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Efficiency of Whatman No. 41 Filter Media
Against a Polydisperse Solid Aerosol:
Interim Report

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EFFICIENCY OF WHATMAN NO. 41 FILTER MEDIA AGAINST
A POLYDISPERSE SOLID AEROSOL:

INTERIM REPORT

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Harry J. Ettinger
Thomas M. Panowski
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ABSTRACT

A preliminary test program was carried out to evaluate the filtration efficiency of Whatman No. 41 filter media using a solid, polydisperse, submicron sodium chloride aerosol. Aerosol generator size characteristics and mass output were calibrated as functions of operating pressure and NaCl solution concentration. Whatman No. 41 filter efficiency was measured as a function of filtration velocity. Test results indicate that filter penetration differs significantly for solid or liquid test aerosol.

INTRODUCTION

An experimental program was initiated at Los Alamos Scientific Laboratory (LASL) to investigate filter efficiency as a function of aerosol particle size and filtration velocity. Although many highly toxic radioactive aerosols are smaller than $0.3\ \mu$, the air cleaning systems designed to remove these materials frequently employ high-efficiency particulate aerosol (HEPA) filters which are quality control tested against $0.3\text{-}\mu$ dioctyl phthalate (DOP) aerosols. Questions have been raised concerning the filtration efficiency of such filter media against particles smaller than $0.3\ \mu$.

Theory predicts that $0.3\text{-}\mu$ particles are among the most difficult to filter and that smaller or larger particles are more readily removed.^{1,2} Optimum particle size for filter penetration has been reported by several investigators.^{3,4} However, other experimental work^{5,6,7} indicates that the smaller the particle size, the greater the filter penetration. The studies noted used a wide variety of test aerosols (i.e., DOP,^{3,5} sodium chloride,⁴ sulfuric acid,⁵ and polystyrene latex⁷).

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To provide a baseline for investigating filter efficiency as a function of aerosol particle size and filtration velocity, this preliminary study investigated filter efficiency as a function of filtration velocity, using a solid polydisperse aerosol. The preliminary work was prompted by major differences reported by various investigators. Comparison of these data indicated significant differences in filter efficiency as measured using solid and liquid aerosols.^{8,9,10,11,12}

The potential discrepancies between results of tests using solid or liquid aerosols also raised questions regarding standardized methods of testing respirator and HEPA space filters in the United States and the United Kingdom. In the United States, liquid DOP ($0.3\text{-}\mu$ monodisperse) is the standard test aerosol.¹³ In the United Kingdom, a polydisperse sodium chloride aerosol is used.¹⁴

PROCEDURE AND TEST RESULTS

A. Development of a Sodium Chloride Aerosol

1. Test Procedure

Sodium chloride was selected as our test aerosol because it is (a) non-toxic, (b) inexpensive,

(c) extremely sensitive to analysis by atomic absorption techniques; and because it (d) provides a distinctive square aerosol, (3) can be generated in the submicron range close to that of $0.3\text{-}\mu\text{DOP}$, and (f) is the standard aerosol in the United Kingdom for testing respirators and high-efficiency space filters.

An aerosol generator was constructed based on a design outlined by Vokes, Ltd.¹⁵ An overall view of the generator is shown in Fig. 1; Fig. 2 details the nebulizing portion. Construction material was stainless steel to minimize corrosion. High pressure (90 to 130 psi) compressed breathing air enters the generator at A (Fig. 2) and passes through three small radial ports (P), aspirating an aqueous solution of sodium chloride from the reservoir below. The mixture is then forced through three jets (J) to form the sodium chloride aerosol.

Figure 3 is a schematic showing the test system used to calibrate the aerosol generator. After leaving the generator, the aerosol enters a 35-gal drum (4) to provide adequate time for drying the aerosol. The sampling system consists of a lucite tube (5) with a Stairmand disc (6) to ensure complete mixing, a 4-in. aerosol assay (AA) Millipore filter (8), and a vacuum pump (10). An aliquot sample, obtained through a centerline probe (7) connected to a point-to-plane electrostatic precipitator (ESP), is used for measurement of aerosol size characteristics. Previous work has shown that this sampler will define representative aerosol size characteristics.¹⁶

Fig. 1. Sodium chloride aerosol generator.

Fig. 2. Nebulizer detail.

Electron microscope samples obtained by the ESP were shadowed with chromium, and electron micrographs, obtained with a Phillips EM 75 electron microscope, were sized on the basis of equivalent area (projected diameter),¹⁷ using the Zeiss TGZ 3 particle-size analyzer. Data were plotted on log-probability paper¹⁸ to permit direct determination of aerosol count median diameter (CMD) and geometric standard deviation (σ_g). Aerosol mass median diameter (MMD) was calculated using the Hatch and Choate equation.¹⁹

Mass output of sodium chloride from the aerosol generator was determined by atomic absorption analysis of the 4-in. Millipore filter. The filter was soaked in water for at least 12 h to ensure complete leaching of the sodium chloride into solution.

Air flow through the generator was calibrated for each operating pressure, using a water-displacement meter prover. A plot of air flow vs operating pressure is shown in Fig. 4.

KEY

1. BOTTLED BREATHING AIR	8. 4" A.A. MILLIPORE FILTER
2. AEROSOL GENERATOR	9. ORIFICE METER
3. PRESSURE GAUGE	10. VACUUM PUMP
4. DRYING CHAMBER	11. ELECTROSTATIC PRECIPITATOR SAMPLER
5. LUCITE SAMPLING TUBE	12. BACK-UP MILLIPORE FILTER
6. STAIRMAND DISC	13. FLOW METER
7. CENTER LINE SAMPLING TUBE TO ESP SAMPLER	14. SMALL VACUUM PUMP

Fig. 3. Aerosol calibration system.

Fig. 4. Nebulizer flow vs operating pressure.

Figure 5 shows a typical electron micrograph of the sodium chloride aerosol.

2. Results

Table I summarizes the NaCl aerosol size characteristics; size analysis was based on 300 to 500 particles for each run. Aerosol CMD ranged from 0.15 to 0.39 μ , with σ_g ranging from 1.77 to 2.72. Aerosol size was directly related to the NaCl solution concentration and operating pressure.

Table II shows that a wide range of aerosol concentration (mg/min or mg/ft³) can be obtained by varying the NaCl solution concentrations. At operating pressures of 110 and 130 psi, generator output is virtually constant when normalized for NaCl solution concentration (0.23 to 0.25 mg/ft³ / %).

TABLE I. SIZE CHARACTERISTICS OF NaCl AEROSOL

% Solution NaCl in H ₂ O	90 psig			110 psig			130 psig		
	CMD (μ)	σ_g	MMD (μ)*	CMD (μ)	σ_g	MMD (μ)*	CMD (μ)	σ_g	MMD (μ)*
2.0	0.19	1.95	0.72	0.18	2.07	0.88	0.15	1.93	0.54
10.0	0.29	2.09	1.48	0.30	1.84	0.90	0.25	2.16	1.53
25.0	0.26	1.91	0.91	0.39	1.77	1.05	0.28	2.72	5.9

*Calculated assuming a log-normal size distribution, using the Hatch-Choate equation.¹⁹

TABLE II. NaCl GENERATOR OUTPUT*

NaCl Solution Concentration	Operating Pressure (psig)					
	90		110		130	
	mg/min	mg/min/%	mg/min	mg/min/%	mg/min	mg/min/%
2.0	1.13	0.57	1.30	0.65	1.63	0.82
10.0	4.86	0.49	7.28	0.73	8.10	0.81
25.0	10.36	0.41	16.67	0.67	20.25	0.81
	mg/ft ³	mg/ft ³ /%	mg/ft ³	mg/ft ³ /%	mg/ft ³	mg/ft ³ /%
2.0	0.47	0.24	0.45	0.23	0.50	0.25
10.0	2.03	0.20	2.51	0.25	2.50	0.25
25.0	4.32	0.17	5.75	0.23	6.23	0.25

*Output measured in terms of mg sodium. $\text{mg NaCl} = \frac{\text{mg Na}}{0.393}$.

B. Filter Efficiency Tests

To provide preliminary data, filter efficiency of Whatman No. 41 filter paper was measured at various filtration velocities, using the polydisperse sodium chloride aerosol described. This filter medium was selected because of (a) its relatively low efficiency, which facilitates accurate measurement of filter penetration, and (b) extensive data available in the literature.

1. Test Procedure

Figure 6 shows a schematic diagram of the test setup. After passing through the drying chamber, the aerosol enters a lucite tube (13) where complete mixing is provided by a Stairmand

disc (5). The aerosol then passes through the 4-in.-diam Whatman No. 41 filter paper under test (8) and the AA Millipore filter (9). Airflow is monitored by an orifice meter (11) downstream from the Millipore filter. To accurately monitor airflow, the orifice meter was calibrated for the different negative pressure existing during the filter test program. At high flow rates, the negative pressure prior to the orifice meter reached several inches of mercury. This pressure was monitored by a mercury manometer connected to a pressure tap (10) downstream from the Millipore filter. To evaluate the effect, if any, of aerosol charge on filter efficiency, an ionizer²⁰ was

Fig. 5. NaCl aerosol shadowed with chromium (original magnification 25,000X).

installed in the system to neutralize any aerosol charge. All filter efficiency tests were run using a 2% NaCl solution and an aerosol generator operating pressure of 110 psi. Under these conditions, aerosol CMD ranged from 0.15 to 0.19 μ , with a σ_g range of 1.8 to 2.2. Aerosol samples for sizing were obtained from the ESP sample (6) noted in Fig. 6.

The Whatman No. 41 and Millipore filters were analyzed using atomic absorption techniques to measure sodium concentration. Instrument error was less than 0.1%. The potential problem of sodium background on the filters was considered. Sodium background on the Whatman No. 41 filter amounted to less than 4% of the sodium found on this filter; multiple blanks showed that the sodium background was virtually constant. A more significant problem was sodium background on the Millipore filter. Under some test conditions, the sodium background amounted to as much as 30% of the total sodium on the filter after testing. This background level, constant as measured by several blanks run during the test program, was compensated for in calculation of filter efficiency. A problem arose during the test program when Gelman GM-4 membrane filters were used in place

KEY

1. BOTTLED BREATHING AIR	7. 4" FILTER HOLDER
2. AEROSOL GENERATOR	8. 4" WHATMAN FILTER
3. PRESSURE GAUGE	9. 4" MILLIPORE FILTER (A.A)
4. DRYING CHAMBER	10. PRESSURE TAP
5. STAIRMAND DISC	11. ORIFICE METER
6. CENTER LINE PROBE
TO ESP SAMPLER	12. VACUUM PUMP
	13. LUCITE TUBE

Fig. 6. Filter efficiency test system.

TABLE III. WHATMAN NO. 41 EFFICIENCY CHARACTERISTICS

Run No.	Velocity (ft/min)	Efficiency (%)	Run No.	Velocity (ft/min)	Efficiency (%)
1	14.6	75.5	71	140.8	98.2
2	29.1	85.9	72	168.7	98.9
3	48.5	88.5	73	185.7	98.8
4	68.0	94.9			
5	87.4	97.4	76	5.5	67.3
6	103.2	98.1	77	8.0	75.8
7	125.0	96.5	78	9.6	72.8
8	140.8	99.0	79	11.2	75.2
9	155.3	99.2	80	13.4	76.3
			81	15.5	83.1
50	5.5	65.9	82	17.9	84.1
51	8.0	68.2	84	36.4	89.3
52/57	9.7	71.0	85	44.9	91.5
53	11.2	74.5	86	59.5	93.9
54	13.4	80.2	88	71.6	96.7
55/58	15.5	83.8	90	93.4	95.5
56	17.9	88.3	91	105.6	95.7
62	35.2	95.7	95	106.8	96.0
61	46.1	94.9	92	117.7	96.2
63	60.7	97.3	93	138.3	96.7
64	72.8	95.9	94	157.8	97.4
67/69	94.7	98.2	99	162.1	96.9
68	109.2	97.3	97	182.0	97.0
70	120.2	97.0

Fig. 7. Filter efficiency (%) vs filtration velocity (ft/min).

of AA Millipore filters. These GM-4 filters had a sodium background level over one order of magnitude greater than that found on the Millipore fil-

ters; they also exhibited a high variation in sodium background level.

2. Results

Whatman No. 41 filter efficiency was calculated as noted below:

$$W 41 \text{ Efficiency} = 1 - \frac{(\text{Na on M.F.}) - (\text{Bgrd. on M.F.})}{(\text{Na on M.F.} + \text{Na on W 41}) - (\text{Bgrd on M.F.} + \text{Bgrd on W 41})}$$

Table 3 summarizes the data obtained.

These data are also plotted in Fig. 7. During the test sequences that included Runs 1 to 9 and 50 to 73, the ionizer previously mentioned²⁰ was not used. The ionizer was employed during the test sequence that included Runs 76 to 99.

Within limits of experimental error and considering possible variations within the filter medium, the data showed good reproducibility. Filter efficiency at extremely low flow rates was of the order of 60 to 80% and increased to 95% at face velocities in excess of 50 ft/min. No significant effect due to aerosol charge was noted by changes in Whatman No. 41 efficiency when the ionizer was used.

Figure 8 shows the pressure-drop characteristics of the Whatman No. 41 filters used in the present study. Also plotted in Fig. 8 are pressure-drop characteristics as reported by two other investigators.^{8,9} This comparison will be

discussed in the following section.

DISCUSSION

Figure 9 shows the filter efficiency data obtained during the test program at LASL, together with similar data that were obtained by other investigators and reported in the open literature^{8,9,10,11}. Figure 9 is limited to the range of face velocities tested at LASL; several of the other reported studies also considered velocities outside of these limits. These data for liquid test aerosols (DOP) show filtration efficiencies that are considerably lower than those shown for solid test aerosols (sodium chloride, latex, and uranine).

Three possible explanations for these differences follow:

(a) Filter efficiencies obtained using a solid vs a liquid aerosol differ with the state of the test aerosol. The differences may be due to break-up of the liquid aerosol on the filter bed, transport of particulates initially collected on the filter bed, or

Fig. 8. Filter pressure drop (in. Hg) vs filtration velocity (ft/min).

Fig. 9. Comparative data: filter efficiency (%) vs filtration velocity (ft/min).

some other mechanism related to liquid aerosols. Efficiency measurements indicate that filter penetrations for liquid DOP aerosols range from 2 to 10 times higher than filter penetrations for solid sodium chloride aerosols. If this difference in filter penetration is primarily due to the differences between solid and liquid aerosols, it suggests that a standardized filter test employing liquid DOP as the test aerosol may not accurately evaluate filter efficiency. DOP does seem to provide a conservative estimate of filter efficiency.

(b) Differences shown for DOP and sodium chloride filter penetration could be due to time variations as a result of loading the Whatman No. 41 filter paper during tests. In our test program, runs were 2 min in duration to provide sufficient time for collection of sodium chloride for analysis. During this time, a significant buildup in pressure

drop occurred across the Whatman No. 41 filter media at the higher flow rates, which might partially account for the higher filter efficiencies measured. At lower flow velocities, however, no measurable increase in pressure drop was noted across the Whatman No. 41 filter media. Table 4 summarizes the initial and final pressure drop across the Whatman No. 41 filters tested at LASL. Figure 8 shows the initial pressure drop and compares the LASL data with other data previously reported.^{8,9} The differences suggest that Whatman No. 41 filters may be variable, which may partially contribute to the differences in filter efficiency previously noted. It does not explain the consistent pattern of higher efficiencies with use of solid test aerosols.

(c) During the filter efficiency tests, the NaCl aerosol CMD ranged from 0.15 to 0.19 μ ,

TABLE IV. INITIAL AND FINAL PRESSURE DROP ACROSS TEST FILTER

Run No.	Velocity (ft/min)	Filter Initial ΔP (in. Hg)	Filter Final ΔP (in. Hg)	Change in Filter ΔP (in. Hg)
1	14.6	0.05	0.05	0
2	29.1	0.21	0.21	0
3	48.5	0.36	0.46	0.10
4	68.0	0.48	0.78	0.30
5	87.4	0.70	2.1	1.4
6	103.2	0.87	2.5	1.63
7	125.0	1.10	2.2	1.1
8	140.8	1.30	3.5	2.2
9	155.3	1.47	3.7	2.23
50	5.5	<0.05	<0.05	0
51	8.0	<0.05	<0.05	0
52/57	9.7	<0.05	<0.05	0
53	11.2	0.05	0.13	0.08
54	13.4	0.06	0.21	0.15
55/58	15.5	0.07	0.27	0.20
56	17.9	0.10	0.30	0.20
62	35.2	0.26	0.86	0.60
61	46.1	0.35	1.15	0.80
63	60.7	0.42	1.62	1.20
64	72.8	0.54	1.79	1.25
67/69	94.7	0.68	2.2	1.52
68	109.2	0.94	2.9	1.96
70	120.2	1.05	3.2	2.15
71	140.8	1.30	3.5	2.2
72	168.7	1.62	5.4	3.78
73	185.7	1.83	5.8	3.97
76	5.5	<0.05	<0.05	0
77	8.0	<0.05	<0.05	0
78	9.6	<0.05	<0.05	0
79	11.2	0.05	0.05	0
80	13.4	0.06	0.10	0.04
81	15.5	0.07	0.22	0.15
82	17.9	0.10	0.30	0.20
84	36.4	0.27	0.72	0.45
85	44.9	0.34	0.74	0.40
86	59.5	0.42	1.17	0.75
88	71.6	0.52	2.1	1.58
90	93.4	0.77	2.6	1.83
91	105.6	0.89	3.2	2.31
95	106.8	0.91	3.3	2.39
92	117.7	1.02	2.5	1.48
93	138.3	1.26	3.3	1.04
94	157.8	1.50	5.6	4.1
99	162.1	1.55	3.9	1.35
97	182.0	1.80	4.6	2.8

with a σ_g range of 1.8 to 2.2. Using the Hatch-Choate equation, a MMD range of 0.6 to 1.1 μ was calculated, which is greater than that provided by monodisperse 0.3- μ DOP.

It is interesting to note that the filter efficiencies measured using the polydisperse, NaCl aerosol agree very closely with the results obtained by Lindeken,¹¹ who used five different monodisperse latex aerosols covering the range of 0.088 to 0.557 μ .

FUTURE WORK

The data obtained to date indicate the need to compare filter efficiency as measured by solid and liquid aerosols having the same particle size. The difference in filter efficiency can then be evaluated solely in consideration of the type of aerosol employed. Future work will initially be directed towards testing Whatman No. 41 filter paper against a monodisperse liquid aerosol (0.3- μ DOP) and two different monodisperse solid aerosols (0.264- and 0.357- μ polystyrene latex). By using two latex

aerosols, one with particles slightly smaller than $0.3\ \mu$ and the other with particles slightly larger than $0.3\ \mu$, particle-size effects will be eliminated.

If filter penetration of a solid aerosol does indeed differ from that of a liquid aerosol, a need will exist to develop extensive filter efficiency data using solid test aerosols. At the present time, data of this type are available for liquid DOP.^{8,9} A secondary problem concerns the significance of standard HEPA filter tests using $0.3\text{-}\mu$ DOP.

Additional studies will include work on filter efficiency as a function of particle size and face velocity to define particle size for maximum filter penetration.

SUMMARY

1. The aerosol generator provides a reproducible, polydisperse, submicron sodium chloride aerosol. By varying NaCl solution concentration, aerosol CMD ranges from 0.15 to $0.39\ \mu$ with a σ_g range of 1.11 to 2.12 .

2. Generator output is approximately 0.23 - to 0.25 -mg sodium/ft³ air/% NaCl solution.

3. Tested against the polydisperse NaCl aerosol, Whatman No. 41 filters exhibit a collection efficiency ranging from 65 to 99% . At filtration velocities greater than 50 ft/min, collection efficiency is greater than 95% .

4. A review of previously reported data indicates that Whatman No. 41 filter efficiency is considerably higher when tested with a solid aerosol as contrasted with a liquid aerosol.

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