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Informal Report

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**Investigation of HEPA Filters Subjected to
Tornado Pressure Pulses
Initial Structural Testing**

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INVESTIGATION OF HEPA FILTERS SUBJECTED

TO TORNADO PRESSURE PULSES

Initial Structural Testing

by

W. S. Gregory, H. L. Horak, P. R. Smith, C. I. Ricketts, and W. Gill

ABSTRACT

Initial results from a program to determine response of 610- x 610-mm (24- x 24-in.) HEPA filters to tornado-induced pressure transients are described. Filters were structurally tested by subjecting them to 20.7-kPa (3-psi) pressure differentials at pressurization rates from 6.9 kPa/s (1 psi/s) to 34.5 kPa/s (5 psi/s). Two sizes of filters were used in the tests: 149 mm (5 7/8 in.) thick and 292 mm (11 1/2 in.) thick. The 149-mm (5 7/8 in.) thick filters failed catastrophically at 20.7-kPa (3-psi) pressure differentials. Pressure drop across the filters, not pressurization rate, appears to be the primary cause of failure. The 292-mm (11 1/2-in.) thick filters were also tested with the above pressurization rates. These units failed by breakage of the folded downstream ends of the fiber mat. Of four 292-mm (11 1/2-in.) thick filters tested, a 20.7-kPa (3-psi) pressure differential produced failure at the lowest and highest pressurization rates, but not at two intermediate rates. Additional tests will be required to determine a possible relationship between structural failure and pressurization rate.

Flow-resistance data were also obtained for the 610- x 610-mm (24- x 24-in.) filters. At relatively low flow rates, the dominant mechanism causing resistance appears to be diffusion, while at higher flow rates momentum exchange appears to dominate. At higher flow rates, probably a majority of the flow is passing through the folded ends of the fiber mat, thereby suggesting that instantaneous filtering efficiency may be degraded.

Other activities described concern construction of small-scale particulate-loading and pressure-testing devices. These devices will be used to test 203- x 203-mm (8- x 8-in.) filters so that methods of testing and instrumentation requirements can be established for the full-scale tests. Progress is also reported on the data acquisition systems, the laser instrumentation system, and the construction of a building over the facility test section.

I. INTRODUCTION

An experimental program to test ventilation system components is in progress at the Los Alamos Scientific Laboratory (LASL) and New Mexico State Uni-

versity (NMSU).¹ We are examining critical nuclear facility air cleaning components for their response to simulated pressure loadings as defined by the

Nuclear Regulatory Commission (NRC) Region I tornado.² We are testing high efficiency particulate air (HEPA) filters at our test facility, which is located at NMSU. These initial tests include filter structural analysis and determination of filter flow-resistance profiles. In addition, we are constructing the peripheral equipment needed in later testing phases and investigating techniques of aerosol generation and detection.

The initial structural tests involved exposure of clean 610- x 610-mm (24- x 24-in.) filters, Size A and Size B,* to a simulation of the NRC Region I tornado. The Region I tornado definition specifies a particular rate and magnitude of depressurization expected from this class of tornado. However, experimental apparatus that produces a pressurization pulse is more convenient to build. Since the important parameter is differential pressure across a component, the test effect is similar. Our interpretation of the Region I tornado resulted in the test overpressure pulse represented by Fig. 1. We also examined the effect of increasing pressurization rate from the specified 6.9 kPa/s (1 psi/s) to 41.4 kPa/s (6 psi/s) while holding the maximum pressure at 20.7 kPa (3 psi).

Fig. 1. Region I tornado transient.

*Filters: Size A -- 610 x 610 x 292 mm (24 x 24 x 11 1/2 in.).

Size B -- 610 x 610 x 149 mm (24 x 24 x 5 7/8 in.).

The flow-resistance tests were performed for the Size A and B filters. Curves relating air flow and resistance were generated by measuring velocity and filter pressure drop (ΔP) for several air supply pressures.

II. FILTER RESISTANCE

Empirical flow-resistance data are used in the computer simulation of ventilation system response to tornado-induced transients. Data are needed to define the mathematical relationship between flow through, resistance of, and pressure drop across filters at high flow rates. Further, examination of the relationship obtained will provide insight into the filtering behavior of HEPA filters at high flow rates.

The pressure drops across both Size A and Size B HEPA filters were measured at flow rates from just above their design flow rates of $0.519 \text{ m}^3/\text{s}$ (1100 cfm) and $0.236 \text{ m}^3/\text{s}$ (500 cfm), respectively, up to nearly $11.328 \text{ m}^3/\text{s}$ (24 000 cfm). Figure 2 shows the pressure in inches of water as a function of flow rate. The Size B filters offer more flow resistance than the Size A filters.

Table A-I (Appendix) shows the test parameter values and filter resistance coefficients (K_L , K_T) for different storage tank pressures. The filter resistance can be characterized as a diffusion process or as a momentum exchange. If the process is entirely diffusion, then the pressure rise will be a function of velocity,

$$\Delta P = K_L \frac{\mu v}{D}, \quad (1)$$

where μ is the dynamic viscosity, v is the velocity, K_L is a resistance coefficient, and D is a characteristic length. This process should occur if the Reynolds number, based upon filter fiber diameter, is on the order of unity. If the process is entirely momentum exchange, then the pressure rise across the filter should be

$$\Delta P = K_T \frac{\rho v^2}{2g}, \quad (2)$$

in which ρ is the density of the air, g is the gravitational constant, and K_T is a resistance coefficient.

Fig. 2. Resistance of Size A and Size B HEPA filters at high flow rates.

Although both diffusion and momentum exchange are occurring at all flow rates, apparently at the low flow rates the diffusion process is dominant, while at high flow rates momentum exchange dominates. As can be seen from Eqs. (1) and (2), a constant value of K_L would result if the former were true, and a constant value of K_T would result if the latter were true. Examination of Table A-1 reveals that at flow rates below $5.19 \text{ m}^3/\text{s}$ (11 000 cfm), K_L is essentially constant for each filter tested. For example, consider filter No. 41310856, a Size A filter. For flow rates from $1.779 \text{ m}^3/\text{s}$ (3770 cfm) to $5.391 \text{ m}^3/\text{s}$ (11 421 cfm), the value of $K_L \times 10^{-6}$ varies from 4.1 to 7.5 with a mean value of 6.61 and a standard deviation of 1.49. Filter No. 41310972, a Size B filter, had a range of $K_L \times 10^{-6}$ from 8.3 to 11.4 with a mean value of 10.13 and standard deviation of 0.95. In the latter case, flow rates varied from $1.770 \text{ m}^3/\text{s}$ (3749 cfm) to $5.465 \text{ m}^3/\text{s}$ (11 579 cfm). These results were typical the Size B filters having a more nearly constant value of K_L at low flow rates than the Size A filters. The Reynolds number, based upon an average fiber diameter of $5 \text{ }\mu\text{m}$, ranged from 3 to 9. Hence, we would expect the diffusion law to hold. Notice that for low flow rates the value of K_T varies as much as 200%, for example, from 26.7 to 46.2 for filter No. 41310856 (Size A) and from 39.2 to 92.3 for filter No. 4130972 (Size B). From this we conclude that from $1.770 \text{ m}^3/\text{s}$ (3749 cfm) to about $5.19 \text{ m}^3/\text{s}$ (11 000 cfm) the diffusion process is dominant.

From about $6.136 \text{ m}^3/\text{s}$ (13 000 cfm) to $11.092 \text{ m}^3/\text{s}$ (23 500 cfm), the value of K_T remains remarkably constant. For filter No. 41310856, a Size A filter, K_T varies from 25.9 to 29.0 with a mean value of 27.25 and a standard deviation of 0.90. For filter No. 4130972, a Size B filter, K_T varies from 35.1 to 36.3 with a mean value of 35.68 and a standard deviation of 0.59. Thus, for flow rates above $6.136 \text{ m}^3/\text{s}$ (13 000 cfm), the filters behave as if momentum exchange is the main cause for pressure loss. Notice that this flow rate of $6.136 \text{ m}^3/\text{s}$ (13 000 cfm) occurs at a pressure differential of 6.9 kPa (1 psi) or less. So, for the Region I tornado for which the pressure drop is 20.7 kPa (3 psi), the flow through the filters should exhibit resistance to flow proportional to the velocity squared (Eq. 2).

During the resistance testing, all the Size B filters failed either by sustaining tears in the folds or by blowing out completely before a 20.7-kPa (3-psi) pressure difference across the filter was obtained. Filter No. 41310856, a Size A filter, failed with a rip in one fold at a pressure difference of 20.4 kPa (2.95 psi). Filter No. 41308004, also a Size A filter, did not visibly fail.

III. PRELIMINARY STRUCTURAL TESTING

Three modes of filter failure are being investigated. First, we are considering structural failure. In this case the filter media may be physically damaged. Preliminary test results were obtained and are described in this report. The two other failure modes, which could occur without structural failure, address the loss of filtration capability during the tornado pulse. These failure modes are the reentrainment of particles from the filter media and the passing of particles entrained in the flow. These modes of failure will be considered in subsequent phases of the investigation.

The Size A and Size B HEPA filters were subjected to 20.7-kPa (3-psi) pressure differentials at various pressurization rates. Nominally, these pressurization rates were to be 6.9 kPa/s (1 psi/s), 13.8 kPa/s (2 psi/s), 27.6 kPa/s (4 psi/s), and 34.5 kPa/s (5 psi/s). However, because of the impedance of the flow system, these pressurization rates could only be approximated. Table 1 contains the pressurization rates applied to each filter.

TABLE I
STRUCTURAL TEST PRESSURIZATION RATES & RESULTS

Filter Size	Pressurization Rate		Frontal Area Destroyed (Z)	DOP (Z)
	kPa/s	psi/s		
A	6.62	0.96	0.69	1
A	12.76	1.85	0.00	0.002
A	24.63	3.57	0.00	0.001
A	31.40	4.55	1.64	6
B	7.66	1.11	100	100
B	13.25	1.92	100	100
B	31.40	4.55	100	100
B	34.50	5.00	100	100

The objective of these tests was to determine if the structural integrity and the efficiency of the filters were affected by the rate of pressurization. Each filter tested was subjected to only one pressure pulse. Efficiency tests were performed at Department of Energy quality assurance stations before the filters were shipped to NMSU. After each filter was pulsed, its efficiency was again measured using the standard dioctylphthalate (DOP) method.

Figures 3 and 4 show the pressure rise across the filters as a function of time for Size A and Size B filters, respectively. Notice that in all cases the maximum pressure drop across the filters, called static pressure in the figures, was within 0.69 kPa (0.1 psi) of 20.7 kPa (3 psi).

Fig. 3. Pressure drop across Size A HEPA filters during structural tests.

Fig. 4. Pressure drop across Size B HEPA filters during structural tests.

For the Size A filters, failures occurred at pressurization rates of 6.62 kPa/s (0.96 psi/s) and 31.40 kPa/s (4.55 psi/s). The failure mode in both cases was a ripping out of a very small percentage of the folded ends on the downstream face of the filter as can be seen in Figs. 5 and 6. In the low-

Fig. 5. Failure of Size A HEPA filter subjected to 6.62-kPa/s (0.96-psi/s) pressure drop. Small tears visible against right-hand wall (Filter No. 41310371).

Fig. 6. Failure of Size A HEPA filter subjected to 30.4-kPa/s (4.55-psi/s) pressure drop (Filter No. 4130365).

pressurization case, 0.69% of the filter frontal area failed, while in the high-pressurization case, 1.64% of the total filter frontal area failed. The two filters subjected to the intermediate pressurization rates showed no visible signs of structural damage.

After testing, the filter efficiency of the four Size A filters was determined using standard DOP techniques. These results are shown in Table I. Filter No. 41310371 was subjected to a pressurization rate of 6.62 kPa/s (0.96 psi/s), sustained a small amount of damage, and had a maximum DOP reading of 1%. Filter No. 4130365, which was subjected to a pressurization rate of 31.40 kPa/s (4.55 psi/s) and also received damage, had a maximum DOP reading of 6%. The other two Size A filters (Nos. 41310842 and 41310843) had DOP readings of 0.002% and 0.001%, respectively.

All four of the Size B filters subjected to the 20.7 kPa (3 psi) pressure pulse at the various pressurization rates failed catastrophically. In each case, the filter was blown out of the filter frame, as can be seen in Fig. 7. We conclude that the maximum pressure, not the rate of pressurization, caused the failure of these filters. Since the entire filter tore out of its frame, a probable failure mode is shearing of the paper at the perimeter where it is glued to the frame. Further, since the Size A filters failed by breakage of a small percentage of the downstream folds, at least two failure modes exist. Because the Size B filters failed completely, their filter efficiency after testing was zero.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

A. Resistance Measurements

The results of the resistance measurements on the Size A and Size B HEPA filters appear to agree with the results found earlier for the 203- x 203-mm (8- x 8-in.) filters.³ At low flow rates, the dominant mechanism causing resistance appears to be diffusion, while at the higher flow rates momentum

Fig. 7. Typical Size B HEPA filter after pressurization to 20.7 kPa (3 psi) at rates varying from 7.5 kPa/s (1.1 psi/s) to 34.5 kPa/s (5 psi/s).

exchange dominates. The latter situation exists when the pressure drop across the filter is approximately 6.9 kPa (1 psi) or greater. For flows in which momentum exchange is the chief mechanism of resistance, a majority of the flow probably is passing through the folded ends of the filter paper and thus instantaneous filtering efficiency may be degraded. Such an occurrence could not be detected by a DOP test made after the fact.

B. Structural Test

Size B HEPA filters subjected to a 20.7-kPa (3-psi) pressure differential at pressurization rates of 6.9 kPa/s (1 psi/s) to 34.5 kPa/s (5 psi/s) failed catastrophically. The pressure rise across the filters, not the pressurization rate, appears to be the primary cause for their failure. These filters could not withstand a NRC Region I tornado. Since the entire filter is ripped from its frame, one failure mode may be shearing of the filter paper at the perimeter. Another possible failure mode is that of plate-like deflection of the center of the filter and a failure when the effective ultimate strength of the material is surpassed.

The Size A HEPA filters failed by breakage of the folded ends of paper. A 20.7-kPa (3-psi) pressure drop across these filters caused failure at the lowest and highest pressurization rates, but not at the two intermediate rates. The two filters that failed subsequently showed large DOP percentages, indicating a failure in ability to filter. However, the two filters that did not fail had DOP percentages within acceptable limits, and therefore no degradation of efficiency occurred. Thus, the Size A filters appeared to fail randomly when subjected to a 20.7-kPa (3-psi) pressure differential. Within the limits of the pressurization rates used, this parameter may or may not have caused failure. Notice that a larger area of filter breakage occurred for the high pressurization rate. On the other hand, if failure occurs randomly because of filter fabrication differences, then pressurization rate may not be important for this pressure difference. The four tests so far performed are not a large enough sample to get statistically meaningful results.

Whatever the cause, the Size A filters do fail. Since the folded ends of these filters break out in a small area of the filter compared to the 100% failure of the Size B filters, at least two modes

of failure probably exist. For the Size A filters, the folded ends may be stretched much like the skin of a balloon is stretched as it is inflated. Failure occurs when the tensile stress in the paper exceeds its ultimate strength.

V. PARALLEL ACTIVITIES

A. Velocity Profiles

Velocity profiles in the test duct were determined using the cruciform stagnation rake shown in Fig. 8. Static pressure was measured at a wall tap at the same location. The profiles were measured at eight different flow rates for pressure drops across a Size A filter ranging from 6.56 kPa (0.95 psi) to 22.08 kPa (3.2 psi).

Figure 9 shows a summary of the vertical and horizontal velocity profile data. Velocity divided by the maximum (center line of duct) velocity is plotted as a function of the nondimensional duct coordinate. The maximum standard deviation for any of the experimental points plotted in this figure was 0.03.

Notice that the vertical profile is essentially symmetric, but horizontal profile displays a very slight asymmetry. At the maximum, the deviation from a symmetric profile is 5% and is within the expected experimental error.

Fig. 8. Cruciform stagnation rake.

Fig. 9. Vertical and horizontal velocity profiles in the test duct.

B. Small-Scale Particulate Loading Device

The small-scale loading device was designed to load 203- x 203-mm (8- x 8-in.) filters with particulate and also to expose these filters to several levels of humidity before subjecting them to pressurization. In addition, this apparatus can be used for testing filter effectiveness using DOP. Both the small-scale loading and testing devices will be used to establish methods of testing, instrumentation requirements, and test procedures before attempting to test Size A and Size B HEPA filters.

A schematic of the device is shown in Fig. 10. It is a positive pressure system with air entering at the fan and exiting downstream of the test filter. The fan is capable of $1.135 \text{ m}^3/\text{s}$ (2400 cfm) at 1619-kPa (6.5 in. of water) total pressure. There is

a bleed-off damper to reduce the flow to $0.024 \text{ m}^3/\text{s}$ (50 cfm) at the test filter. A single $0.024\text{-m}^3/\text{s}$ (50-cfm) HEPA filter prefilters the air just after the damper and before entering the humidifier.

The humidifier is an evaporative cooler that uses a counterflow air-water system through 0.057 m^3 (2 ft³) of cooler pads. The air is ducted from the top of the humidifier into a 1.2- x 1.2-m (48- x 48-in.) mixing chamber. Here, the loading particulate is introduced and allowed to thoroughly mix with the air before exiting into a duct section that leads to the test filter. This duct is of sufficient length for the air to achieve uniform flow before impinging upon the test filter. The flow finally exits through another 0.61-m (2-ft) length of duct. The system has multiple taps for pressure measurement, and the duct upstream and downstream from the filter is modified for DOP testing.

Calibration tests to establish humidity and flow values have been completed using the device. At $0.024 \text{ m}^3/\text{s}$ (50 cfm), a 50% rise in relative humidity is possible when the ambient humidity is 20%. Significant pressure drops across test filters have not been noted for continuous operation up to 8 h.

C. Small-Scale Testing Devices

A small-scale testing device that was used to apply pulsed pressure loadings on 203- x 203-mm (8- x 8-in.) filters in an earlier investigation is being rebuilt.³ Rebuilding this apparatus will

Fig. 10. Small-scale particulate HEPA filter loading device.

allow investigation of potential problems and techniques on a much smaller scale before these techniques are applied to the full-scale facility. Further, the quantity of aerosol needed for this device is several times smaller than that required for testing the 610- x 610-mm (24- x 24-in.) filters. The data acquisition and laser instrumentation systems will be evaluated with this device before installation at the 610- x 610-mm (24- x 24-in.) testing facility.

D. Data Acquisition System

All parts for the data acquisition system have been received and fabrication has begun. Wiring of the system is 75% completed. All prebuilt components such as the tape recorder and video terminal have been tested and integrated into the system. Software programming has begun and should be completed. Final check-out of the system is anticipated by July 31, 1977.

E. Laser Instrumentation System

The second laser was received after a 4-month delay. A surplus lathe bed has been located and will serve as a mobile base for mounting the lasers and associated optics. Some initial calculations were made to establish the laser measuring volume size assuming a 400-mm focal length and a 50.8-mm focusing lens diameter. These calculations were necessary to establish preliminary particle generation requirements.

F. Building

NMSU is constructing a building around part of the existing large-scale testing facility. The dimensions of the building are 12.2 x 12.2 x 30.5 m (40 x 40 x 10 ft), and it is constructed of metal on a concrete slab floor. It will enclose the valves, prefilter chamber, and duct test section and will provide additional work space. The building will also serve as part of a shield for the laser instrumentation, thereby reducing extraneous scattered light and particulates in the air.

VI. SUMMARY

The initial structural test results indicate that the Size B filters fail completely under Region I tornado conditions. The entire filter medium is removed at a pressure level of approximately 17.25 kPa (2.5 psi). The test results for the Size A filters

are not as conclusive. The Region I tornado simulation caused structural failure in two of the four tests completed. These failures occurred at pressurization rates lower and higher than that specified for the Region I tornado. We feel that four tests are not a large enough sample to give statistically meaningful results. We would recommend additional testing along with investigation of the failure mechanism. We have suggested several mechanisms in this report, but additional investigations would be necessary for conclusive results.

The results of the resistance measurements on the 610- x 610-mm (24- x 24-in.) filters appear to agree with earlier results obtained for 203- x 203-mm (8- x 8-in.) filters. Diffusion and momentum exchange may be used to explain the shape of the resistance curves. At relatively low flow rates, the dominant mechanism causing resistance appears to be diffusion, while at higher flow rates, momentum exchange appears to dominate. When momentum exchange dominates, a majority of the flow is probably passing through the folded ends of the fiber mat only, thereby increasing the possibility of inefficient filtration.

Verification of the velocity profiles in the simulated pressure loadings was also performed. This analysis indicated that relatively symmetric and uniform velocity profiles were obtained.

We have also described parallel activities including progress in construction of the laser and data acquisition systems. Small-scale loading and testing devices were also described. These devices will provide insight into instrumentation requirements and limitations using the 203- x 203-mm (8- x 8-in.) filters and will establish testing methods and procedures that can be used in evaluation of the 610- x 610-mm (24- x 24-in.) filters.

VII. NEXT WORK PHASE

In the next quarter, the small-scale equipment will be used to do preliminary aerosol work. Test aerosols will be selected, and the requirements and construction of the aerosol generator will be completed. Calibration, verification tests, and loading procedures will be established. The laser and data acquisition systems will be calibrated and checked against more conventional measuring techniques

such as DOP methods, intracavity laser instrumentation, or other postanalysis sampling techniques.

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2. E. H. Markee, Jr., and J. G. Beckerley, "Technical Basis for Interim Regional Tornado Criteria," U.S. Atomic Energy Commission, Office of Regulation, Wash 1300 (May 1974).
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APPENDIX

EXPERIMENTAL DATA

TABLE A-I

FILTER RESISTANCE TESTS

Filter Number: 41310856										Filter Thickness: 11 1/2 in.				
Tank		Duct								Filter				
Total Press PSIG	Total Temp F	Static Pressure PSIG	Dynamic Pressure PSI	Total Pressure PSIG	Pressure Loss PSI	Total Temp F	Velocity Ft/S	Rel Hum %		K_T	$K_L \times 10^{-6}$	ΔP in H ₂ O	Entrance Flow CFM	Velocity Pressure in H ₂ O
10.	144.	0.05	0.0022	0.052	9.948	92.	17.9	37.		23.1	2.1	1.4	3780.	0.06
20.	148.	0.10	0.0022	0.102	19.898	91.	17.8	37.		46.2	4.1	2.8	3770.	6.06
30.	144.	0.15	0.0043	0.154	29.846	91.	25.2	39.		34.6	4.4	4.2	5321.	0.12
40.	140.	0.25	0.0065	0.256	39.743	91.	30.7	42.		38.5	6.0	6.9	6492.	0.18
50.	137.	0.30	0.0097	0.310	49.690	91.	37.6	44.		30.8	5.9	8.3	7936.	0.27
60.	136.	0.40	0.0108	0.411	59.589	90.	39.4	44.		36.9	7.5	11.1	8326.	0.30
70.	133.	0.50	0.0162	0.516	69.484	91.	48.1	43.		30.8	7.7	13.9	10167.	0.45
80.	133.	0.55	0.0206	0.571	79.429	91.	54.1	42.		26.7	7.5	15.2	11421.	0.57
90.	132.	0.70	0.0249	0.725	89.275	91.	59.2	41.		28.1	8.7	19.4	12496.	0.69
100.	132.	0.80	0.0282	0.828	99.172	91.	62.7	40.		28.4	9.4	22.2	13237.	0.75
110.	130.	0.90	0.0336	0.934	109.066	91.	68.2	39.		26.8	9.7	24.9	14401.	0.93
120.	130.	1.05	0.0379	1.088	118.912	92.	72.1	38.		27.7	10.7	29.1	15231.	1.05
130.	128.	1.15	0.0444	1.194	128.806	92.	77.8	37.		25.9	10.9	31.9	16425.	1.23
140.	125.	1.30	0.0487	1.349	138.651	92.	81.0	36.		26.7	11.8	36.0	17116.	1.35
150.	125.	1.45	0.0509	1.501	148.499	93.	82.4	35.		28.5	12.9	40.2	17413.	1.41
160.	126.	1.60	0.0596	1.660	158.340	93.	88.7	34.		26.9	13.3	44.3	18739.	1.65
170.	125.	1.75	0.0650	1.815	168.185	94.	92.3	34.		26.9	13.9	48.5	19486.	1.80
180.	125.	1.90	0.0704	1.970	178.030	94.	95.5	33.		27.0	14.6	52.6	20178.	1.95
190.	122.	2.05	0.0758	2.126	187.874	94.	98.6	33.		27.0	15.2	56.8	20833.	2.10
200.	122.	2.20	0.0758	2.276	197.724	94.	98.1	32.		29.0	16.4	60.9	20728.	2.10
210.	122.	2.40	0.0866	2.487	207.513	93.	104.1	32.		27.7	16.9	66.5	21995.	2.40
220.	121.	2.60	0.0921	2.692	217.308	94.	106.7	32.		28.2	17.9	72.0	22542.	2.55
230.	105.	2.75	0.0975	2.847	227.153	93.	109.2	31.		28.2	18.5	76.2	23065.	2.70
240.	117.	2.95	0.1029	3.053	236.947	92.	111.4	31.		28.7	19.5	81.7	23527.	2.85

Filter Number: 41308004										Filter Thickness: 11 1/2 in.				
Tank		Duct								Filter				
Total Press PSIG	Total Temp F	Static Pressure PSIG	Dynamic Pressure PSI	Total Pressure PSIG	Pressure Loss PSI	Total Temp F	Velocity Ft/S	Rel Hum %		K_T	$K_L \times 10^{-6}$	ΔP in H ₂ O	Entrance Flow CFM	Velocity Pressure in H ₂ O
14.	90.	0.10	0.0011	0.101	13.899	73.	12.4	29.		92.3	6.1	2.8	2620.	0.03
25.	106.	0.15	0.0032	0.153	24.847	73.	21.4	29.		46.2	5.3	4.2	4530.	0.09
40.	112.	0.20	0.0065	0.206	39.794	73.	30.3	30.		30.8	5.0	5.5	6394.	0.18
60.	106.	0.35	0.0119	0.362	59.638	75.	40.8	31.		29.4	6.5	9.7	8672.	0.33
80.	105.	0.55	0.0195	0.569	79.430	75.	51.8	32.		28.2	8.1	15.2	10946.	0.54
100.	109.	0.75	0.0271	0.777	99.223	75.	60.6	32.		27.7	9.4	20.8	12804.	0.75
120.	108.	0.95	0.0368	0.987	119.013	75.	70.2	32.		25.8	10.3	26.3	14835.	1.02
140.	100.	1.20	0.0477	1.248	138.752	76.	79.3	32.		25.2	11.5	33.2	16738.	1.32
160.	98.	1.50	0.0574	1.557	158.443	76.	86.1	31.		26.1	13.2	41.6	18176.	1.89
180.	97.	1.75	0.0682	1.818	178.182	76.	93.0	31.		25.6	14.2	48.5	19645.	1.89
200.	96.	2.10	0.0780	2.178	197.822	77.	98.3	30.		26.9	16.1	58.2	20770.	2.16
220.	94.	2.40	0.0929	2.490	217.510	77.	104.5	30.		26.7	17.4	66.5	22079.	2.49
240.	94	2.80	0.1029	2.903	237.097	77.	110.4	29.		27.2	19.2	77.6	23316.	2.35
255.	93.	3.05	0.1072	3.157	249.843	78.	111.9	29.		28.4	20.6	84.5	23632.	2.97

Filter Number: 41310972

Filter Thickness: 5 7/8 in.

Tank		Duct							Filter				
Total Press PSIG	Total Temp F	Static Pressure PSIG	Dynamic Pressure PSI	Total Pressure PSIG	Pressure Loss PSI	Total Temp F	Velocity Ft/S	Rel Hum %	K_T	$K_L \times 10^{-4}$	ΔP in H ₂ O	Entrance Flow CFM	Velocity Pressure in H ₂ O
10.	120.	0.10	0.0011	0.101	9.899	90.	12.6	47.	92.3	5.9	2.8	2661.	0.03
20.	125.	0.20	0.0022	0.202	19.798	90.	17.8	47.	92.3	8.3	5.5	3749.	0.05
30.	134.	0.30	0.0032	0.303	29.697	90.	21.7	49.	92.3	10.2	8.3	4574.	0.09
40.	130.	0.40	0.0065	0.406	39.593	90.	30.5	50.	61.6	9.7	11.1	6450.	0.18
50.	126.	0.50	0.0087	0.509	49.491	90.	35.1	51.	57.7	10.5	13.9	7419.	0.24
60.	114.	0.60	0.0130	0.613	59.387	90.	42.9	50.	46.2	16.3	16.6	9052.	0.36
70.	116.	0.70	0.0173	0.717	69.283	90.	49.3	50.	40.4	10.5	19.4	10414.	0.48
80.	116.	0.85	0.0217	0.872	79.128	90.	54.8	46.	39.2	11.4	23.5	11579.	0.60
90.	117.	0.95	0.0227	0.973	89.027	91.	56.0	45.	41.8	12.5	26.3	11831.	0.63
100.	116.	1.05	0.0260	1.076	98.924	92.	59.7	43.	40.4	12.9	29.1	12612.	0.72
94.	85.	0.95	0.0238	0.974	93.026	69.	56.2	40.	39.9	13.0	26.3	11864.	0.66
100.	84.	1.00	0.0271	1.027	98.973	70.	59.8	39.	36.9	12.8	27.7	12634.	0.75
110.	86.	1.15	0.0314	1.181	108.819	71.	64.1	38.	36.6	13.7	31.9	13545.	0.87
120.	86.	1.30	0.0357	1.336	118.664	71.	68.1	38.	36.4	14.6	36.0	14372.	0.99
130.	86.	1.45	0.0412	1.491	128.509	72.	72.7	37.	35.2	15.2	40.2	15354.	1.14
140.	86.	1.60	0.0455	1.645	138.355	72.	76.0	37.	35.2	16.1	44.3	16057.	1.26
150.	86.	1.75	0.0498	1.800	148.200	72.	79.2	36.	35.1	16.9	48.5	16717.	1.38
160.	88.	1.95	0.0552	2.005	157.995	73.	82.8	36.	35.3	17.9	54.0	17497.	1.53
170.	88.	2.10	0.0596	2.160	167.840	73.	85.6	36.	35.3	18.7	58.2	18078.	1.65
180.	88.	2.30	0.0639	2.364	177.636	74.	88.1	35.	36.0	19.9	63.7	18615.	1.77
190.	88.	2.45	0.0682	2.518	187.482	75.	90.7	35.	35.9	20.5	67.9	19156.	1.89
200.	88.	2.65	0.0726	2.723	197.277	75.	93.0	35.	36.5	21.6	73.4	19643.	2.01

Filter Number: 41310977

Filter Thickness: 5 7/8 in.

Tank		Duct							Filter				
Total Press PSIG	Total Temp F	Static Pressure PSIG	Dynamic Pressure PSI	Total Pressure PSIG	Pressure Loss PSI	Total Temp F	Velocity Ft/S	Rel Hum %	K_T	$K_L \times 10^{-4}$	ΔP in H ₂ O	Entrance Flow CFM	Velocity Pressure in H ₂ O
12.	88.	0.10	0.0011	0.101	11.899	65.	12.3	35.	92.3	6.3	2.8	2601.	0.03
20.	108.	0.20	0.0022	0.202	19.798	65.	17.3	35.	92.3	8.9	5.5	3664.	0.06
30.	110.	0.30	0.0043	0.304	29.696	65.	24.4	35.	69.3	9.5	8.3	5161.	0.12
40.	113.	0.40	0.0065	0.406	39.593	66.	29.8	36.	61.6	10.3	11.1	6303.	0.18
50.	108.	0.45	0.0087	0.459	49.541	66.	34.4	37.	51.9	10.1	12.5	7264.	0.24
60.	106.	0.55	0.0119	0.562	59.438	67.	40.2	40.	46.2	10.5	15.2	8493.	0.33
70.	105.	0.65	0.0152	0.665	69.335	67.	45.2	42.	42.9	11.1	18.0	9553.	0.42
80.	105.	0.80	0.0195	0.819	79.180	68.	51.0	44.	41.0	12.0	22.2	10781.	0.54
90.	102.	0.90	0.0238	0.924	89.076	69.	56.7	45.	37.8	12.3	24.9	11885.	0.66
100.	102.	1.00	0.0271	1.027	98.973	70.	59.8	45.	36.9	12.8	27.7	12634.	0.75
110.	100.	1.10	0.0325	1.132	108.868	70.	65.3	45.	33.9	12.9	20.5	13790.	0.90
120.	101.	1.25	0.0379	1.288	118.712	72.	70.3	44.	33.0	13.6	34.6	14840.	1.05
130.	101.	1.40	0.0412	1.441	128.559	73.	72.9	44.	34.0	14.6	38.8	15394.	1.14
140.	102.	1.55	0.0466	1.597	138.403	74.	77.2	43.	33.3	15.3	42.9	16303.	1.29
150.	101.	1.70	0.0520	1.752	148.248	75.	81.2	42.	32.7	15.9	47.1	17149.	1.44
160.	101.	1.85	0.0563	1.906	158.094	75.	84.1	42.	32.9	16.7	51.2	17772.	1.56
170.	101.	2.00	0.0606	2.061	167.939	75.	86.9	41.	33.0	17.5	55.4	18349.	1.68
180.	100.	2.20	0.0661	2.266	177.734	76.	90.1	40.	33.3	18.5	60.9	19038.	1.83
190.	98.	2.40	0.0704	2.470	187.530	78.	92.6	39.	34.1	19.6	66.5	19555.	1.95
200.	97.	2.55	0.0747	2.625	197.375	78.	94.9	39.	34.1	20.3	70.6	20049.	2.07
210.	98.	2.80	0.0791	2.879	207.121	76.	96.7	37.	35.4	21.9	77.6	20421.	2.19

Filter Number: 41310973

Filter Thickness: 5 7/8 in.

Tank		Duct							Filter				
Total Press PSIG	Total Temp F	Static Pressure PSIG	Dynamic Pressure PSI	Total Pressure PSIG	Pressure Loss PSI	Total Temp F	Velocity Ft/S	Rel Hum %	K_T	$K_L \times 10^{-4}$	ΔP in H ₂ O	Entrance Flow CFM	Velocity Pressure in H ₂ O
12.	77.	0.10	0.0011	0.101	11.899	72.	12.4	34.	92.3	6.2	2.8	2618.	0.03
25.	101.	0.20	0.0032	0.203	24.797	71.	21.4	34.	61.6	7.2	5.5	4513.	0.09
40.	104.	0.35	0.0054	0.355	39.645	71.	27.4	35.	64.6	9.8	9.7	5793.	0.15
60.	105.	0.50	0.0119	0.512	59.488	72.	40.5	37.	42.0	9.4	13.9	8551.	0.33
80.	102.	0.70	0.0173	0.717	79.283	73.	48.5	38.	40.4	11.0	19.4	10245.	0.48
100.	100.	0.90	0.0249	0.925	99.075	74.	57.8	38.	36.1	11.9	24.9	12203.	0.69
120.	98.	1.15	0.0336	1.184	118.816	75.	66.5	38.	34.3	13.1	31.9	14051.	0.93
140.	97.	1.45	0.0422	1.492	138.508	75.	73.8	37.	34.3	14.9	40.2	15593.	1.17
160.	97.	1.75	0.0617	1.803	158.188	74.	80.2	36.	28.3	15.1	48.5	16920.	1.41
180.	96.	2.10	0.0606	2.161	177.839	74.	86.4	35.	34.6	18.5	58.2	18257.	1.68
200.	94.	2.50	0.0715	2.571	197.429	75.	92.7	35.	35.0	20.5	69.3	19575.	1.98