Effect of DOP Heterodispersion on HEPA-Filter-Penetration Measurements

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HEPA-FILTER-PENETRATION MEASUREMENTS*

by

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Abstract

The accuracy of the standard U.S. test method for certifying High-Efficiency Particulate Air (HEPA) filters has been in question since the finding by Hinds, et al. that the dioctyl phthalate (DOP) aerosol used in the test is not monodisperse as had been assumed and that particle-size analyzers, or owls, could not distinguish between different particle-size distributions with the same owl reading. We have studied theoretically and experimentally the filter efficiency for different DOP size distributions with the same owl reading. Our studies show that the effect of varying DOP size distributions on the measured HEPA-filter penetration depends on the light-scattering-photometer response and on the HEPA-filter penetration curve, both measured as a function of particle size. HEPA-filter penetration for a heterodisperse DOP aerosol may be increased, decreased, or remain the same when compared to the filter penetration for monodisperse aerosols. Using experimental HEPA-filter penetration and photometer response curves, we show that heterodisperse DOP aerosols (D_{cmd} 0.19 and $\sigma g = 1.4$) yield 24% lower penetrations than that for monodisperse DOP aerosols ($D_{cmd} = 0.3$ and $\sigma g = 1.0$). This surprisingly small effect of the DOP heterodispersion on HEPA-filter penetration is due to the response function of the owl that is similar to the response of the photometer. Changes in the particle-size distribution are therefore seen in a similar fashion by both the photometer and the owl. We also show that replacing the owl with modern particle-size spectrometers may lead to large errors in filter penetration because the particle-size spectrometers do not provide measurements that correspond to the photometer measurements.

1. Introduction

All of the standard filter-test methods used by the U. S. and other countries are based, more or less, on a heterodisperse test aerosol which challenges the filter and on integrated measurements of the sample aerosol concentration before and after the filter. Table 1 compares the four most widely used filter-test methods.

A large number of studies have been reported in the literature describing the major filter test methods listed in Table 1.[1-5] Correlations among the various test methods have also been reported.[6,8] One manufacturer of HEPA filters even reports filter penetration for each of the filter-test methods in their commercial literature.[9]

It is important to note that the same filter tested with each of the four methods described in Table 1 has different penetration results, with the British NaCl test yielding the lowest penetration and the French uranin test the highest. In general, for these four test methods, the smaller the particle size, the higher the penetration. This trend is illustrated in Fig. 1 where we have

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Table 1. Comparison of the four major filter-test methods used world-wide today.

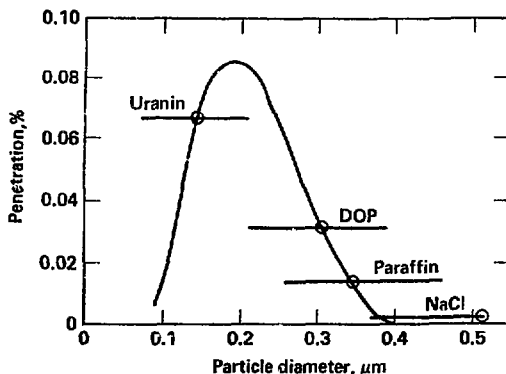| Method (ref)	Test aerosol	Volume average diameter of aerosol	Aerosol measurement
German Paraffin [5]	nebulizing hot paraffin oil, liquid aerosol	0.35)m	light-scattering photometer measures aerosols directly
British NaCl [3]	nebulizing NaCl water solution, solid aerosol	0.65)m	flame photometer measures aerosols directly
U. S. DOP [3,4]	thermal-generated DOP, liquid aerosol	0.30)m	light-scattering photometer measures aerosols directly
French uranin [2]	nebulizing uranin water solution, solid aerosol	0.15)m	aerosols first collected on filter sample; uranin dissolved from filter and measured by fluorimetry

Fig. 1. Comparison of four major filter-test methods showing the portion of the filter-penetration curve measured by each technique.

plotted the HEPA-filter penetration as a function of particle diameter against the various filter-test methods. Note that the difference in the average particle-size results in considerable variation in measured penetrations. Since the aerosols listed in Table 1 also have a broad range of particle sizes, filter-penetration tests thus represent, at best, an average penetration integrated over the particle-size range.

Although experts have recognized the disparity in the results obtained from the different test methods for many years, no one seemed to question the accuracy of these methods. In reviewing the four test methods, Dorman[5] points out that each of the tests only "give a figure of merit toward the particular test aerosol and may bear little relation to that achieved in practice." The test methods using NaCl, DOP, paraffin, and uranin aerosols have been independently developed by Great Britain, United States, West Germany, and France, respectively, and these tests have evolved into national standards for certifying HEPA filters. Each filter method has been successfully used for many years to ensure that HEPA filters meet certain minimum standards. The fact that the same filter had different penetration values for different test methods did not matter, since each test method was at least repeatable and was able to distinguish between good and bad HEPA filters. Of course, this self-consistency argument fails when filter-test results are used in complying with absolute environmental and safety standards.

In 1978, Hinds, et al. questioned the ability of the U.S. DOP test method to even provide a reliable, if not absolute, measurement of HEPA penetration.[10] They found that the DOP aerosols are not monodisperse and the owl could not distinguish between different particle-size distributions having the same owl reading. The concern was that these different particle-size distributions would yield different filter penetrations as measured by the light-scattering photometer. We shall show that the effect of DOP heterodispersion has only a small effect on the HEPA penetration measurements.

II. Theory of Present Filter Test Methods

The basic problem with present filter-test methods is that the measured filter penetration, P_M, varies with the number of particles in a given size range, r, designated as $N(r)$ [or the particle-size distribution], and the instrument response function, $R(r)$.

In general, the way in which the instruments in Table 1 respond varies approximately with the volume of particles. The measurement of aerosols sampled before the filter, M_B, therefore, is an integrated measurement of the product of $N(r)$ and $R(r)$:

$$M_B = \int_0^\infty N(r)\,R(r)\,dr \quad , \tag{1}$$

where r is the particle size. This measurement of aerosols sampled before the filter is illustrated in Fig. 2, where we have plotted relative values of $N(r)$, $R(r)$, and the product $N(r)R(r)$ as a function of r. Note that the instrument-response function gives primary weight to the larger particles in the tail of the particle distribution.

The measurement of aerosols sampled after the filter requires an additional factor to take into account that the filter has removed particles and thus has an altered particle-size distribution. The particle-size distribution of aerosols
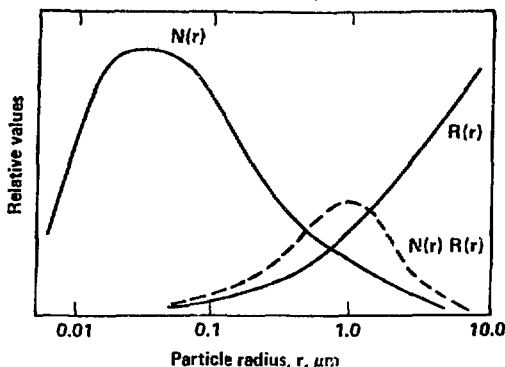
Fig. 2. The measurement of a typical heterodisperse aerosol with a single-valued detector (e.g., a photometer) equals the number of particles, $N(r)$, multiplied by the instrument response, $R(r)$, at each particle size, r, summed over all particle sizes.

sampled after the filter is the product of filter penetration, $P_F(r)$, defined by the fraction of particles passing through the filter, and the initial particle-size distribution of aerosols before the filter, $N(r)$. Figure 3 illustrates this type pf particle-size distribution. The measurement of aerosols sampled after the filter, M_A, is

$$M_A = \int_0^\infty N(r)\, P_F(r)\, R(r)\, dr \quad , \tag{2}$$

and is illustrated in Fig. 4 where we have plotted the curves for the particle-size distribution of aerosols after the filter, $N(r)P_F(r)$, $R(r)$, the product of all three terms.

The complete filter-penetration measurement, P_M, is

$$P_M = \frac{M_A}{M_0} = \frac{\displaystyle\int_0^\infty N(r)\, P_F(r)\, R(r)\, dr}{\displaystyle\int_0^\infty N(r)\, R(r)\, dr} \quad . \tag{3}$$

The primary effect of a widely ranging particle-size distribution is an underestimation of the actual filter penetration, P_F, by the measured penetration, P_M, (or conversely, an overestimation of the filter efficiency). We would like to be able to measure the filter penetration directly, and that is only possible if we have monodisperse particles. In that case, the size distribution function becomes a delta function, $\delta(r-r_0)$, where r_0 is the monodisperse size. and Eq. 3 reduces to

$$P_M = P_M(r_0) = \frac{N_A}{N_B} \tag{4}$$

-4-

where N_A is the number of particles after the filter, and N_B is the number of particles before the filter. The filter penetration at particle size r_0 can, therefore, be determined by measuring the ratio of particles before and after the filter.
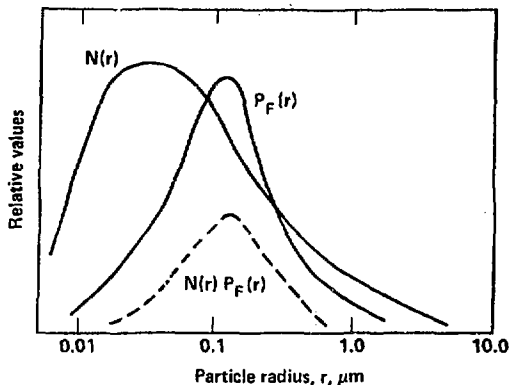

Fig. 3. The particle-size distribution of aerosols sampled after the filter equals the particle-size distributions before the filter, $N(r)$, multiplied by the filter penetration, $P_F(r)$.
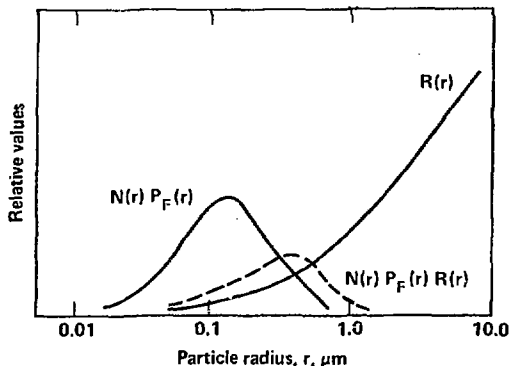

Fig. 4. The measurement of aerosols sampled after the filter with a single-valued detector (e.g., a photometer) equals the number of particles after the filter, $N(r)P_F(r)$, multiplied by the instrument response, $R(r)$, at each particle size, summed over all particle sizes.

In order to avoid the overestimation of filter efficiency due to heterodisperse DOP aerosols, a large and complex vaporizer/condenser is used to generate monodisperse aerosols. Recent findings, however, have shown that DOP is not a monodisperse aerosol.

III. Accuracy of DOP Filter-Certification Test and Filter Penetration is Questioned

Several investigators have found that DOP aerosols in the HEPA-filter-certification tests are not monodisperse 0.3-μm-diameter particles as had been assumed, but rather, are heterodisperse aerosols with a count median diameter of 0.18 μm and a geometric standard deviation of 1.4.[7-12] There was serious concern that, because of the heterodispersion of this aerosol, the measured values of filter penetration were underestimations of the true filter penetration $[P_F(0.3)]$. This concern was compounded when researchers also discovered that the owl gave the same reading for a large number of different particle-size distributions.

The owl is an instrument that measures the size of monodisperse aerosols by measuring the ratio of scattered light at two polarizations. Parameters that control the DOP-aerosol generator are adjusted until the proper owl reading is obtained corresponding to 0.3-μm-diameter particles. A filter-penetration measurement can then be made by measuring an aerosol sample with a light-scattering photometer before and after the filter as shown in Fig. 5.

The owl's problem with the discovery that DOP aerosols are not monodisperse is its inability to uniquely define the particle-size distribution and the possible underestimation of the filter penetration. This is illustrated in Fig. 6 where three particle-size distributions yield the same owl reading. The broadest distribution in Fig. 6 is representative of the DOP aerosols used in HEPA-certification tests. Hinds et al.[10] determined that the owl sees an average particle size weighted to the power 8.1:

$$R_{owl}(r) = K_1 \overline{r^{8.1}} \qquad (5)$$

where $R_{owl}(r)$ = the owl response to a particle of radius r and K_1 is a proportionality factor.

Any number of particle-size distributions, like the ones in Fig. 6 that have the same weighted average size given by Eq. 5, will yield the same owl reading. Thus, the validity of current DOP tests has been placed in question by the inability of the owl to uniquely measure the particle-size distribution.
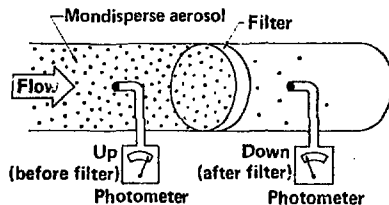

Fig. 5. Schematic showing the key components of a filter-test method using monodisperse aerosols and a single valued detector.
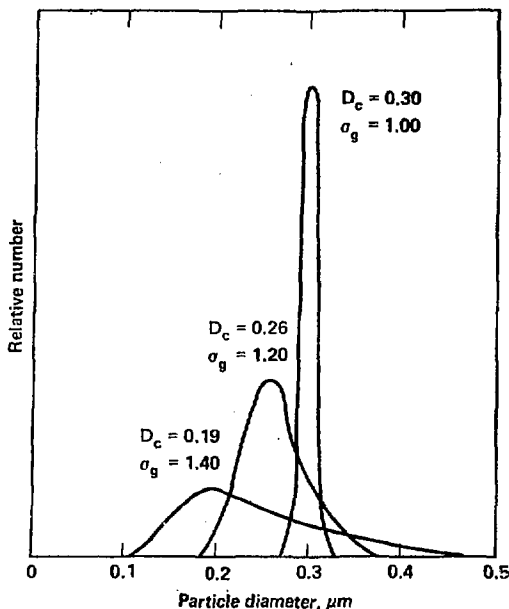
Fig. 6. Three different particle-size distributions that produced identical measurements of average size by the "owl."

IV. The Owl Performs Much Better than the Laser Spectrometer in the DOP Filter Certification Test

There is an effort by some researchers to replace the owl in the present DOP test with an instrument like the PMS-laser spectrometer (Particle Measuring System, Inc., Boulder, CO). This is an effort that we feel is unwarranted if filter penetrations are still measured with a light-scattering photometer. This effort is motivated by the fact that the owl cannot measure particle-size distributions while the PMS-laser can.[13] Independent tests with a PMS-laser spectrometer have shown that DOP aerosols have a broad range of particle-size distributions with a significant number of particles exceeding 0.3 μm in diameter. The concern is that these larger particles create deceivingly low HEPA-filter penetrations since a small increase in the size of DOP aerosols will result in a large decrease in filter penetration (Fig. 1). We feel that replacing the owl with a laser spectrometer may create serious problems with filter-efficiency tests.

Our analysis of the DOP filter tests has shown that the owl performs a complicated and necessary function in the filter test. The owl is used in adjusting the particle-size distribution so that the light-scattering photometer sees the heterodisperse DOP aerosol as monodisperse 0.3-μm-diameter particles. Figure 7 shows that the owl and the photometer have a similar instrument response as a function of particle diameter. Thus, as a first approximation, the
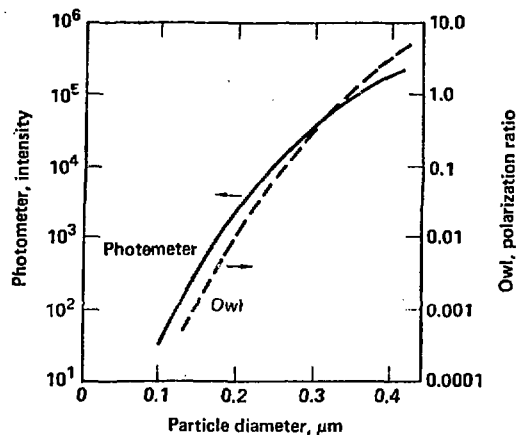
-7-

Fig. 7. Response of light—scattering photometer and owl to different particle sizes.

photometer also sees the various particle-size distributions shown in Fig. 6 as monodisperse 0.3-µm-diameter particles. This is only an approximation, and, as Fig. 7 shows, the two curves do not overlap exactly. The comparable equation for the photometer response was taken from data by Tillary, et al.[14] and is

$$R_{phot}(r) = K_2 \, r^{6.3} \quad , \tag{6}$$

where K_2 is a proportionality constant. This equation is valid from diameters of 0.1 to 0.4 µm. If the particles have a log-normal distribution, then it is possible to calculate an equivalent monodisperse diameter that will give the same readings on either the photometer or the owl. The equivalent monodisperse diameters for the owl and the photometer are given by Eqs. 7 and 8, respectively:

$$\tag{7}$$

$$\ln D_{owl} = \ln D_{cmd} + 4.05 \ln^2 \sigma_g \quad \text{and}$$

$$\ln D_{phot} = \ln D_{cmd} + 3.1 \ln^2 \sigma_g \quad , \tag{8}$$

where D_{cmd} is the count median diameter and σ_g is the geometric standard deviation of the particle-size distribution.

Equation 8 can be used to calculate equivalent monodisperse-particle diameters for heterodisperse aerosols as measured by the photometer. Figure 8 shows the equivalent diameter plotted as a function of increasing hetero-
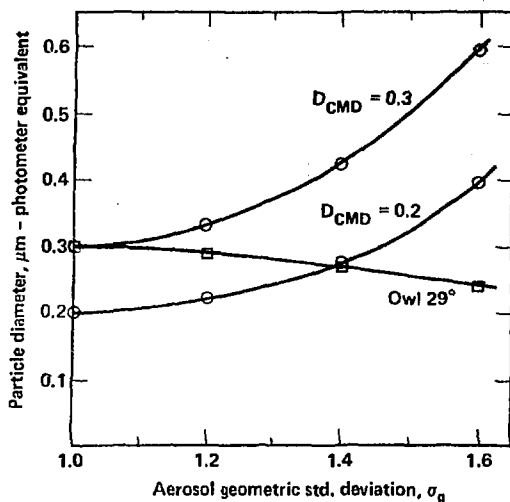
-8-

Fig. 8. The equivalent photometer diameter calculated from Eq. 9 for three different particle-size distributions as a function of increasing aerosol heterodispersion. The particle-size distributions for two of the curves have a constant count median diameter, D_{cmd}, as the heterodispersion, σ_g, increases. The particle-size distribution for the owl with a 29° reading is determined from Eq. 8 and shown in Fig. 6.

dispersion for three cases. The two identified as $D_{cmd} = 0.3$ and $D_{cmd} = 0.2$ represent particle-size distributions in which the count median diameters are kept constant and the heterodispersion is allowed to increase. Note that the equivalent photometer diameter increases significantly with increasing heterodispersion. The curve labeled owl 29° represents a series of increasingly heterodisperse aerosols, as shown in Fig. 6, in which the owl sees an equivalent 0.3-μm-diameter aerosol, as given by Eq. 7. Note that the equivalent photometer diameter for a constant owl value decreases only slightly as the heterodispersion of the aerosols increases. Thus, we see that the owl provides an approximate measure of 0.3-μm aerosol as seen by the photometer even for heterodisperse aerosols. We would therefore expect that the filter-penetration measurement using heterodisperse aerosols having a photometer equivalent diameter of 0.3 μm would yield similar results to penetration measurements using monodisperse 0.3-μm aerosols.

To test this hypothesis, we computed the penetration of a HEPA filter using Eq. 3 for various particle-size distributions, $N(r)$, all having the same owl reading. Particle-size distributions with various D_{cmd} and σ_g were selected that had $D_{owl} = 0.3$ μm in Eq. 7. The filter-penetration function, $^gP_F(r)$, used in these calculations is the solid curve shown in Fig. 9 that represents a least-squares best fit of a log-normal distribution to the experimental measurements shown as triangles. The best fitting log-normal curve is characterized by $D_{cmd} = 0.143$ μm and $\sigma_g \approx 1.47$. Details of the experimental technique used to generate the HEPA-filter penetration curve are given in Appendix A. The photometer
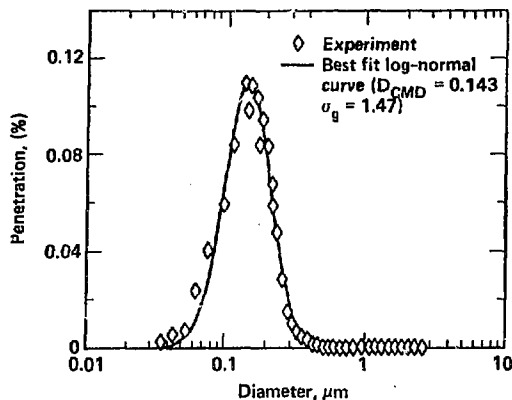
-9-

Fig. 9. Experimental penetration of a HEPA filter as a function of DOS particle diameter.

response function $R(r)$ used in these calculations is given by Eq. 6 which is derived from data presented by Tillary, et al.[14] Figure 10 shows that increasing the heterodispersion of particle-size distributions that have the same owl reading of 29° (Fig. 6 shows three of these distributions) causes only a 24% reduction in filter penetration. In contrast, increasing the heterodispersion while maintaining a constant count medium diameter of 0.2 μm causes an 87% reduction in the filter penetration. The purpose of measuring the particle size in DOP filter certification tests is to ensure that filter-penetration measurements are made with DOP aerosols having an effective diameter of 0.3 μm. It is clear from Fig. 10 that the owl is better suited for measuring the effective particle size in the current filter test than a laser particle-size spectrometer.

Although these aerosol-size spectrometers are able to uniquely define the particle-size distributions, they are unable to perform the function that the owl so simply and so elegantly performs. Figure 10 also shows that potentially serious errors in filter penetration can arise with the replacement of the owl by an optical spectrometer. Only when the σ_g is within a narrow range of about 1.4 will the filter efficiencies obtained with an aerosol size spectrometer have results comparable to that of using an owl.
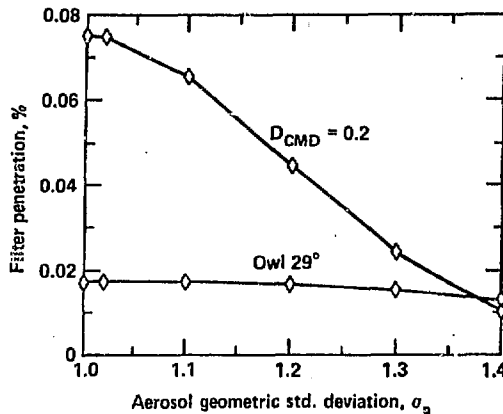
Fig. 10. Calculated filter penetration using Eq. 3 as a function of increasing aerosol heterodispersion. The curve for Owl 29° was calculated for particle size distributions satisfying Eq. 6 with $D_{Owl} = 0.3$ μm. The curve for $D_{cmd} = 0.2$ was calculated for particle size distributions having a constant D_{cmd}.

V. Sensitivity of DOP Filter Test to Heterodisperse Aerosols, HEPA Penetration Curve and Photometer Response Function

The filter penetration measurement is a function of the particle-size distribution, the filter penetration curve, and the photometer response as shown by Eq. 3. Our analysis of the effect of DOP heterodispersion on HEPA penetration was based on using experimental HEPA penetration and photometer response curves. However, in order to determine the sensitivity of our penetration calculations to variations in the HEPA penetration and photometer response curves, we repeated the calculations in the previous section.

The HEPA penetration curve used in generating Fig. 10 is characterized by a log-normal curve having $D_{cmd} = 0.143$ μm and $\sigma_g = 1.47$. We repeated the calculation of the filter penetration measurement using Eq. 3 for other values of D_{cmd} and σ_g. The previous photometer response curve given by Eq. 5 was also used in these calculations. As before, the parameters for the particle-size distributions having a constant owl reading of 29° are given by Eq. 7.

Figure 11 shows the calculated HEPA penetration using Eq. 3 as a function of increasing DOP heterodispersion for HEPA-filter penetration curves characterized by a constant $D_{cmd} = 0.143$ μm and σ_g values of 1.3, 1.4, 1.47 and 1.6. The solid curves represent filter-penetration calculations for DOP aerosols having a constant 29° owl reading. The parameters for these aerosol distributions are given by Eq. 7. The dashed lines represent DOP aerosols having a constant $D_{cmd} = 0.2$ μm and the σ_g values indicated on the abscissa. Figure 11 shows that the relative HEPA penetration for aerosol distributions having a constant owl reading
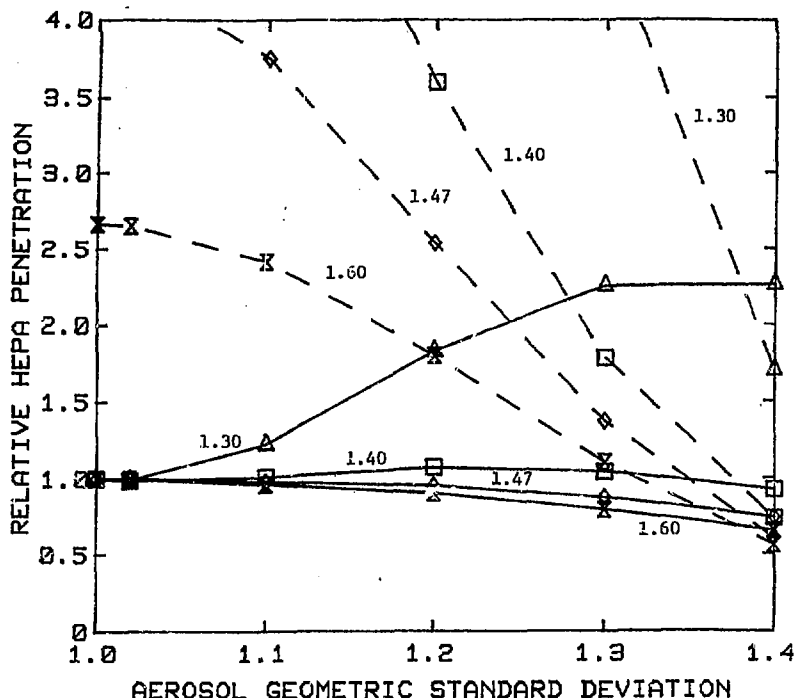
-11-

Fig. 11. Calculated filter penetration using Eq. 3 as a function of increasing aerosol heterodispersion for HEPA filter penetration curves characterized by a constant D_{cmd} = 0.143 μm and σ_g values of 1.3, 1.40, 1.47, and 1.6. The solid lines represent penetration calculations for DOP aerosols having a constant 29° reading (Eq. 7) while the dashed lines represent aerosols with a constant D_{cmd} = 0.2 μm.

deviates much less with increasing DOP heterodispersion than does the penetration for aerosol distributions having a constant D_{cmd}. It is noteworthy that the calculated filter penetration for aerosols having a constant owl reading is relatively insensitive to a broadening of the penetration curve as the σ_g increased from 1.47 to 1.6. However, a narrowing of the penetration curve from σ = 1.47 to 1.30 shows a significant deviation in calculated filter penetrations between monodisperse and heterodisperse DOP aerosols. In contrast, all of the curves in Fig. 11 for aerosols having a constant D_{cmd} = 0.2 μm show major charges in calculated filter penetration between monodisperse and heterodisperse DOP aerosols.

A similar series of calculated filter penetrations were made for HEPA-filter penetration curves having a constant σ_g = 1.47 and D_{cmd} values of 0.1, 0.143, 0.12, and 0.2. These calculations are shown in Fig. 12 for DCP aerosols having a constant 29° reading (solid lines) and for DOP aerosols having a constant D_{cmd} =
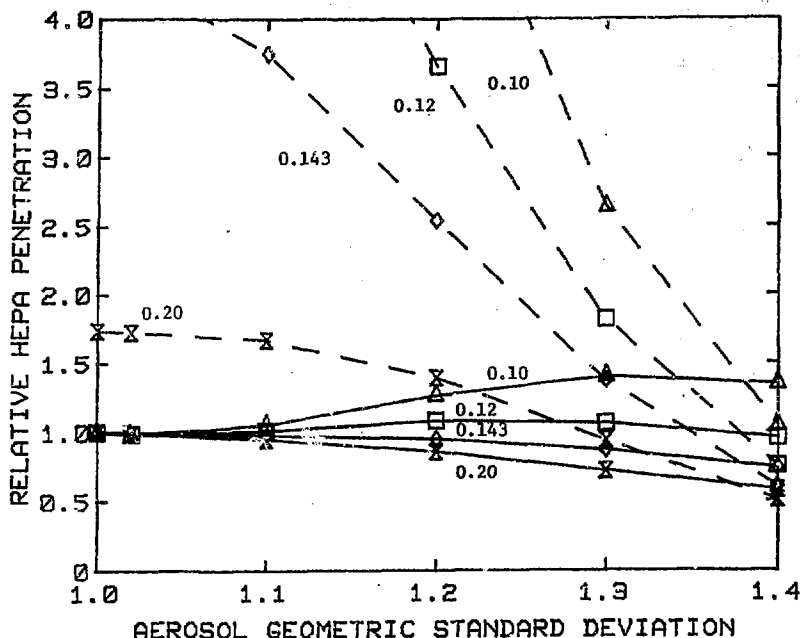
Fig. 12. Calculated filter penetration using Eq. 3 as a function of increasing aerosol heterodispersion for HEPA filter penetration curves characterized by a constant $\sigma_g = 1.47$ and D_{cmd} values of 0.10, 0.12, 0.143, and 0.20. The solid lines represent penetration calculations for DOP aerosols having a constant 29° reading (Eq. 7) while the dashed lines represent aerosols with a constant $D_{cmd} = 0.2$ μm.

0.2 μm (dashed lined). Again, it is apparent that the owl is preferred over particle-size spectrometers to maintain the desired DOP size distribution for use in HEPA-penetration measurements.

The sensitivity of the photometer response curve on the calculated HEPA penetrations was then examined. We used Eq. 6 in our previous calculations since this equation was derived from both theoretical[14] and experimental[15] data. To determine the sensitivity of changes in the photometer response curve on the calculated HEPA penetration, we have repeated the calculations using the following response functions.

$$R_{phot}(r) = K_3 \, r^5 \tag{9}$$

$$R_{phot}(r) = K_4 \, r^7 \tag{10}$$
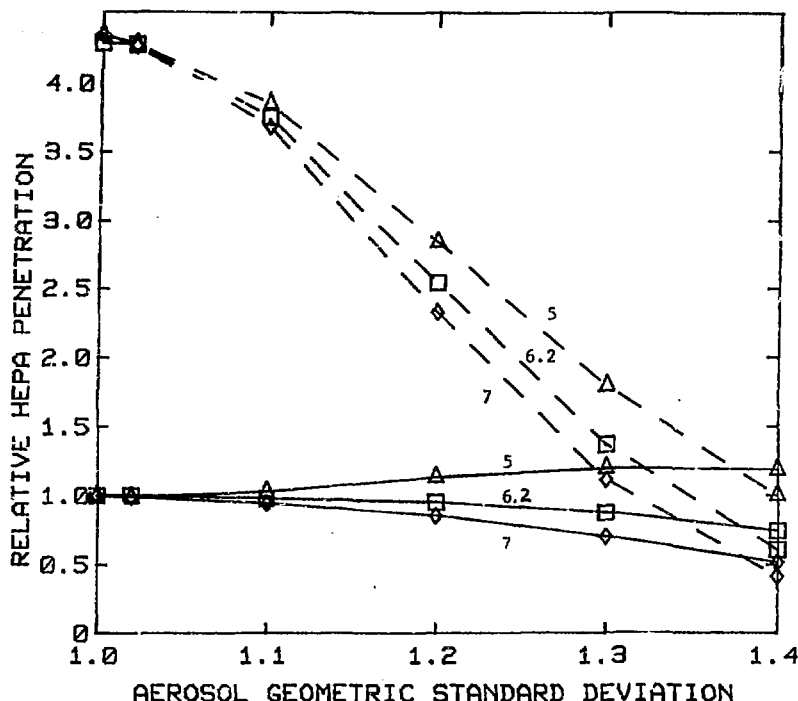
-13-

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Fig. 13. Calculated filter penetration using Eq. 3 as a function of increasing aerosol heterodispersion, for different photometer response functions characterized by r^5, $r^{6.2}$, and r^7. The solid lines represent penetration calculations for DOP aerosols having a constant $29°$ reading (Eq. 7) while the dashed lines represent aerosols with a constant $D_{cmd} = 0.2$ μm.

Figure 13 shows that the penetration curves for DOP aerosols having a constant $29°$ reading are relatively insensitive to changes from monodisperse to heterodisperse aerosols, while the calculated penetration for DOP aerosols having a constant $D_{cmd} = 0.2$ μm shows major changes in HEPA penetration as the DOP aerosol changes from monodisperse to heterodisperse.

A comparison of Figs. 11-13 shows that the DOP filter test is only moderately sensitive to the degree of aerosol heterodispersion, HEPA penetration, and the photometer response when the aerosol size distribution maintains a constant owl value of $29°$. However, if the DOP aerosols are maintained at a constant $D_{cmd} = 0.2$ μm, then the DOP filter test becomes very sensitive to these three parameters. Although the owl cannot measure the size distribution of heterodisperse aerosols, the owl is superior to the spectrometers for measuring aerosol size in the current DOP-filter test. Figures 11-13 show that the DOP

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filter test is far less sensitive to test variables when the owl is used than when a particle-size spectrometer is used for controlling the particle size. The primary reason for the owl's superior performance is that a constant owl reading yields a nearly constant photometer equivalent particle size as the degree of heterodispersion is increased.

This behavior is shown in Fig. 8. In contrast, maintaining a constant D_{cmd} with the aid of a particle-size spectrometer as the degree of heterodispersion increases will significantly shift the equivalent photometer diameter.

VI. Conclusion

We investigated the effect of DOP heterodispersion on HEPA-filter penetration measurements and determined that a typical heterodisperse DOP aerosol (D_{cmd} = 0.19 µm and σ_g = 1.4) results in a 24% lower penetration than that obtained for monodisperse DOP aerosols (D_{cmd} = 0.3 and σ_g = 1.0). The surprisingly small effect of the DOP heterodispersion on the HEPA-filter penetration is due to the response function of the owl that is similar to the response of the photometer. Changes in the particle-size distribution are therefore seen in a similar fashion by both the photometer and the owl. We have also shown that replacing the owl with particle-size spectrometers may lead to large errors in filter penetration. These errors are produced because the particle-size spectrometers do not provide measurements that correspond to the photometer measurements.

VII. Appendix A

Experimental Technique for Measuring HEPA-Filter Penetration as a Function of Particle Size

The essential experimental apparatus used to generate the HEPA-filter penetration as a function of DOS particle size is shown in Fig. A-1. An aerosol spectrometer is used to measure the concentration of aerosols as a function of particle size before and after the HEPA filter. The ratio of the aerosol concentration before and after the HEPA filter for each particle size increment yields the HEPA penetration as a function of particle size. The aerosol spectrometer used in these tests consists of two instruments: (1) a differential mobility analyzer (DMA) coupled to a condensation nuclei counter (CNC) (Thermal Systems, Incorporated, Minneapolis, Minnesota) for measuring particle-size distributions from 0.01 to 0.5 µm diameter, and (2) a LAS-X laser particle counter (Particle Measuring Systems, Bolder, Colorado) to measure particle-size distributions from 0.1 to 3.0 µm. Both of these instruments are interfaced to a LSI-11 computer that gathers data and reduces it to graphical output.

A dilution system is required to reduce the high aerosol concentration before the HEPA filter to a level acceptable to the aerosol spectrometer. The dilution system is primarily required for the LAS-X laser particle counter to prevent counting more than one particle at the same time. Figure A-2 is a schematic of the diluter we used. In order to reach the desired dilution rate of 1500:1, we had to use two diluters in series.

An important factor to know when using a diluter is the particle losses in the dilution system that results in a variable dilution as a function of particle size. Figure A-3 shows the dilution ratio as a function of particle size for the dilution system used in our tests. We have taken this variable dilution into account in computing the HEPA-filter penetration as a function of particle size that is shown in Fig. 9.
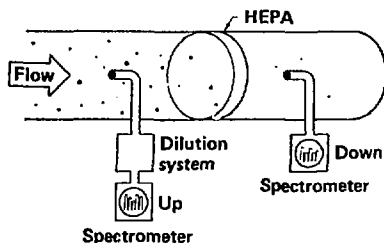
Fig. A-1. Schematic of filter test method for measuring filter penetration of HEPA filters as a function of particle size by using a dilution system to reduce the upstream concentration of aerosols.
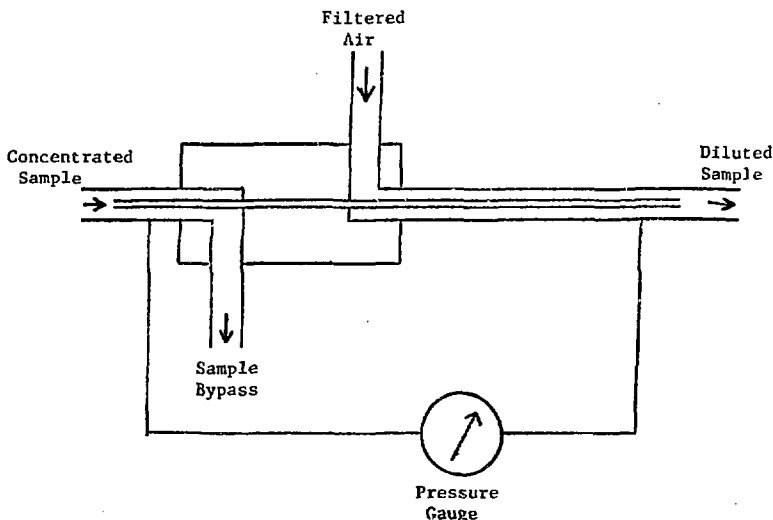

Fig. A-2. Schematic of diluter based on the principle of transferring a small volume of concentrated aerosols through a needle to a large volume of filtered air. The pressure differential across the needle determines the flow through the transfer needle.
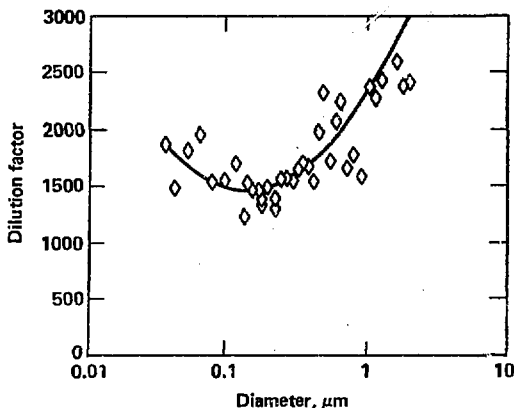
-16-

Fig. A-3. Dilution ratio as a function of particle size for two diluters in series. Solid curve represents least-squares fit.

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