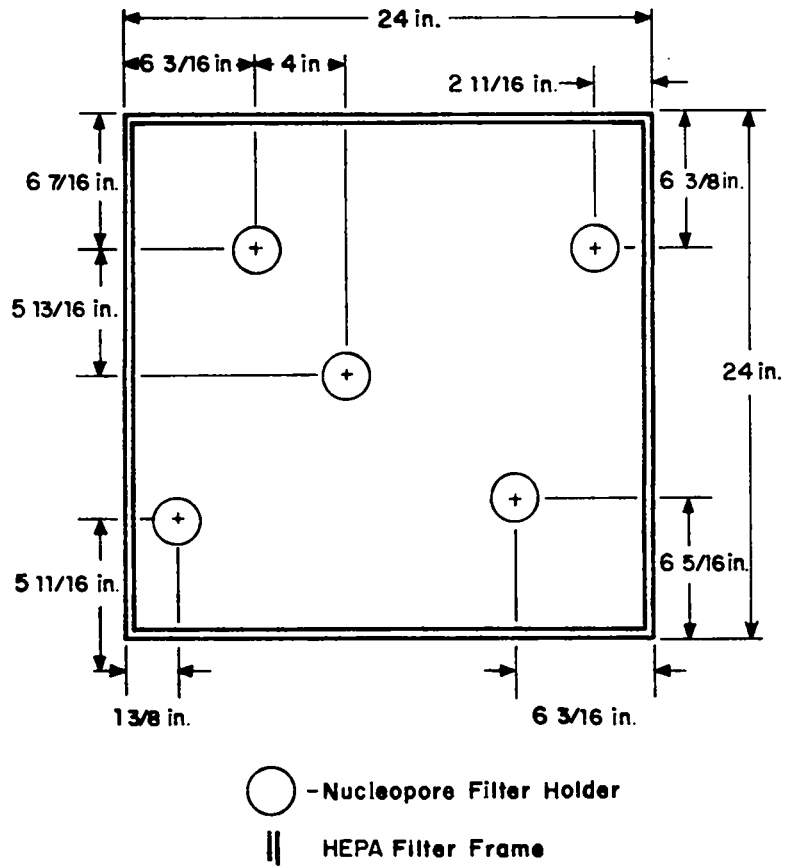


Fig. 3.  
Schematic of nucleopore filter locations.

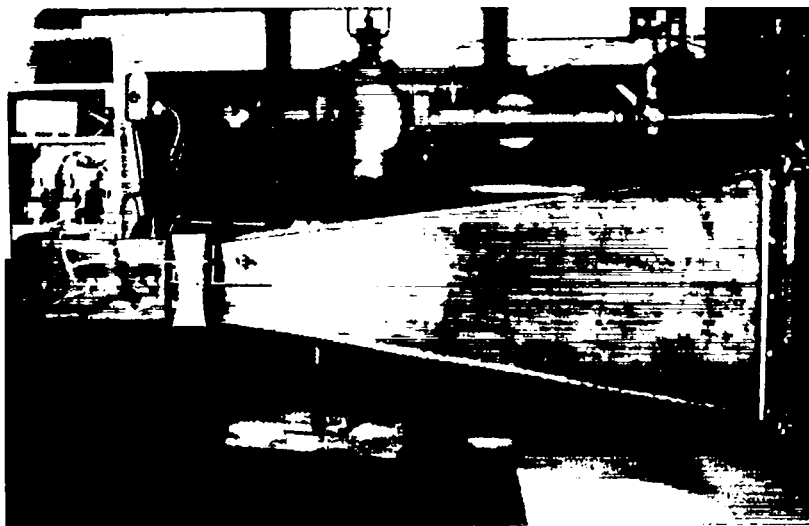


Fig. 4.  
Cone diffuser for nucleopore filters.

the structural failure studies. For the material loss tests, we selected only one manufacturer's filter (Brand A) for testing. This was done for two reasons—a limited amount of material available and the extreme length of loading time required (~4 to 5 weeks).

The nucleopore filters were examined with an electron microscope after each tornado test, and the number of particles released was determined by direct count. Figure 5 is a typical photomicrograph showing polystyrene particles on a small portion of a nucleopore filter.

## 2. Material Loss from Loaded Standard 0.2- $\mu$ m by 0.2- $\mu$ m HEPA Filters.

The 0.2- $\mu$ m by 0.2- $\mu$ m standard HEPA filters were preloaded with NaCl particles combined with uranine (flourescein-disodium salt) dye using a Laskin-type generator to produce the particulate. The NaCl/uranine was selected for this test because of the sampling method used. These filters were small enough to use a diffuser with a wall of micropore filters to catch all of the material released. The uranine then could be analyzed through a chemical analysis to determine the amount of material released. This method was not practical for the larger (0.61- $\mu$ m by 0.61- $\mu$ m) filters because of the large micropore area required. The mean mass diameter of the NaCl/uranine particles was 0.446  $\mu$ m with a geometric standard deviation of 1.75, and therefore, the particulate was monodisperse. An airflow of 0.04 m<sup>3</sup>/s entrained the particulate, which then impinged on the test filter. Filters were loaded to pressure drops across the

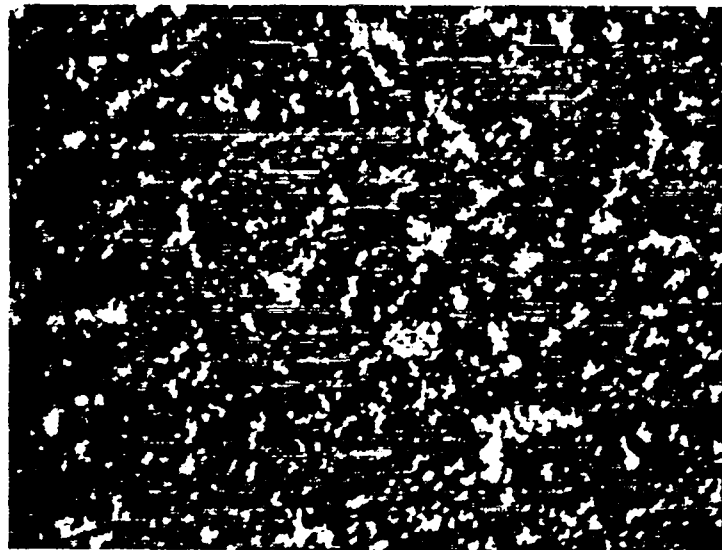


Fig. 5.  
Photomicrograph of polystyrene particulate.

filters ranging from 39 mm of water to 130 mm of water vs 381 mm (38.1 cm) for 0.61-m by 0.61-m filters. A lower amount of material, with a corresponding lower pressure drop, was loaded on the 0.2-m by 0.2-m filters. These tests were performed before the tests on the larger filters, and our loading apparatus did not have the capacity to load the filters to a larger pressure drop.

The amount of mass released from loaded standard 0.2-m by 0.2-m HEPA filters was determined by placing them on the exhaust of the small-scale blowdown wind tunnel. Downstream of the test filter, a diffuser was placed that slows the exiting air as it approaches a wall of micropore filters. The entire arrangement is shown in Fig. 6. The micropore filters catch a large percentage of the NaCl/uranine particles released from the loaded HEPA filter during the tornado pressure transient. A chemical analysis of the micropore filters performed at Los Alamos then determined the amount of particulate released from the HEPA filter.

3. Efficiency of Clean Standard 0.61-m by 0.61-m HEPA Filters. Polystyrene latex particles ranging in size from 0.3  $\mu\text{m}$  to 1.0  $\mu\text{m}$  with a mean of 0.46  $\mu\text{m}$  were introduced upstream of clean HEPA filters from a Laskin-type particle generator until the entire volume of the blowdown wind tunnel from the



Fig. 6.  
Small scale blow down wind tunnel with diffuser  
and micropore filter wall in foreground.

prefilter chamber to the outlet was filled with particulate. The HEPA filter was isolated from the particulate during this time by a set of internal doors just upstream of the filter. Samples of the aerosol were analyzed by a Royco particle counter just before the tornado transient was applied to the HEPA filter to determine the uniformity of the particle distribution within the tunnel. If the distribution was satisfactory (that is, if the distribution matched the known distribution of the solution containing the particles), the tornado transient was initiated. Particulate was collected during the transient by a single nucleopore filter centered upstream of the HEPA filter and by five nucleopore filters located downstream of the HEPA filter (Fig. 3.). The particulate count on the nucleopore filters was made using an electron microscope. Efficiency was calculated by taking the ratio of the number of particles detected downstream per unit area to the number of particles detected upstream per unit area and subtracting this ratio from unity.

#### 4. Efficiency of Clean Standard 0.2-m by 0.2-m HEPA Filters.

NaCl/uranine particles were introduced upstream of clean 0.2-m by 0.2-m standard HEPA filters using a Laskin-type generator. During particulate loading of the volume upstream of the HEPA filter, the filter was isolated from the particulate by a wax paper diaphragm. The diaphragm burst upon application of the simulated tornado transient, allowing the particulate to impinge on the HEPA filter. Particulate passing through the HEPA filter was captured on a micropore filter located downstream of a diffuser used to slow down the airflow. The amount of particulate within the volume upstream of the filter was determined by running the Laskin-type generator for the same length of time before each test (1 h) and performing one test with no HEPA filter in place. Chemical analysis at Los Alamos of the micropore filter medium determined how much particulate had passed through the test HEPA filter. Efficiency was calculated by taking the ratio of the particulate mass on the micropore filter with the HEPA filter in place to the particulate mass on the micropore filter with no HEPA filter in place and subtracting this ratio from unity.

### B. Explosive Transients

1. Material Loss from Loaded High-Capacity 0.61-m by 0.61-m Filters. To determine the amount of mass that might be released from high-capacity HEPA filters preloaded with a particulate upon impingement by a shock wave, filters were loaded as described in Sec. II.A. Five nucleopore filters in the pattern

shown in Fig. 3 were placed downstream of the HEPA filter on the end of the shock tube. The face of each nucleopore filter was 5 cm from the downstream face of the test HEPA filter. A vacuum of 12 cm of mercury applied to the rear of the nucleopore filters during shock overpressure assured that the released particulate would collect on the nucleopore filters. Each HEPA filter was subjected to only one shock overpressure, and shock overpressures were selected to be just below the structural failure limits determined in our previous tests and reported in Ref. 3.

2. Efficiency of Clean High-Capacity 0.61-m by 0.61-m HEPA Filters. The efficiency of clean high-capacity HEPA filters was tested by first loading the driven section of the shock tube with a polystyrene latex aerosol from a Laskin-type generator. Five nucleopore filters were placed downstream of a clean HEPA filter located at the exhaust of the shock tube (Fig. 7.) Samples of the aerosol were analyzed by a Royco particle counter just before the shock tube was fired to determine the uniformity of particulate distribution within the shock tube. If a satisfactory distribution existed, the shock tube was fired. Particulate was collected during the shock overpressure by the nucleopore filters, which again were subjected to a 12 cm of mercury vacuum. Particulate count on the nucleopore filters again was determined using an electron



Fig. 7.  
Five nucleopore filter holders located just downstream of a V-type HEPA filter ready for shock testing.

microscope. The average efficiency of the HEPA filter during the shock overpressure then could be calculated from the measured velocities at the face of the nucleopore filters and upstream of the test HEPA filter.

#### IV. RESULTS

##### A. Tornado Transients

###### 1. Material Loss from Loaded Standard 0.61-m by 0.61-m HEPA Filters.

Table I presents the results of subjecting two standard HEPA filters of the same brand to tornado-like pressure pulses. The pressurization rate of the pulse was 14.7 kPa/s, and the maximum pressure difference across the filters reached 14.7 kPa and was maintained for 3 s. The mass of the particulate released was 4.05  $\mu\text{g}$  for one filter and 14.6  $\mu\text{g}$  for the other. Mass was calculated by using the mean diameter of the polystyrene latex particles to find the volume, which then was multiplied by the density and the number of articles released.

###### 2. Material Loss from Loaded Standard 0.2-m by 0.2-m HEPA Filters.

Table II presents the results of subjecting four loaded standard 0.2-m by 0.2-m HEPA filters of two different brands to simulated tornado pressure transients. Pressurization rates were about 14 kPa/s, and peak overpressure was about 20 kPa for all tests. Peak overpressure was maintained for 3 s. The mass of particulate released from the three type A filters was 1.95  $\mu\text{m}$ , 1.45  $\mu\text{m}$ , and 1.81  $\mu\text{m}$ , whereas it was 6.45  $\mu\text{m}$ , for the type F filter. Mass was determined by chemical analysis of the micropore filter medium upon which the released particulate was captured.

TABLE I  
PARTICULATE RELEASED FROM LOADED STANDARD 0.61-M BY 0.61-M HEPA  
FILTERS DURING A SIMULATED TORNADO TRANSIENT

Filter Manufac- turer	Pressurization Rate (kPa/s)	Maximum Pres- sure Differ- ential (kPa)	Dwell at Maximum Pressure (s)	Number of Particulate Released	Mass of Released Per ( $\mu\text{g}$ )	Particulate Area ( $\mu\text{g}/\text{m}^2$ )
A	14.7	14.7	3	$27.3 \times 10^7$	14.60	39.24
A	14.7	14.7	3	$7.6 \times 10^7$	4.05	10.88

TABLE II

PARTICULATE RELEASED FROM LOADED STANDARD 0.2-M BY 0.2-M HEPA FILTERS  
DURING A SIMULATED TORNADO TRANSIENT

Filter Manufacturer	Size <sup>a</sup>	Peak Pressure (kPa)	Flow (m <sup>3</sup> /s)	Pressure Released (kPa/s)	Particulate Release (μg)	Particulate Released Per Area μ/m <sup>2</sup>
A	S	22.41	0.48	12.75	1.95	48.75
A	S	20.13	0.22	14.68	1.45	36.25
F	S				1.81	45.25
F	L	22.34	0.48	15.65	6.45	161.25

<sup>a</sup>S = 0.2-m by 0.2-m by 0.088-m filter, L = 0.2-m by 0.2-m by 0.16-m filter.

3. Efficiency of Clean 0.61-m by 0.61-m Standard HEPA Filters. Table III presents the results of the efficiency testing of four manufacturers' brands of standard 0.61-m by 0.61-m HEPA filters during tornado transients. The first four columns of Table III are identical to those of Table I. The fifth column gives the number of particles challenging the HEPA filter, and the sixth column

TABLE III

EFFICIENCY OF STANDARD 0.61-M BY 0.61-M HEPA FILTERS  
DURING A SIMULATED TORNADO TRANSIENT

Filter Manufacturer	Pressure Rate (kPa/s)	Maximum Pressure (kPa)	Dwell At Maximum Pressure (s)	Number Upstream Particulate	Number Downstream Particulate	Efficiency (%)
A	13.3	13.3	3.0	$8.75 \times 10^9$	$7.0 \times 10^7$	99.2
A	14.0	14.7	3.1	$8.84 \times 10^9$	$10.6 \times 10^7$	98.8
C	15.3	15.3	—	$8.69 \times 10^9$	$11.3 \times 10^7$	98.7
C	13.3	14.0	3.0	$9.15 \times 10^9$	$8.2 \times 10^7$	99.1
M	13.3	14.0	3.0	$8.90 \times 10^9$	$11.6 \times 10^7$	98.7
M	13.3	13.3	3.0	$8.80 \times 10^9$	$16.7 \times 10^7$	98.1
F	14.0	7.3	2.9	$8.94 \times 10^9$	$12.5 \times 10^7$	98.6
F	13.3	7.3	2.8	$9.00 \times 10^9$	$3.6 \times 10^7$	99.6

gives the number of particles that passed through the HEPA filter during the tornado pressure pulse. The last column gives the average efficiency for the filters during the pressure transient and is calculated as

$$\text{Efficiency} = \left(1 - \frac{\text{Number Downstream Particulate}}{\text{Number Upstream Particulate}}\right) \times 100 \text{ .}$$

Notice that the efficiency during the tornado pulse varied from about 98.1% to 99.6%.

4. Efficiency of Clean Standard 0.2-m by 0.2-m HEPA Filters. Table IV presents the results of the efficiency testing of two manufacturers' brands of standard 0.2-m by 0.2-m HEPA filters subjected to simulated tornado transients. The measured amounts of NaCl/uranine particulate that passed through the HEPA filters ranged from 1.69  $\mu\text{g}$  to 3.58  $\mu\text{g}$ . The amount of particulate within the chamber upstream of the HEPA filter after generation was found to be 1365  $\mu\text{g}$ . Thus, the HEPA filter efficiency can be calculated as:

$$\text{Efficiency} = \left(1 - \frac{\text{Particulate Release, } \mu\text{g}}{1365 \mu\text{g}}\right) \times 100 \text{ .}$$

As shown in Table IV, efficiencies ranged from 99.74% to 99.88%.

TABLE IV

EFFICIENCY OF STANDARD 0.2-M BY 0.2-M HEPA FILTERS DURING A SIMULATED TORNADO TRANSIENT

<u>Filter Manufacturer</u>	<u>Thickness (m)</u>	<u>NaCl/Uranine Released, (<math>\mu\text{g}</math>)</u>	<u>Efficiency (%)</u>
A	0.088	1.69	99.88
A	0.088	2.20	99.84
A	0.16	2.33	99.83
F	0.16	3.58	99.74
N/A	--	1365.0	--



## B. Explosive Transients

### 1. Material Loss from Loaded High-Capacity 0.61-m by 0.61-m HEPA

Filters. Two brands of high-capacity 0.61-m by 0.61-m HEPA filters were pre-loaded with polystyrene latex aerosol and then subjected to simulated explosive transients. Test results are shown in Table V. The pressure rise across the shock wave is listed as Maximum Pressure in Col. 2; Cols. 3 and 4 give the number of particles released during the transient. The mass loss, 341 g, for the first filter listed apparently occurred because the filter medium was damaged slightly during the test.

2. Efficiency of Clean High-Capacity 0.61-m by 0.61-m HEPA Filters. A single clean, high-capacity 0.61-m by 0.61-m HEPA filter was tested for efficiency during a simulated explosive transient. The data from this test are presented in Table VI. The number of particles that challenged the filter during the shock pulse was  $4.59 \times 10^{10}$ ; the number of particles passing through the filter was  $1.32 \times 10^{10}$ . Therefore, the efficiency of the HEPA filter during the shock transient was 71%.

## V. DISCUSSION OF RESULTS

### A. Tornado Transient Simulation

1. Material Loss from Loaded HEPA Filters. From Table I we find that, for the two 0.61-m by 0.61-m standard type A filters, the particulate release was 4.05  $\mu\text{g}$  and 14.6  $\mu\text{g}$  or 10.88  $\mu\text{g}/\text{m}^2$  and 39.24  $\mu\text{g}/\text{m}^2$ . The particulate in this case was polystyrene latex with a mean size of 0.46  $\mu\text{m}$ . In contrast, we find from Table II that the particulate release was 145  $\mu\text{g}$ , 1.81  $\mu\text{g}$ , and 1.95  $\mu\text{g}$  or 36.75  $\mu\text{g}/\text{m}^2$ , 45.25  $\mu\text{g}/\text{m}^2$ , and 48.75  $\mu\text{g}/\text{m}^2$  for the three type A filters. In this case, the particulate was NaCl/uranine with a mean size of 0.446  $\mu\text{g}$ . Notice that the amount of particulate released from both sizes of

TABLE V  
PARTICULATE RELEASED FROM LOADED HIGH-CAPACITY 0.61-M BY 0.61-M HEPA  
FILTERS SUBJECTED TO SIMULATED EXPLOSIVE TRANSIENTS

<u>Filter Manufacturer</u>	<u>Type</u>	<u>Maximum Pressure (kPa)</u>	<u>Number Particulate Released</u>	<u>Mass of Parti- culate Released (<math>\mu\text{g}</math>)</u>	<u>Particulate Release Per Area (<math>\text{g}/\text{m}^2</math>)</u>
L	V	6.83	$6.39 \times 10^{15}$	341.26	917.12
L	V	3.70	$1.90 \times 10^{10}$	0.00105	0.0028
F	No Sep.	3.86	$4.22 \times 10^{10}$	0.0021	0.0056

TABLE VI  
EFFICIENCY OF A HIGH-CAPACITY 0.61-M BY 0.61-M HEPA FILTER DURING A  
SIMULATED SHOCK TRANSIENT

<u>Filter Manufacturer</u>	<u>Type</u>	<u>Maximum Pressure (kPa)</u>	<u>Number Upstream Particulate</u>	<u>Number Downstream Particulate</u>	<u>Efficiency (%)</u>
L	V	6.89	$4.59 \times 10^{10}$	$1.32 \times 10^{10}$	71

HEPA filter was of the same order of magnitude per unit area. Because the methods of measuring released mass were different for the two sizes, this agreement lends validity to mass release measurements for the type A filters.

Because there is only one data point for the type F filter (in Table II), the amount of particulate released,  $6.45 \mu\text{g}$  or  $161.25 \mu\text{g}/\text{m}^2$ , cannot be taken to be necessarily representative for this brand of filter.

2. Efficiency of Clean HEPA Filters. The data in Tables III and IV represent 12 separate efficiency tests of standard HEPA filters subjected to a simulated tornado pressure transient. Four different manufacturers' brands were tested: A, C, M, and F.

If the results for both 0.61-m by 0.61-m and 0.2-m by 0.2-m HEPA filters are lumped together, the mean efficiency for the 12 tests is 99.17% with a standard deviation of 0.6. Hence, taken as a group, all the brands of HEPA filters tested have mean efficiency that falls well below the 99.97% required for filters of this type. If just the 0.61-m by 0.61-m HEPA filters are considered (Table I), then the mean efficiency for the nine tests is 98.85% with a standard deviation of 0.45. If only the 0.2-m by 0.2-m HEPA filters are considered (Table II), the mean efficiency is 99.82% with a standard deviation of 0.06. Thus, the smaller HEPA filters seem to be more efficient than the larger HEPA filters during a tornado-like pressure transient.

## B. Explosive Transients

1. Material Loss from Loaded High-Capacity HEPA Filters. The results for the material loss from loaded 0.61-m by 0.61-m high-capacity HEPA filters are very tentative because of the small number of tests run. Two tests were run with the European-made V-type filters. The first of these was for a shock overpressure of 6.83 kPa, and the filter apparently was on the verge of structural failure of the filter paper. Microscopic examination revealed creasing of the filter paper over most of the face of the filter. This probably explains the very large amount of material released (341.26 g), and therefore,

this cannot be considered a representative example except for a partially damaged filter. The second V-type HEPA filter underwent a shock overpressure of 3.79 kPa and released 1.05 mg or 2.8 mg/m<sup>2</sup> of particulate.

The third test was of a type F separatorless high-capacity HEPA filter subjected to a shock overpressure of 3.86 kPa. This filter released 2.1 mg or 5.6 mg/m<sup>2</sup> of particulate. In all cases, the particulate was polystyrene latex with a mean diameter of 0.46 μm.

The particulate mass released from the two tests where filter damage did not occur was of the same order of magnitude for both brands of filter. Notice that, in the case of particulate release because of shock impingement, we see milligrams of material, but in the case of particulate release resulting from a tornado-like pressure transient, we see only micrograms of material. Hence, it appears that shock waves are more severe than slower pressure transients in terms of their effect on material release from loaded HEPA filters.

2. Efficiency of Clean HEPA Filters. Only one V-type 0.61-m by 0.61-m HEPA filter was tested for efficiency. The peak shock overpressure for this test was 6.89 kPa, and the efficiency of the filter was 71%. Microscopic examination of the filter paper after the test did not reveal any apparent failure of the filter paper in this case.

Obviously, the filter efficiency during the explosive transient was degraded substantially. However, the limited test data available places doubt on the reliability of the actual numerical value of this efficiency. Further testing would be required if it is necessary to have accurate data on filter efficiency for these explosive conditions.

## VI. CONCLUSIONS

### A. Tornado Transient Simulation

#### 1. Material Loss from Loaded HEPA Filters.

- (1) For a particular manufacturer, the material release from 0.2-m by 0.2-m and 0.61-m by 0.61-m standard HEPA filters is of the same order of magnitude per unit area.
- (2) The two methods used for measuring mass release produce virtually the same results.
- (3) The mass released from preloaded standard HEPA filters was of the order of micrograms per square meter.

## 2. Efficiency of Clean Standard HEPA Filters.

- (1) Efficiencies of both the 0.2-m by 0.2-m and 0.61-m by 0.61-m standard HEPA filters are degraded substantially from the normal operating condition efficiencies.
- (2) The mean efficiency of 0.61-m by 0.61-m standard HEPA filters is degraded by a full percentage point more than is the mean efficiency of 0.2-m by 0.2-m standard HEPA filters.
- (3) All brands of standard HEPA filters tested had efficiencies less than required at normal operating conditions.

## B. Explosive Transients

### 1. Material Release from Preloaded High-Capacity HEPA Filters.

- (1) A large amount of particulate (as much as 340 g) can be released from a preloaded 0.61-m by 0.61-m V-type HEPA filter when subjected to a shock impulse that causes incipient structural failure.
- (2) When preloaded high-capacity filters are subjected to shock waves of approximately 50% of the structural limit, 1 to 2 mg of particulate is released.
- (3) Material release from high-capacity HEPA filters subjected to shock overpressures is on the order of milligrams, whereas material release of standard HEPA filters because of tornado-like pressure transients is on the order of micrograms.
- (4) The results in this area should be used carefully because of the limited test data available.

### 2. Efficiency of Clean High-Capacity HEPA Filters.

- (1) The filter efficiency for explosive transients below structural failure can be decreased by a substantial amount.
- (2) The results in this area should be used carefully because of the limited test data available.

## VII. APPLICATION OF HEPA FILTER DATA TO TORNADO AND EXPLOSION ACCIDENT ANALYSIS

Experimental results from subjecting HEPA filters to simulated accident conditions are needed by analysts concerned with the design and safety of nuclear facilities. Typically, safety analyses require predicting the conse-

quences of accidents affecting nuclear facilities. In many of these analyses, the accident-induced challenge to the air cleaning system must be predicted. The analyst must know the structural limits, filtration efficiency, and possible material release from critical HEPA filters during the accident. We believe that the experimental data reported here, when coupled with computer codes that can predict accident-induced loadings, will allow an analyst to determine the response of nuclear facilities to tornado and explosive conditions. In this section, we illustrate how and where HEPA filter experimental data can be used.

The effects of tornado depressurization on a nuclear facility air cleaning system can be evaluated using the Los Alamos computer code TORAC.<sup>4</sup> This code is capable of predicting pressures, flows, and material concentrations at all filter locations within the facility. Knowing the predicted pressures and flows, an analyst then can turn to the structural limit data to see if structural filter failure can occur. If the structural limit is surpassed, the analyst can restart the problem with new flow conditions that simulate the filter failure mode. If the analyst has no knowledge of the type of filter used in the facility, the lowest structural limit of 9.0 kPa (1.3 psi) should be used to give the most conservative analysis.

The experimental data for filter efficiency and material loss data can be used by coupling the data with the analysis using the TORAC code. The procedure would be similar to that outlined above. For tornado transients, the HEPA filter efficiency should be degraded to 98.8%. The material loss data are rather qualitative because of the limited amount of data. However, an average value of 9.35 g may be used to simulate material dislodged from a filter when subjected to the tornado pulse. The problem would be restarted with a material release at the HEPA filter downstream node.

The structural limit data for explosive transients can be used in the same manner as discussed for tornado transients. However, for explosions, the analyst should use the Los Alamos computer code EXPAC.<sup>5</sup> Our data indicate that shock pressures should be less than 13.8 kPa (2 psi) for standard filters and less than 6.9 kPa (1 psi) for high-capacity HEPA filters to preclude filter destruction.

No data are available for efficiency or material loss from standard HEPA filters. The data that are available for high-capacity filters are very qualitative. This is a result of the limited number of tests that we were able to

perform. Experiments show that large amounts of particulate can be released at the initial point of failure. Further, even if structural failure does not occur and the peak pressure is 50% below the failure point (6.83 kPa or 1 psi), significant amounts of particulate will be released under explosive transients. Again, this material loss situation can be simulated with EXPAC in the same manner as outlined above and using the TORAC code for tornado-induced material loss.

Efficiency values for high-capacity filters, based on only a single test, indicate a degradation of efficiency down to 70%. However, these data should be used with caution because of their limited amount. Again, restarting the EXPAC code at a 50% structural failure point and using a 70% efficiency for the HEPA filter would be the appropriate way to analyze the problem.

We should point out that there is no reason that the data could not be incorporated into the codes so that the efficiency change or material loss would take place automatically. This would save the analyst considerable work that usually is required to restart the problem.

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Pressure transients in nuclear facility air cleaning systems can originate from natural phenomena such as tornadoes or from accident-induced explosive blast waves. This study was concerned with the effective efficiency of high-efficiency particulate air (HEPA) filters during pressure surges resulting from simulated tornado and explosion transients. The primary objective of the study was to examine filter efficiencies at pressure levels below the point of structural failure. Both standard and high-capacity 0.61-m by 0.61-m HEPA filters were evaluated, as were several 0.2-m by 0.2-m HEPA filters. For a particular manufacturer, the material release when subjected to tornado transients is the same (per unit area) for both the 0.2-m by 0.2-m and the 0.61-m by 0.61-m filters. For tornado transients, the material was on the order of micrograms per square meter. When subjecting clean HEPA filters to simulated tornado transients with aerosol entrained in the pressure pulse, all filters tested showed a degradation of filter efficiency. For explosive transients, the material release from preloaded high-capacity filters was as much as 340 g. When preloaded high-capacity filters were subjected to shock waves approximately 50% of the structural limit level, 1 to 2 mg of particulate was released.

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