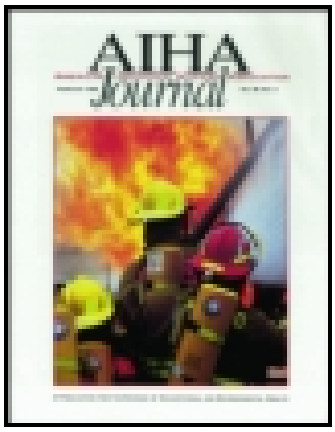
This article was downloaded by: [Stephen B. Thacker CDC Library]
On: 26 February 2015, At: 06:18
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

Collection Efficiency of Respirator Filters Challenged with Monodisperse Latex Aerosols

L.M. BROSSEAU [a] , J.S. EVANS [a] , M.J. ELLENBECKER [b] & M.L. FELDSTEIN [c]

[a] Department of Environmental Science and Physiology, Harvard University, School of Public Health, Boston, MA 02115

[b] Department of Work Environment, College of Engineering, University of Lowell, Lowell, MA 01854

[c] Departrnent of Biostatistics, Harvard University, School of Public Health, Boston, MA 02115

Published online: 04 Jun 2010.

To cite this article: L.M. BROSSEAU , J.S. EVANS , M.J. ELLENBECKER & M.L. FELDSTEIN (1989) Collection Efficiency of Respirator Filters Challenged with Monodisperse Latex Aerosols, American Industrial Hygiene Association Journal, 50:10, 544-549, DOI: 10.1080/15298668991375137

To link to this article: http://dx.doi.org/10.1080/15298668991375137

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Am. Ind. Hyg. Assoc. J. 50(10):544–549 (1989)

Collection Efficiency of Respirator Filters Challenged with Monodisperse Latex Aerosols*

L.M. BROSSEAU[A], J.S. EVANS[A], M.J. ELLENBECKER[B], and M.L. FELDSTEIN[C]
[A]Department of Environmental Science and Physiology, Harvard University, School of Public Health, Boston, MA 02115;
[B]Department of Work Environment, College of Engineering, University of Lowell, Lowell, MA 01854;
[C]Department of Biostatistics, Harvard University, School of Public Health, Boston, MA 02115

Collection efficiency was evaluated for 10 respirator manufacturers' electrostatically-charged dust/mist filters challenged with eight sizes of latex spheres in a range representative of the silica aerosol used in National Institute for Occupational Safety and Health (NIOSH) certification tests. Minimum efficiency occurred at or below the smallest size of 0.102 μm. Appreciable differences were found in the performances of filters distributed by the 10 manufacturers. Filters produced by 1 manufacturer exhibited significantly lower collection efficiency than other filters tested; those produced by 2 manufacturers performed somewhat better than the others tested. Statistical evaluation of Weibull-transformed data using analyses of covariance and Tukey's significant difference test allowed classification of the 10 manufacturers into three performance categories.

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015

Introduction

Electrostatically charged filters are utilized in air purifying respirators designed for use in environments contaminated by moderately hazardous aerosols, *i.e.*, those with permissible exposure levels equal to or greater than 0.05 mg/m^3. Currently, the National Institute for Occupational Safety and Health (NIOSH) evaluates the performance of such filters by challenging them with a polydisperse silica test aerosol (geometric mean of 0.5 μm and geometric standard deviation of less than 2.0) under steady flow conditions.[1] A drawback of the NIOSH protocol is that it yields little information useful for estimating a filter's performance when challenged with other aerosols or under different conditions of use, *e.g.*, cyclic flow.

To investigate alternatives to the NIOSH test protocol, experiments were designed to include

- theoretical modeling of the filter's efficiency,
- empirical modeling of the filter's overall performance characteristics, based on measurement of its size-specific performance, and
- a new test protocol using cyclic flow and both silica and asbestos test aerosols.

It is difficult to predict the collection efficiency of these filters because the filter's electrostatic charge, which accounts for a significant amount of collection, is unknown and difficult to measure.[2] At the time of this study, few data were available on size-specific penetration of electrostatically charged dust/mist respirator filters.

Reported here are results of experiments in which the size-specific performance of 10 manufacturers' filters was determined using monodisperse latex spheres ranging from 0.1 to 2.0 μm in diameter. These experiments had two purposes: (1) to provide data needed in the empirical modeling effort and (2) to assist in selection of a subset of filters for use in subsequent experiments.

Methods and Materials

Suspensions of latex spheres (10% solids, Seragen, Inc., Indianapolis, Ind.) ranging in size from 0.102 to 2.02 μm were diluted in water and aerosolized with jet nebulizers, which were found to disperse an aqueous suspension of latex particles in a uniform manner such that few doublets and triplets were formed. The RETEC X-70/N nebulizer (Cavitron Corp., Portland, Oreg.) was used for the five larger particle sizes (0.460–2.02 μm) and the MISTY-OX nebulizer (Medical Molding Corp. of America, Costa Mesa, Calif.) for the three remaining sizes (0.102–0.238 μm). The mean diameter, standard deviation, and chemical composition of each size latex sphere, and information on the appropriate nebulizer and dilution ratio (volume of latex spheres to volume of water) are given in Table I. Initial dilution ratios were chosen as recommended by Raabe[3] and adjusted by trial and error to obtain singly dispersed, aerosolized particles. These eight sizes of latex particles were chosen to represent the range of particle sizes of the polydisperse silica aerosol used to certify these respirator filters.[1]

The experimental apparatus is shown in Figure 1. Spheres were aerosolized into a glass tube to which dried, filtered air (6580 cm^3/min for the RETEC and 11 280 cm^3/min for the MISTY-OX) was added. Air was drawn from the tube through a KR-85 charge neutralizer (TSI, Inc., St. Paul, Minn.) into the test apparatus. The dilution flows were selected to ensure a relative humidity of 50% within the test apparatus.

A brass pipe was connected at its center to the outlet of the charge neutralizer. A custom-designed filter holder with a

*This paper was prepared in partial fulfillment of doctoral degree requirements and was supported by NIOSH grant 5 R01 OH02154-02. Drs. Evans and Ellenbecker received support from NIOSH grant 5 T15 OH078096.

Copyright 1989, American Industrial Hygiene Association

TABLE I
Description of Latex Spheres

Latex Sphere Size (μm)		Chemical		Dilution Ratio
Mean	SD	Composition	Nebulizer	(mL latex/mL water)
0.102	0.0072	carboxylate modified	Misty-Ox	3.0×10^{-6}
0.173	0.0068	polystyrene	Misty-Ox	3.6×10^{-6}
0.238	0.0034	polystyrene	Misty-Ox	3.6×10^{-6}
0.460	0.0048	polystyrene	RETEC X-70/N	5.9×10^{-4}
0.643	[A]	polyvinyltoluene	RETEC X-70/N	1.1×10^{-3}
0.803	[A]	polystyrene	RETEC X-70/N	2.3×10^{-3}
1.370	[A]	polyvinyltoluene	RETEC X-70/N	9.1×10^{-3}
2.020	0.0135	polyvinyltoluene	RETEC X-70/N	3.2×10^{-3}

[A]No standard deviation was given by the manufacturer.

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015

2.2-cm diameter opening was connected to one end of the pipe. Attached to the filter holder and the other end of the pipe were lengths of Tygon® tubing, which were joined together with a "T" at their opposite ends. The third leg of the T was attached to a laser light-scattering photometer, described below. The portion of the test apparatus with the filter holder represents the "downstream" side of the respirator (that aerosol which passes through the filter into the respirator facepiece); the opposite side of the test apparatus represents air found "upstream" or outside of the respirator. The pipe and Tygon tubing for each side were matched carefully in length and configuration to minimize differences in particle losses between the two sides. Upstream and downstream (with no filter in place) particle concentrations were measured periodically to confirm uniformity. Two clamps located on each Tygon tube were used to close one side, allowing air to be routed entirely through the other side. The filter holder was sealed with three adjustable hand clamps.

Latex sphere concentrations were measured in the upstream and downstream portions of the test apparatus with a forward light-scattering laser photometer (Particle Measuring Systems, Boulder, Colo.). A laser probe (CSASP-100) attachment was used to sample for the larger particle sizes (0.460–2.02 μm). The entire system airflow of 2700 cm^3/min was drawn through the probe; the purge flow was operated at 28 cm^3/min. A different laser probe attachment (ASASP-X) was used to measure the aerosol concentration for the smaller-sized latex spheres with sample and purge flows of 90 and 1200 cm^3/min, respectively. The latter probe can be operated at a maximum flow of 90 cm^3/min; thus, a sampling probe was designed to sample isokinetically from the total 2700 cm^3/min airflow, such that a concentration representative of that in the entire airflow was measured.[4]

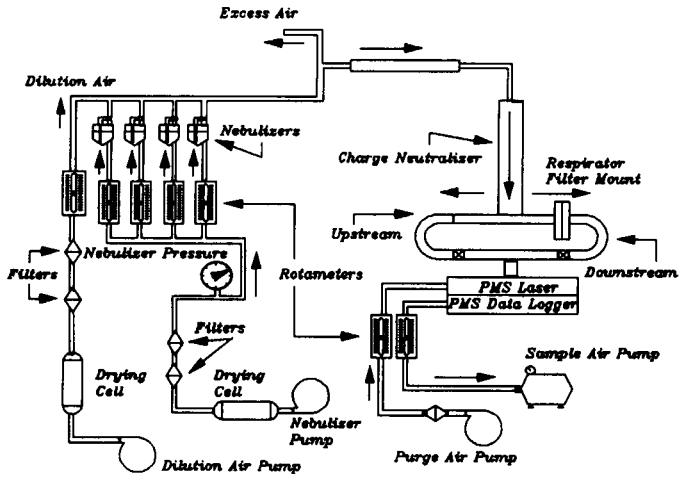


Figure 1—Respirator filter test system

At the time of these experiments, no standard methods for testing filtration penetration with latex aerosols were available. Shortly afterward, however, the American Society for Testing and Materials (ASTM) published Special Technical Publication 975, in which Nicholson[5] outlined a standard test method for measuring filter media efficiency using monodisperse latex spheres. The ASTM method is similar to that used in the present experiments. The primary difference is in the approach taken for measurement of upstream and downstream particle concentrations. The ASTM method involves measurements physically upstream of the filter, whereas in the present experiments the upstream concentration was sampled by diverting the flow around the filter.

Filters from 10 respirator manufacturers were selected from the most recent list of NIOSH-certified dust/mist filter and respirator combinations.[6] Dust/mist filters were bought either from local distributors or directly from the manufacturers. Manufacturers were not aware of the purpose of these purchases. Three samples of each manufacturer's filters were selected randomly from one lot and cut to fit the experimental filter holder; thus, a total of 30 filters were included in the experiments.

Of the 10 manufacturers' filter media tested in these experiments, 9 were fabricated from a resin-impregnated wool and polypropylene felt. Most manufacturers obtain the felt filter material from the same source. Differences in filters may exist, however, because each respirator manufacturer specifies the amount of resin, the porosity and nature of the filter material, and the degree of processing (needling or other

methods used to condition the material) used in its filter medium. In addition, a manufacturer also may process the filter material further after it is received from the supplier.[7,8] The one manufacturer's filters not made of resin-impregnated felt consisted of an "electret" medium, formed from fibers obtained by shredding charged sheets of polypropylene.

The air velocity through a filter significantly affects its collection efficiency.[4] To obtain a velocity representative of NIOSH test conditions, it was necessary to scale down the NIOSH test airflow of 32 000 cm^3/min by the ratio of the filter area tested to the actual filter area. The actual filter area was determined by measuring the area of the filter after it was sealed within its particular respirator cartridge, and ranged from 36.1 to 48.8 cm^2. An average test airflow of 2700 cm^3/min was selected on the basis of these measurements.

Two experiments were performed, the first to test large particle collection and the second to test collection of the smaller sizes. In the first experiment, the 30 test filters were placed, in random order, into the filter holder. For each filter, the five larger latex particle sizes (0.460, 0.643, 0.803, 1.37, 2.02 μm) were generated in random order. The particle concentration was allowed to stabilize for several minutes and was checked in the downstream section with the photometer. Upstream and downstream aerosol concentrations were measured sequentially for 1-min periods. Three upstream and two downstream samples were taken for each latex sphere size, with approximately 1.5 min between each sample. Penetration was calculated by dividing the average downstream count by the average upstream count.

In the second experiment, the same 30 filters were tested with the three smaller particle sizes (0.238, 0.173, and 0.102 μm). The same protocol was used as in the previous experiment. Although it might have been preferable to test the smaller sizes first, calculations showed that, at most, 0.2 mg of the five larger latex aerosols would be collected on the filters. This represents 0.1% of the mass of the test filter and, thus, would not affect significantly the filtration of the smaller latex aerosols.

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015

Results

The results of these experiments are summarized in Figure 2, which presents the average penetration for all 10 manufacturers' filters as a function of particle size. Visual examination of the data reveals a strong dependence of collection efficiency on particle size. Penetration ranged from approximately 10% at the smallest experimental sizes (0.102 or 0.238 μm) to about 1% at a particle diameter of 0.460 μm and decreased to less than 0.5% at the largest diameter (2.02 μm).

Although most of the filters exhibited quite similar collection characteristics, those produced by Manufacturer 1 appeared to perform worse than most, and those of Manufacturers 4 and 9 appeared to perform somewhat better than most. This is illustrated in Figure 3, which presents the fractional penetration of four of the eight particle sizes tested, chosen to illustrate the size dependence of the manufacturer-specific data.

Although this simple description of the data provided a sense of the manufacturer- and size-specific behavior of the filters tested, it did not provide an accurate understanding of the variability of the results and the sources of such variability. By fitting a model to the data, a more stable estimate of the within-manufacturer and between-size variability of results could be obtained, and meaningful groups of filters with similar performance characteristics could be formed.

A two-parameter Weibull function was found to characterize adequately the relationship between penetration, P, and particle diameter, d_p:

$$P = e^{-kd_p^v} \quad (1)$$

The Weibull model was chosen because the parameters of the model, k (location) and v (shape), can be estimated easily by ordinary least squares regression of the transformed expression:

$$\ln(-\ln P) = \ln(kd_p^v) = \ln(k) + v \ln(d_p) \quad (2)$$

The transformed expression is a linear function with two estimable parameters: ln(k)—the intercept, and v—the slope.

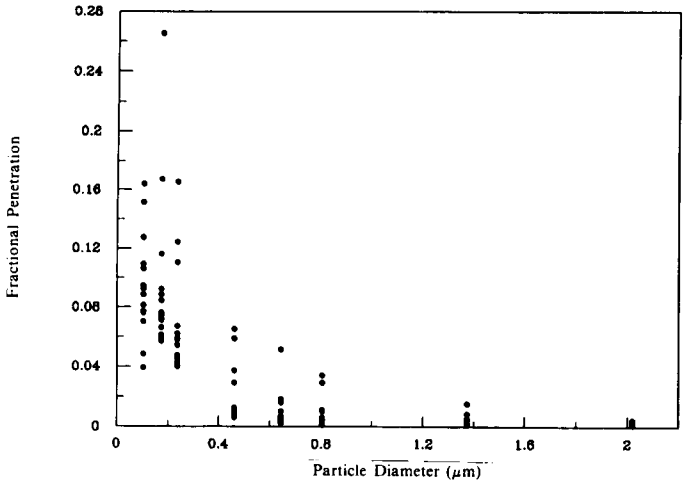


Figure 2—Size-specific performance (all data)

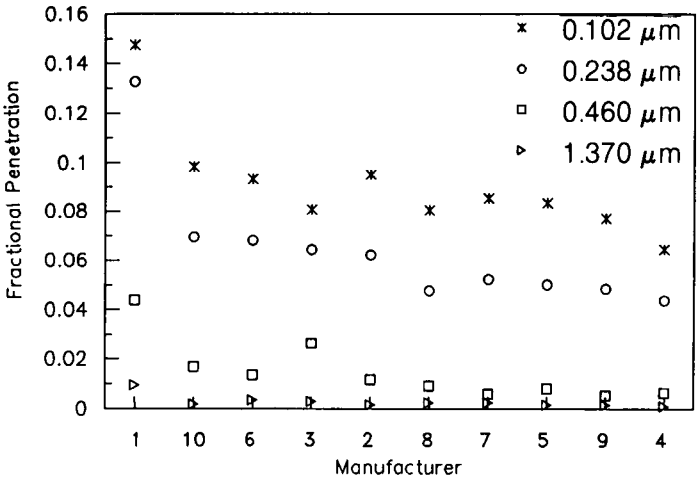


Figure 3—Penetration (four sizes) ranked by maufacturer

TABLE II
Coefficients, Standard Errors, and R^2 from Regression of $\ln(-\ln P) = \ln(k) + v \ln(d_p)$ for Ten Manufacturers[A]

Manufacturer	ln k ($se_{\ln k}$)	v (se_v)	R^2	$se_{\ln(-\ln P)}$
1	1.4 (0.04)	0.43 (0.03)	.87	0.16
2	1.7 (0.02)	0.41 (0.02)	.97	0.10
3	1.7 (0.04)	0.40 (0.03)	.86	0.15
4	1.8 (0.03)	0.38 (0.03)	.89	0.13
5	1.8 (0.03)	0.39 (0.03)	.90	0.13
6	1.7 (0.03)	0.38 (0.02)	.93	0.11
7	1.8 (0.04)	0.39 (0.03)	.89	0.14
8	1.8 (0.03)	0.39 (0.02)	.91	0.12
9	1.8 (0.04)	0.39 (0.03)	.85	0.16
10	1.7 (0.03)	0.42 (0.02)	.94	0.11
Pooled	1.7 (0.01)	0.40 (0.01)	.84	0.17

[A]Particle diameter (d_p) must be expressed in μm.

Estimates of ln(k) and v (with particle diameter in μm) for each of the 10 manufacturer's filters are given in Table II. Also given are estimates of ln(k) and v derived from the full data set formed by pooling the results from all 10 manufacturers. The model explains between 85% and 97% of the variation in the transformed data. The estimates of ln(k) range from 1.44 (Manufacturer 1) to 1.82 (Manufacturers 4 and 9). The estimates of v vary from 0.38 (Manufacturers 4 and 6) to 0.43 (Manufacturer 1). To investigate systematic bias in model performance, residual plots were prepared and inspected; no significant problems were found.

To test the hypothesis that the size-specific collection efficiency was similar for all manufacturers, an analysis of covariance was employed. The null hypothesis that there were no manufacturer-related performance differences was rejected.

To determine which manufacturer's filters were responsible for the observed difference in intercepts, the residuals from the pooled regression were examined using Tukey's honestly significant difference test. This test allowed the manufacturers to be grouped into three performance categories:

Set 1 (high penetration)	Manufacturer 1
Set 2 (typical performance)	Manufacturers 6, 3, and 10
Set 3 (low penetration)	Manufacturers 9 and 4

The four remaining manufacturers (2, 8, 7, 5) could be placed in sets 2 or 3. The one manufacturer which utilized "electret" material as a filter medium was located in the set exhibiting low penetration in comparison with most of the other manufacturers' (resin-impregnated felt) filters.

Details of the statistical tests are included in the Appendix.

Discussion

These experiments provide evidence of size- and manufacturer-specific performance of electrostatically-charged filters challenged with neutralized monodisperse latex spheres in a range of diameters between 0.1 and 2.0 μm. The observation that the greatest fractional penetration occurs for particles 0.1 μm in diameter or smaller is consistent with the observations of Stevens and Moyer.[9] For continuous airflows between 16 000 and 85 000 cm^3/min, they found that particles with diameters between 0.03 and 0.1 μm were collected least efficiently by dust/mist filters.

The results, which were described adequately by a two-parameter Weibull distribution, may be used as inputs to semiempirical models designed to predict the overall penetration that would be expected when such filters are challenged by polydisperse aerosols with known size distributions. The estimates of the standard deviation of the residuals from fitting such models provide some indication of the uncertainty inherent in such estimates of overall penetration.

Of course, any attempt to predict the behavior of a filter challenged with a specific aerosol must account for several factors not addressed by these experiments. In particular, the influence on collection efficiency of any charge the aerosol may carry and the potential degradation of electrostatic filter performance during storage must be considered.

Electrostatic filters carry a significant charge, and it has been shown that charged aerosols are collected differently from "neutralized" ones.[10,11] In the case of the present experiments, the aerosol was neutralized, such that it carried a Boltzmann charge distribution.[7] The NIOSH respirator approval tests do not call for aerosol neutralization.[1] Moyer and Stevens[10] found that charged silica aerosols were collected by dust/mist filters with higher efficiency than were similar neutralized aerosols (at 16 000 cm^3/min), whereas a charged lead fume aerosol was collected with slightly lower efficiency than was the neutralized aerosol. Thus, it would be difficult to predict how a charged aerosol might be collected by these respirator filters, unless more were known about the type and degree of charge.

The charge on electrostatic filters has been shown to degrade after prolonged exposure to high relative humidity, high temperature, and oil aerosols.[10,12-14] The experiments described here utilized newly purchased filters; no special efforts were made to protect the filters. The filters were stored for, at most, 18 months in a research facility where the temperature normally is between 17° and 20°C and the relative humidity tends to remain below 40%. Thus, the results are thought to describe the behavior of filters which have experienced very little charge degradation.

It should be noted that the Weibull model is intended to describe penetration only in the range of particle sizes studied in the present experiments (0.1–2.0 μm). It is well known that the penetration of an aerosol through a filter will reach a maximum and then decrease at sizes both smaller and larger than the "most penetrating size."[7,9] Thus, the Weibull models used in this study would not be expected to represent well the penetration through these particular filters of particles smaller than about 0.1 μm.

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015

TABLE AIII
Tukey's Significant Difference Test, Mean Residual and q Statistic Values

Manufacturer		Manufacturer #								
#	Mean Resid[A]	1	6	3	10	2	8	7	5	9
1	-0.28									
6	-0.01	0.26[B]								
3	-0.01	0.27[B]	0.00							
10	0.00	0.28[B]	0.01	0.01						
2	0.03	0.30[B]	0.04	0.04	0.03					
8	0.05	0.33[B]	0.07	0.06	0.05	0.03				
7	0.08	0.36[B]	0.09	0.09	0.08	0.05	0.03			
5	0.09	0.37[B]	0.10	0.10	0.09	0.06	0.04	0.01		
9	0.12	0.40[B]	0.13[B]	0.13[B]	0.12[B]	0.10	0.07	0.04	0.03	
4	0.14	0.41[B]	0.15[B]	0.14[B]	0.14[B]	0.11	0.08	0.06	0.04	0.01

[A]Mean of the manufacturer-specific residuals from the pooled regression of ln(-ln P) on $\ln(d_p)$.

[B]Indicates q is greater than $q^*_{0.05,230,10}$. Here $q^* = 4.56$ and $q = d_{i,j}/(s^2/n)^{1/2}$, where s^2 (the mean square residual) is 0.017 and n (the number of observations for each manufacturer) is 24.

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015

Conclusions

The strong dependence of electrostatic filter efficiency on particle size, the variability of industrial aerosol size distributions,[15] and the recognition that lung dose depends on particle size as well as on mass concentration suggest that information about fractional penetration over a range of sizes would allow users to select filters appropriate for their particular operations. The current NIOSH certification protocol, using a single aerosol with a specific size distribution, does not provide such information.

Acknowledgment

Special thanks are extended to Mr. Kenneth Martin for his help in developing the experimental apparatus.

References

1. "30 Mineral Resources," *Code of Federal Regulations* Title 30, Part 11, 1980. pp. 7-70.
2. **Brown, R.C.:** The Behaviour of Fibrous Filter Media in Dust Respirators. *Ann. Occup. Hyg. 23*:367-380 (1980).
3. **Raabe, O.G.:** The Dilution of Monodisperse Suspensions for Aerosolizations. *Am. Ind. Hyg. Assoc. J. 29*:439-443 (1968).
4. **Hinds, W.C.:** *Aerosol Technology.* New York: John Wiley and Sons, Inc., 1982. pp. 187-194.
5. **Nicholson, R.M.:** Standardized Test Method for Using Latex Aerosols and Optical Particle Counters to Determine Particle Size Initial Efficiency of Flat Sheet Filter Media. In *Fluid Filtration: Gas.* Volume I, (ASTM STP 975) R.R. Raber ed. Philadelphia, Pa.: ASTM, 1986. pp. 141-151.
6. **National Institute for Occupational Safety and Health:** *Certified Equipment List.* (DHHS/NIOSH Pub. No. 85-101). 1985.
7. **Matheson, J.:** November 1988. [Personal correspondence]. J. Matheson, Consultant, 4100 Post Road #9, Warwick, RI 02886.
8. **American Felt and Filter:** November 1988. [Correspondence]. American Felt and Filter, 34 John Street, Newburgh, NY 12550.
9. **Stevens, G.A. and E.S. Moyer:** "Worst Case" Aerosol Testing Parameters: I. Sodium Chloride and Dioctyl Phthalate Aerosol Filter Efficiency as a Function of Particle Size and Flow Rate. *Am. Ind. Hyg. Assoc. J. 50(5)*:257-264 (1989).
10. **Moyer, E.S. and G.A. Stevens:** "Worst Case" Aerosol Testing Parameters: II. Efficiency Dependence of Commercial Respirator Filters on Humidity Pretreatment. *Am. Ind. Hyg. Assoc. J. 50(5)*:265-270 (1989).
11. **Moyer, E.S. and G.A. Stevens:** "Worst Case" Aerosol Testing Parameters: III. Initial Penetration of Charged and Neutralized Lead Fume and Silica Dust Aerosols through Clean, Unloaded Respirator Filters. *Am. Ind. Hyg. Assoc. J. 50(5)*:271-274 (1989).
12. **Los Alamos National Laboratory:** *Respiratory Studies for the National Institute for Occupational Safety and Health, July 1, 1972, through June 3, 1973,* by E.C. Hyatt, J.A. Pritchard, B.J. Held, D.A. Bevis, T.O. Davis, L.A. Geoffrion, A.L. Hack, P.L. Lowry, T.O. Moore, C.P. Richards, and L.D. Wheat (Los Alamos National Laboratory Progress Report LA-5620-PR). Los Alamos, Calif.: Los Alamos National Laboratory, 1974. pp. 20-24.
13. **Los Alamos National Laboratory:** *Respirator Studies for the National Institute for Occupational Safety and Health, July 1, 1974, through June 30, 1975,* by D.D. Douglas, W. Revoir, J.A. Pritchard, A.L. Hack, L.A. Geoffrion, T.O. Davis, P.L. Lowry, C.P. Richards, L.D. Wheat, J.M. Bustos, and P.R. Hesch (Los Alamos National Laboratory Progress Report LA-6386-PR). Los Alamos, Calif.: Los Alamos National Laboratory, 1976. pp. 13-18.
14. **Ackley, M.W.:** Degradation of Electrostatic Filters at Elevated Temperature and Humidity. In *World Filtration Congress III.* Croydon, England: Uplands Press, 1982. pp. 169-176.
15. **Hinds, W.C. and P. Bellin:** Effect of Facial-Seal Leaks on Protection Provided by Half-Mask Respirators. *Appl. Ind. Hyg. 3(5)*:158-164 (1988).
16. **Zar, J.H.:** *Biostatistical Analysis.* Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1984. pp. 292-304.

APPENDIX

The analysis of covariance began with estimation of the full model:

$$y = a_0 + a_1m_1 + \ldots + a_9m_9 + b_0x + b_1m_1x + \ldots + b_9m_9x \quad \textbf{(A1)}$$

where $y = \ln(-\ln(P))$; $x = \ln(d_p)$; $a = \ln(k)$; b = shape parameter (v); and $m_1, m_2, \ldots m_9$ are binary dummy variables used to indicate manufacturer. Implicitly, a_0 stands for the tenth manufacturer, and thus, only nine such binary variables are necessary. See Table AI.

The F test for the significance of the interaction terms, *i.e.*, equal slopes, was

$$F = \frac{0.23/9}{3.8/220} = 1.46$$

Since the critical value of $F_{0.05(1),9,220} = 1.93$, the null hypothesis that slopes are equal could not be rejected ($P > 0.25$).

Since location parameters were not significantly different among the manufacturers, interaction terms were dropped, and the parameters of the reduced model were fit:

$$y = a_0 + a_1m_1 + \ldots + a_9m_9 + b_0 \quad \textbf{(A2)}$$

See Table AII.

The F test for the significance of the dummy variables, *i.e.*, equal intercepts, was

$$F = \frac{2.9/9}{3.9/229} = 18.4$$

Since the critical value of $F_{0.05(1),9,229} = 1.91$, the null hypothesis that the intercepts are equal was rejected ($P < 0.0005$), and it was concluded that there were significant differences in performance among the 10 manufacturers' filters.[16]

To determine which manufacturer's filters were responsible for the observed difference in intercepts, the residuals from the pooled regression were examined using Tukey's honestly significant difference test. The sample means of the manufacturer-specific residuals were arranged in increasing order, and the pairwise differences in means were computed. The significance of each observed pairwise mean difference was evaluated by computing the q statistic (the Studentized range) and comparing it with tabulated values (at $\alpha = 0.05$):

$$q = \frac{d_{i,j}}{\sqrt{s^2/n}} \quad \textbf{(A3)}$$

TABLE AI
Analysis of Covariance, Full Model

Source	df[A]	SS[B]	MS[C]
Mean	1	488.3	
Slope	1	35.0	
Dummy variables	9	2.8	0.31
Interaction terms	9	0.2	0.02
Residual	220	3.8	0.02
Total	240	530.1	

[A]df = degrees of freedom.
[B]SS = sum of squares.
[C]MS = mean square.

TABLE AII
Analysis of Covariance, Model without Interaction Terms

Source	df[A]	SS[B]	MS[C]
Mean	1	488.3	
Slope	1	35.0	
Dummy variables	9	2.9	0.33
Residual	229	3.9	0.02
Total	240	530.1	

[A]df = degrees of freedom.
[B]SS = sum of squares.
[C]MS = mean square.

where $d_{i,j}$ is the observed difference between the mean residuals of Manufacturers i and j; s^2 is the residual mean square from the pooled regression; and n is the product of the number of replications (3) and particle sizes (8) tested for each manufacturer.

If this q value is less than or equal to the critical value of $q_{\alpha,df,k}$ (where α is the significance level [0.05], df is the residual degrees of freedom from the analysis of variance [230], and k is the total number of means tested [10 manufacturers]), then the null hypothesis is rejected. The critical q value for this situation is 4.5, as determined from a table of the q distribution found in Zar.[16] See Table AIII.

5 July 1988; Revised 20 April 1989

Downloaded by [Stephen B. Thacker CDC Library] at 06:18 26 February 2015